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Rothermel's Model and the Role of Fuel Bed Structure

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Introduction

Half a century after its introduction Rothermel's flame spread model (Rothermel 1972) continues to find widespread use within fire modelling tools (e.g. BehavePlus, NEXUS, FARSITE) with few modifications incorporated (Albini 1976; Andrews *et al.* 2013). Rothermel's model is underpinned by a physics-based framework based on conservation of energy, with the spread rate (R) described as the ratio between the energy transferred to the fuel (heat source) and the energy required for ignition (heat sink),

$$R = (I_R \, \xi \, (1 + \phi_w + \phi_s)) / (\rho_b \, \epsilon \, Q_{ig}) \qquad (1)$$

where the energy transferred to the unburnt fuel incorporates reaction intensity (I_R), propagating flux ratio (ξ), and wind (ϕ_w) and slope correction factors (ϕ_s). Energy required for ignition is given by the product of the oven-dry bulk density (ρ_b), effective heating number (ϵ), and heat of pre-ignition (Q_{ig}).

Empirical values of reaction intensity (the heat release rate per unit area of the fire front) across a range of packing ratios were obtained through laboratory-based experiments in three fuel types (excelsior, ½ and ¼ inch sticks), however, the fuel loading was not held constant within or between the three different fuel types. This lack of systematic variation limits understanding of the independent effects of fuel loading and packing ratio despite the importance of both fuel properties on the fire behavior within surface fuel layers (Campbell-Lochrie *et al.* 2021; Gallagher *et al.* 2021) and it has been suggested that the model may be oversensitive to fuel height (Cruz and Fernandes 2008).

Changes in fire management strategies, focusing on increasing prescribed burning, drive a need for improved fire behavior models to aid in planning, training, and strategy development (Hiers *et al.* 2020; Sample *et al.* 2022). It is therefore important to understand the implications of using a model developed using a small number of fuel types to predict the effect of fuel structure on the rate of spread across a range of natural fuel types. In this study, the performance of the Rothermel model across a range of (pine needle) fuel bed structures was investigated through comparison with an existing experimental dataset (Campbell-Lochrie *et al.* 2021).

Methods

The effect of fuel bed structure on fire behavior in surface fuels was previously studied in a series of quiescent (no wind or slope) laboratory-based flame spread experiments (Campbell-Lochrie *et al.* 2021) involving linear flame spread (as shown in Figure 1). The spread rate was measured through video analysis of the flame front position over time. The Heat Release Rate was calculated using oxygen consumption calorimetry and converted to fireline intensity by dividing by the length of the fire front.

Figure 31. Example of linear flame spread experiments conducted in quiescent, laboratory environment

Fuel beds (1.5 m by 0.67 m) were constructed from either Pitch Pine (*Pinus Rigida* Mill.) or Pitch-Loblolly Pine hybrid *(Pinus rigida x taeda)* needles, with fuel moisture content measured prior to ignition. The fuel loading and bulk density of pine needle beds were independently varied (by controlling fuel height) and ranged from 0.2 to 1.6 kg/m^2 and 10 to 40 kg/m^3 respectively. The overall fuel bed structure was described by the single parameter $\alpha\sigma\delta$ which combines fuel bed porosity (α), surface-to-volume ratio (σ) and fuel bed height (δ) and was shown to be strongly correlated with spread rate.

For spread-rate predictions, Rothermel's original model was used, however Albini's modifications (Albini 1976) were incorporated along with conversion to SI units (Wilson 1980). The Albini modifications relevant to homogeneous fuel beds involve updated terms for the combustible dry fuel loading, mineral damping coefficient and reaction velocity variable. This model was implemented within MATLAB and verified through comparison with BehavePlus (Version 6).

Results

Rate of Spread

Experimental observations and Rothermel model predictions both indicate a positive trend between Rate of Spread (RoS) and either fuel loading or ασδ, and a negative trend between RoS and bulk density. As shown in Figure 2, predicted RoS values were typically lower than experimental observations. The model predicted flame spread at the lowest fuel loading (0.2 kg/m^2) for Pitch-Loblolly hybrid pine needle fuel beds, however sustained flame spread did not occur in the experiments.

The deviation between experimental and observed RoS was calculated according to the Absolute Percent Error and ranged from -75 % to 12 %. As shown in Figure 2, the deviation varied with ασδ with the greatest under-predictions occurring in the lower ασδ range (ασδ =49 to ασδ =200) with little deviation at greater ασδ values (max. absolute deviation of 13 % for ασδ > 200). Deviation also increased at greater packing ratios (lower fuel heights) for a given fuel loading, which supports previous suggestions of an oversensitivity to compaction.

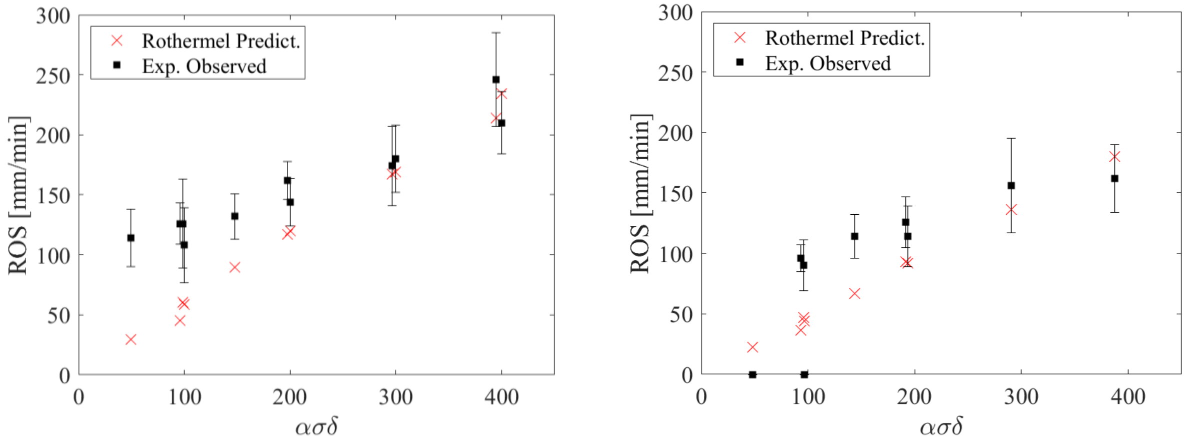

Figure 32. Comparison of predicted and experimentally observed Rate of Spread (RoS) for (left) Pitch Pine and (right) Pitch-Loblolly hybrid Pine Needles

Reaction Intensity

According to Equation 1, under-predictions of the RoS may occur due to under-prediction of the heat source term or over-prediction of the heat sink term. In this study, the experimentally observed fireline intensity allows further analysis of the suitability of the predicted reaction intensity across a range of fuel bed conditions.

Byram's fireline intensity describes the heat release rate per unit length of the flame front whereas the reaction intensity describes the heat release rate per unit area of the fire front. The experimentally observed Byram fireline intensity (I_B) was converted to a reaction intensity using

$$I_B = (I_R \, t_R \, R) / 60 \qquad (2)$$

where the residence time (t_R) was estimated using (Anderson 1969)

$$t_R = 8d = 384 / \sigma \tag{3}$$

Diameter (d) and surface-to-volume ratio (σ) measurements for both species were used with the average residence time calculated (20 seconds).

As shown in Figure 3, comparison of the experimentally observed and predicted reaction intensity resulted in underestimates with increased divergence in the lower $\alpha\sigma\delta$ range ($\alpha\sigma\delta = 49$ to $\alpha\sigma\delta = 200$). This suggests an under-prediction of the energy release within the flame front particularly in lower $\alpha\sigma\delta$ fuel beds in which the greatest deviations in predicted and observed spread rates occurred.

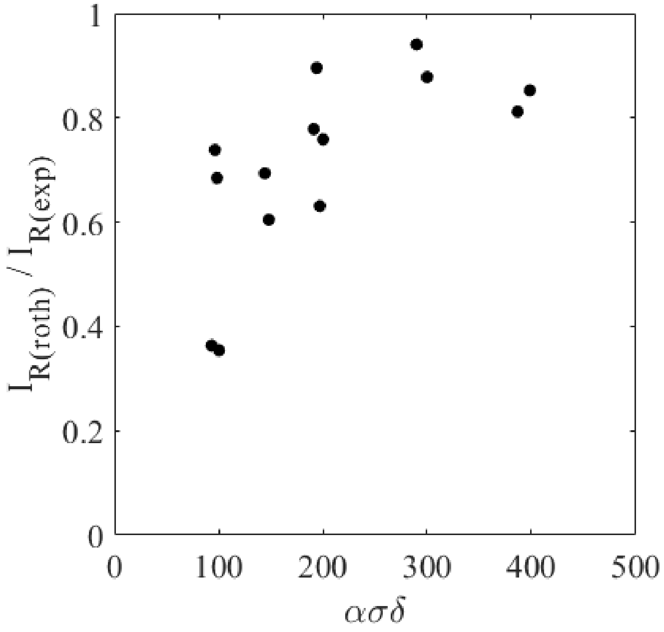

Figure 33. Ratio of predicted reaction intensity ($I_{R(roth)}$) to experimentally observed reaction intensity ($I_{R(exp)}$) for both pine needle species. Lowest fuel loading cases excluded due to the lack of sustained linear flame front.

Conclusions

An oversensitivity of Rothermel's flame spread model to fuel bed compaction was observed for low-intensity flame spread in pine needle beds. Comparison of experimental observations of spread rate with Rothermel model predictions resulted in increased divergence for fuel beds of lower $\alpha\sigma\delta$ values ($\alpha\sigma\delta = 49$ to $\alpha\sigma\delta = 200$). For fuel beds of constant fuel loading, greater under-predictions of spread rate occurred for compressed (lower fuel height, greater packing ratio) fuel beds. This appears to be at least in part due to the under-prediction of reaction intensity particularly in the lower $\alpha\sigma\delta$ range. Incorporating an increased understanding of the effect of fuel structure will aid the continued use of the Rothermel model in the planning of fuels management and prescribed fire operations by supporting the use of refined fuel representations and by improving predictions of energy release outputs that subsequently drive flame-spread and fire-effects predictions.

Acknowledgements

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