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ON THE FIRE-SPREAD RATE INFLUENCE OF SOME FUEL BED PARAMETERS DERIVED FROM ROTHERMEL'S MODEL THERMAL ENERGY BALANCE

O UTJECAJU POJEDINIH PARAMETARA LOŽIŠTA IZVEDENIH IZ ROTHERMELOVOG MODELA RAVNOTEŽE TOPLINSKE ENERGIJE NA STOPU ŠIRENJA POŽARA

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Summary

We analysed the role of some fuel bed properties on forest fire-spread rate based on the thermal energy balance upon which the well-known fire-spread rate model of Rothermel (1972) was developed, showing that neither fuel bed height, load or density directly influence the thermal energy balance. The influence of such parameters, often inferred from empirical descriptions of spread rate, must result from indirect effects on heat transfer mechanisms. The fraction of heat transferred from the flame to the unburned fuel depends mostly on fuel moisture content and is independent of spread rate and flame geometry. Because empirical models usually implicitly assume the underlying mechanisms of fire spread for describing fire behaviour, this study results can assist at idealizing and delineating future experiments and approaches.

KEY WORDS: fire behaviour, forest fires, combustion, heat transfer.

INTRODUCTION
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The ability to predict fire behaviour characteristics such as rate of spread, flame dimensions and heat release rate is central to effective forest fire management, from planning to operational decision-making. Rothermel (1972), following the formulation of Frandsen (1971), proposed a fire-spread model based on several empirical parameters determined from laboratory burn experiments. This model became the basis for well-known fire behaviour prediction systems and, although many fire-behaviour modelling studies were published since, no other has replaced it in terms of popularity. This is understandable because forest fire involves complex phenomena to which several fundamental subjects pertain, namely combustion, heat transfer, and fluid mechanics (Finney et al. 2015; Rossa et al. 2015), and finding a better compromise between a rigorous physical approach and the simplicity of empirical modelling is a difficult task.

Rothermel (1972) formulated rate of spread (R) based on the ratio between the net heat flux through the fuel bed ($Q^{"}$) and the amount of energy necessary for igniting the fuel, which depends on fuel bed density (ρ_b). A considerable number of empirical formulations for predicting R have

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used ρ_b ever since (*e.g.*, Thomas 1971; Catchpole et al. 1998; Anderson et al. 2015; Rossa and Fernandes 2017), sometimes arguing that its negative effect on R could be explained based on Rothermel's formulation. Although ρ_b depends on fuel load (w) and bed height (δ), the effect of w on R is not as consensual as the effect of ρ_b on R, being variously reported as non-existent (*e.g.*, Cheney et al. 1993), negligible (McAlpine 1995), or positive (*e.g.*, McArthur 1962; Dupuy 1995). Fuel bed height is also recurrently used in empirical formulations and its positive effect on R is quite consensual.

Empirical models are undeniably useful. However, the fundamental reasons behind the effects of input variables are seldom present, as a theoretical basis to understand the physical mechanisms underlying fire spread is missing. We believe that, possibly because of misinterpretation of previous physical modelling efforts, both in the case of the well-established influence of ρ_b on R as well as in the disputed effect of w on R, the role of such fuel bed parameters in fire spread is not well understood.

This work discusses the influence of some fuel bed parameters on R. The discussion is based on a simplified thermal energy balance of fire spread derived from an R formulation given by the ratio between Q'' and the energy necessary for fuel ignition (Thomas 1971; Frandsen 1971; Rothermel 1972).

ANALYSIS OF THE THERMAL ENERGY BALANCE DURING FIRE SPREAD
ANALIZA RAVNOTEŽE TOPLINSKE ENERGIJE TIJEKOM ŠIRENJA POŽARA

Formulation of fire-spread rate – *Definiranje stope širenja požara*

Equation (1), like that used as a base for Rothermel's (1972) model development, gives steady-state R as the ratio between Q" originated by the flame (heat source) and the energy absorbed by the fuel until ignition is achieved (heat sink):

$$R = \frac{Q''}{\rho_b Q_i} \qquad (1)$$

where Q_i is the heat per unit mass necessary for igniting the fuel. Basically, this relation describes what happens but not how it happens. Concluding that a ρ_b increase will decrease R based only on this thermal energy balance implies ignoring that an increase on the amount of fuel acting as an heat sink also means an increase on the amount of flaming fuel releasing heat and therefore on Q'', as will be shown below.

Equation (2) gives ρ_b, which quantifies the amount of fuel per unit volume of the bed:

$$\rho_b = \frac{w}{\delta} \qquad (2)$$

and Q_i can be calculated using:

$$Q_i = c_f(T_i - T_f) + \frac{M}{100}\left[c_w(T_v - T_f) + Q_w\right] \qquad (3)$$

where c_f is the fuel-specific heat, T_i the ignition temperature, T_f the fuel initial temperature, M moisture content expressed as a percentage of the oven-dry fuel mass, c_w water-specific heat, T_v water boiling temperature, and Q_w water latent heat of evaporation. Q'' determination in Rothermel (1972) includes a term obtained by integration over flame depth (D). Nevertheless, the resulting propagating flux refers to the horizontal net heat power transferred per unit vertical cross section of the fuel bed (Frandsen 1971). Thus, Q'' can be computed as:

$$Q'' = \frac{\dot{Q}_{fl}\,\eta}{\delta} \qquad (4)$$

where Q_{fl} is the power released per unit fireline length, *i.e.*, Byram's intensity (Byram 1959), used in a plethora of studies (*e.g.*, Kucuk et al. 2015), and η the fraction of heat transferred from the flame to the unburned fuel. On the other hand, Q_{fl} can be obtained from:

$$\dot{Q}_{fl} = \frac{Q_f\, w\, f_{fl}\, D}{t_r} \qquad (5)$$

where Q_f, f_{fl}, and t_r are, respectively, fuel low heat content, the fraction of fuel that burns in flaming combustion, and flame residence time. Substituting equation (2) in (1) and successively substituting equation (5) in (4) and in (1) we obtain:

$$R = \frac{D}{t_r}\frac{Q_f\, f_{fl}\,\eta}{Q_i} \qquad (6)$$

We can confirm that this R formulation does not depend on ρ_b because both the numerator and denominator of equation (1) are a function of the amount of fuel per unit volume of the bed, *i.e.*, w/δ, which allowed removing it from the equation. This means that the effect of ρ_b, established in a great number of empirical studies, cannot be directly inferred from the thermal energy balance expressed in equation (1), which is equivalent to equation (6).

Fraction of heat transferred from the flame to the unburned fuel – *Udio topline koja se prenosi od plamena do nesagorijelog goriva*

A further analysis of equation (6) allows concluding that, because the 1st term on the right side of the equation (D/t_r) yields R by itself (Anderson 1964), the 2nd term must equal unity. Having this in mind, we can obtain:

$$\eta = \frac{Q_i}{Q_f\, f_{fl}} \qquad (7)$$

i.e., η can be deduced from the ratio between the energy that a unit mass of fuel needs for being ignited and the energy it

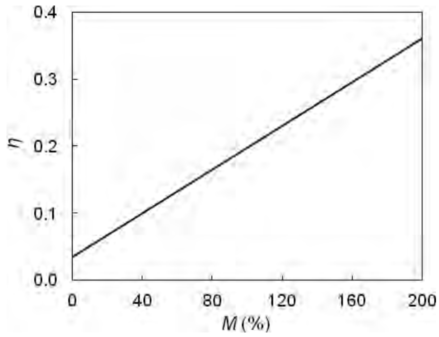

Figure 1. Fraction of heat transferred from the flame to the unburned fuel (*M*) as a function of fuel moisture content (*M*) for a fixed fuel temperature (T_f) of 20 °C.

Slika 1. Udio topline prenesen od plamena do nesagorijelog goriva (η) kao funkcija sadržaja vlage goriva (*M*) za fiksnu temperaturu goriva (T_f) od 20 °C.

releases during flaming combustion. The determination of η depends on two variables, T_f and *M*, and on several parameters that can be assumed constant. This leads to a somewhat counterintuitive conclusion: the fraction of heat transferred from the flame to the fuel bed does not depend on *R* or on any aspect of flame geometry. During its heat sink phase, *i.e.*, before igniting and becoming a heat source, fuel can only absorb a fraction of the energy released by combustion corresponding to ignition requirements, which implies that the remaining heat is dissipated elsewhere, regardless of flame configuration or how fast fire spreads. This is similar to what happens when we have a pan with boiling water above a flame: if flame power is increased, a unit mass of water does absorb energy beyond evaporation requirements, there is just a bigger amount of water being vaporized.

To compute η we used experimental data for foliage fuels from Susott (1982) to obtain averaged Q_f and f_{fl} values of, respectively, 22111 kJ kg^{-1} and 0.719. Values of the physical constants in equation (3) were taken as c_f = 1.82 kJ kg^{-1} °C^{-1} (Balbi et al. 2014), T_i = 320 °C, T_v = 100 °C, Q_w = 2260 kJ kg^{-1} and c_w = 4.19 kJ kg^{-1} °C^{-1} (Catchpole and Catchpole 1991). We chose an arbitrary value of T_f = 20 °C for obtain η as a function of *M* (Figure 1).

DISCUSSION AND CONCLUSION
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Based on equation (1) we derived equation (6) and inferred that the thermal energy balance presented in (1) is independent from ρ_b, and thus from *w* and δ. This does not imply that they do not influence *R* nor that empirical studies should not use them. But because equation (1) does not give any information on the processes that lead to the establishment of such balance, namely on the mechanisms of heat transfer, effects of those fuel properties on *R* cannot be directly inferred from Rothermel's model thermal energy balance. Nevertheless, the model from Rossa (2017) for the ratio between *R* in the absence of wind or slope and δ, developed based on an extensive laboratory experimental program where fuel bed parameters were varied over a wide range (δ 0.02–0.55 m, *w* 0.5–3.5 kg m^{-2}, ρ_b 1.9–30 kg m^{-3}, *M* 6–179 %), shows that, at least for no-wind and no-slope conditions and constant δ, *w* and thus ρ_b do not significantly influence *R*.

Although we assumed a fixed T_f for obtaining η as a function of *M*, in real fire-spread situations the relationship between these variables is still approximately linear because T_f has little influence on Q_i, when compared to *M*, and varies within a relatively narrow range. This means that η is nearly constant for constant *M* values. Thus, high *R* values, for example in wind-driven fires, are attained because more heat is generated and transferred from the flame to the unburned fuel, despite the ratio between the heat released by the flame and that absorbed by the fuel remains the same.

Empirical models can provide accurate descriptions of fire behaviour by properly combining variables that account for the key influences on fire spread, *i.e.*, weather, topography and fuel complex metrics, even without grasping the fundamental propagation mechanisms. However, because the amount of variables is vast, narrowing them down to a selected few to consider during model development is needed. For such reason researchers usually rely on pre-established knowledge on the physical mechanisms underlying fire spread for making that selection. Thus, the results from the present study are useful to inform future empirical experiments and approaches, in particular the development of *R* prediction models. One major practical application of accurate *R* estimates is the obtaining of improved fire size and shape estimates (Anderson 1983), which are key in assisting both prevention and suppression operations.

LIST OF SYMBOLS
POPIS SIMBOLA

c_f fuel-specific heat – *specifična toplina izgaranja*, kJ kg^{-1} °C^{-1}

c_w water-specific heat – *specifična toplina vode*, kJ kg^{-1} °C^{-1}

D flame depth – *dubina plamena*, m

δ fuel bed height – *visina ložišta*, m

η fraction of heat transferred from the flame to the unburned fuel – *udio topline prenesene od plamena do nesagorijelog goriva*

f_{fl} fraction of fuel consumed in flaming combustion – *udio goriva potrošenog u sagorijevanju*

M fuel moisture content – *sadržaj vlage goriva*, %

Q'' average horizontal net heat flux through the fuel bed – *prosječna količina horizontalnog strujanja topline kroz ložište*, kW m^{-2}

Q_f low heat content per unit mass of fuel – *donja ogrijevna vrijednost po količinskoj jedinici goriva*, kJ kg^{-1}

$\dot{Q}_{fl}$ power released per unit fireline length – *snaga oslobođena po jedinici duljine vatrene linije*, kW m^{-1}

Q_i heat per unit mass of fuel necessary for ignition – *toplina po količinskoj jedinici goriva potrebnog za izgaranje*, kJ kg^{-1}
Q_w water latent heat of evaporation – *latentna toplina isparavanja vode*, kJ kg^{-1}
R fire-spread rate – *stopa širenja požara*, m s^{-1}
ρ_b fuel bed density – *gustoća ložišta*, kg m^{-3}
t_r flame residence time – *vrijeme zadržavanja plamena*, s
T_f fuel initial temperature – *početna temperatura goriva*, °C
T_i fuel igniting temperature – *temperatura zapaljenja goriva*, °C
T_v water boiling temperature – *temperatura vrelišta vode*, °C
w fuel load – *količina goriva*, kg m^{-2}

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Sažetak

Analizirana je uloga pojedinih svojstava ložišta u stopi širenja šumskog požara, na temelju ravnoteže toplinske energije, iz koje je razvijen poznati Rothermelov model širenja požara (1972), pokazujući da niti visina ložišta, jednako kao ni količina i gustoća ne utječu izravno na ravnotežu toplinske energije. Utjecaj tih parametara, često izvedenih iz empirijskih opisa stope širenja, nužno proizlazi iz neizravnih utjecaja na mehanizme prijenosa topline. Udio topline prenesen iz plamena na nesagorijelo gorivo, pretežno ovisi o sadržaju vlage u gorivu te je neovisan od stope širenja te oblika plamena. S obzirom na to da empirijski modeli uglavnom impliciraju mehanizme širenja požara u opisivanju njegovog ponašanja, rezultati ove studije mogu biti od pomoći u osmišljavanju i ocrtavanju budućih eksperimenata i pristupa.

KLJUČNE RIJEČI: ponašanje požara, šumski požari, sagorijevanje, prijenos topline.