ADVANCES IN FOREST FIRE RESEARCH

2022

Edited by
DOMINGOS XAVIER VIEGAS
LUÍS MÁRIO RIBEIRO

Impact of the bulk density on fire spread through a homogenous vegetation layer

Carmen Awad *[1]; Jacky Fayad [1]; Nicolas Frangieh [1]; Frédéric Morandini [1]; Jean Louis Rossi [1] ; François Joseph Chatelon [1]; Thierry Marcelli [1]; Dominique Morvan [2] ; Gilbert Accary [3]

[1]UMR CNRS SPE 6134, Université de Corse, 20250 Corte, France, {awad_c, fayad_j, frangiyeh_n, morandini_f, rossi_j, marcelli_t, chatelon_j}@univ-corse.fr
[2]Aix Marseille Université, CNRS, Centrale Marseille, M2P2, Marseille, France, {dominique.morvan@univ-amu.fr}
[3]Scientific Research Center in Engineering, Lebanese University, Lebanon, {gaccary@ul.edu.lb}

** Corresponding author*

Keywords

Fire spread modelling; fuel properties; numerical simulations; fire behavior and dynamics; laboratory experiment

Abstract

The bulk density as definition represents the ratio between the packing ratio and the density of the vegetation. Therefore, it is directly related to the fuel load, the height and to the porosity of the vegetation. In fact, the bulk density plays an important role in fire propagation and behavior. Due to its dependence on the fuel porosity, the bulk density influences heat transfers inside the fuel bed, so, it can affect directly the rate of spread. Or, the bulk density influences also the fire intensity and flame characteristics (residence time, height and depth) due to its dependence of the fuel load and fuel bed height. However, despite the important influence of the bulk density on fire propagation, the literature does not clarify its impact on fire behavior, different points of view can be exanimated.

So, the aim of this study is to investigate the role played by the bulk density upon both propagation parameters and heat transfer of a surface fire through a homogeneous vegetation layer. Investigations were conducted numerically using "FireStar2D", a complete physical model based on multiphase formulation. Also, experimentally, tests were constructed at the university of Corsica at laboratory scale under no wind and no slope condition. In order to study the elementary effect of the bulk density on fire behavior, three different cases were evaluated: (a) variable fuel load with a constant bulk density, (b) variable fuel load and variable bulk density, (c) variable bulk density with a constant fuel load.

Case (a) was only studied numerically, the obtained results are in agreement with the literature: the rate of spread increases with the fuel load until a specific value where the ROS becomes independent of it. Case (b) was evaluated numerically and experimentally using a fix fuel bed height. The numerical and the experimental results showed that the ROS is barely affected by both fuel load and bulk density. Finally, the results of the last case, with a constant fuel load, showed numerically the same tendency proposed by Rothermel: the rate of spread reaches a maximum value at an optimal packing ratio that depends of the surface-volume ratio of the vegetation. Or, experimentally the ROS decreases with the increase of the bulk density. Different variables such as the optical thickness, the fire intensity, the residence time, the radiation and convection heat fluxes have been analyzed.

1. Introduction

Surface fire spread behavior is always related to the vegetation complex structure (Rothermel and Anderson 1966; Balbi et al. 2010; Rossa 2017), described by the properties of the fuel particles (fuel moisture content, density, surface to volume ratio, fuel load, bulk density, fuel bed depth, and packing ratio). Each one of these properties has its own effect on fire propagation. For instance, several studies have showed that the rate of spread decreases with the increase of fuel moisture content (Morvan 2013; Awad et al. 2021). Others showed that the rate of spread increases with the fuel bed height, and the fuel load (Morvan and Dupuy 2004; Rossa and Fernandes 2018; Awad et al. 2020). However, the effect of the vegetation bulk density and packing ratio on fire behavior has always been an examination subject due to the different point of views of its impact listed in the literature (Morvan and Dupuy 2004; Rossa and Fernandes 2018; Awad et al. 2020). In fact, as mentioned, the bulk density is directly dependent on the vegetation fuel load, height and porosity which can have opposite effects on fire behavior. Several studies noted a decrease of the rate of spread with the bulk density or the packing ratio (Rothermel and Anderson 1966; Catchpole et al. 1998). Several explanations of this tendency were proposed: a large bulk density, therefore a large packing ratio and a low porosity leads to less diffusion of oxygen inside the fuel bed. Also, the radiation from burning fuel particles, heated by the flame base, impinges on the unburnt fuel on a distance equal to the extinction depth δ (Balbi et al. 2007) (equation 1) that is inversely proportional to the bulk density.

$$\delta = 4/\beta s \qquad (1)$$

Where, β is the packing ratio and s is the surface to volume ratio.

However, other studies showed another tendency. Rothermel (Rothermel and Anderson 1966) performed several experiments using fuel beds of excelsior and sticks, showed that the ROS reaches a peak under an optimal packing ratio. For $\beta \leq \beta_{opt}$, the heat loss between fuel particles was important, it was explained by the increase of the air cooling effect inside the fuel bed with higher porosity. Or, for $\beta \geq \beta_{opt}$, the porosity decreases and the ratio of air fuel decreases. Qianqian He et al 2022 (He et al. 2022) showed that the surface heat transfer increases under lower packing ratios which increases the rate of spread (ROS). Or, under higher packing ratios, the surface heat transfer does not vary significantly, and, the ROS reduction in this case is attributed mainly to the internal heat transfer dominated by radiation.

The main purpose of this is to determine the elementary effect of the bulk density of fire behavior. Therefore, three different cases were evaluated: (a) variable fuel load with a constant bulk density, (b) variable fuel load and variable bulk density, and finally (c) variable bulk density with a constant fuel load. Several numerical simulations and experimental tests were conducted. Fire propagation parameters have been analyzed as the rate of spread, the fire intensity, the radiative and the convective heat transfer, and the residence time.

2. Study case (a): Variable fuel load with a constant bulk density

Previous studies showed that the fuel load has impact on fire behaviour, especially on the rate of spread and on fire intensity (Rothermel 1972; Morvan and Dupuy 2001; Weise David R., Zhou Xiangyang, Sun Lulu 2005; Zhou et al. 2005). Morvan and Dupuy (Morvan and Dupuy 2004) have demonstrated that the fuel load with a constant bulk density is a factor that determines the mode (thin or thick) of the porous medium where the fire front propagates. They found out that the rate of spread increases with fuel load until a specific value where it becomes independent. This behaviour can be explained by introducing a critical optical thickness τ_{opt} related to the fuel extinction length δ and to fuel height that determines if the vegetation medium is considered to be thick or thin.

$$\tau_{opt} = \frac{s\beta}{4}.e \qquad (2)$$

In fact, if $\tau_{opt} < 1$ the porous medium is considered as a thin and all the vegetation depth participates to the fire front propagation. And, if $\tau_{opt} > 1$ only a depth equal to the extinction length δ that participates to the fire front propagation.

In order to study the influence of the fuel load on fire behavior with a constant bulk density, simulations were performed using fireStar2D, in a 2D domain, 170 m long and 35 m height. A homogenous layer of Australian grassland, whose physical properties are described in Table 1, lied between x = 20 m and x = 170 m. Different fuel loads are considered in this study by changing the fuel height between 0.3 and 1 m and maintaining the same fuel density and packing ratio.

Figure 1 shows that ROS increases with the fuel load (up to 0.5 kg/m^2) until reaching a value beyond which the dependence of the fuel load becomes relatively weak. This tendency can be related to the fire propagation mode in the porous medium.

Table 1- Vegetation characteristics

Fuel density (Kg/m^3)	500
Surface to volume ratio S/V (m^{-1})	4000
Packing ratio	0.002
Fuel load (Kg/m^2)	0.3-1
Height (m)	0.3-1

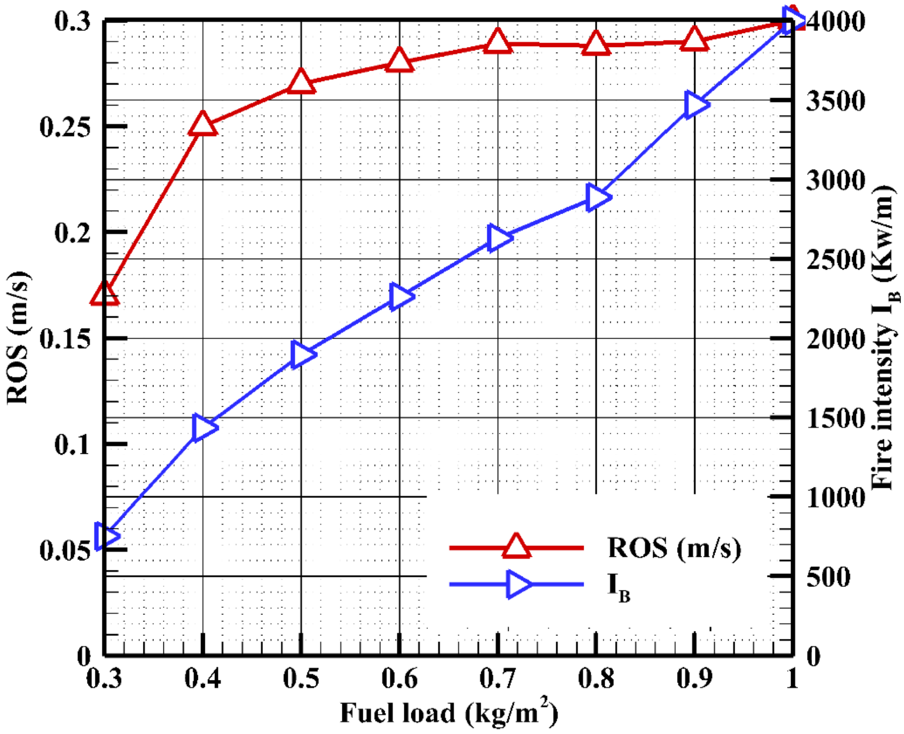

Figure 1- The rate of spread and Fire intensity evaluated for the grass for different fuel load with a constant bulk density under no slope no wind condition using FireStar2D

For a relatively thin vegetation medium ($\tau_{opt} < 1$) obtained for e < 0.5 m all the fuel-bed depth participates to the fire propagation. Therefore, the ROS increases with the fuel load. But, for a thicker vegetation medium, $\delta > e$, radiative heat transfer does not penetrate the entire depth of the fuel bed. The lower fuel bed layers are not heated enough to participate to fire front propagation.

In another hand the fire intensity continues to increases with fuel load, as shown in figure 1. In fact, fire intensity depends directly of mass degradation rate and of the heat of combustion of the vegetation:

$$I = \dot{m} \,. \Delta H_c \quad (3)$$

Where $\dot{m}$ (kg $m^{-1}s^{-1}$) is the vegetation degradation rate evaluated by the summation of mass losses due to pyrolysis and charcoal combustion producing CO and CO_2 gases.

3. Study case (b): variable fuel load and variable bulk density

3.1. Numerical tests

In this paragraph the fuel bed height remains constant or the fuel load and the bulk density (packing ratio) are variables. Simulation were conducted using the grassland (table 1) under no wind and no slope conditions. The different configurations are represented in table 2.

Table 2- Different configurations of grassland evaluated with Firestar2D

Packing ratio	0.0014-0.0032
Fuel load (Kg/m^2)	0.49-1.12
Height (m)	0.7

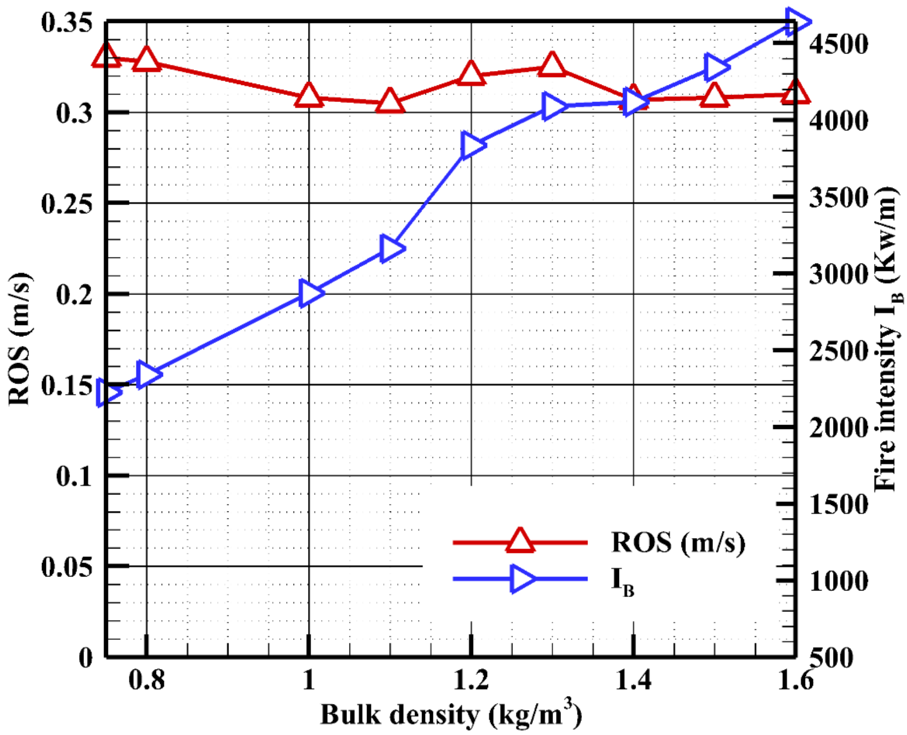

Figure 2- ROS and the Fire intensity variation in function of the bulk density for a constant fuel bed height 0.7 m evaluated using FireStar2D

Figure 2 shows that for a constant fuel bed height, with variable packing ratio and fuel load, the variation of the ROS is barely dependent on either bulk density or fuel load. In fact for the different configurations, the optical thickness τ is higher than 1 ; so the fire propagates in a thick medium where the extinction length δ is always less than the fuel bed height. Or, δ is inversely proportional to the packing ratio, therefore the depth of the vegetation that really participates to the fire propagation decreases with the increase of the packing ratio. This tendency is in agreement with the experimental results showed by Campell Lochrie (Campbell-Lochrie et al. 2021).

3.2. Experimental tests

Twelve tests were conducted at the laboratory of the university of Corsica with the excelsior in order to evaluate the influence of the bulk density and the fuel load when the fuel bed height remains constant.

Four different bulk densities were evaluated. The properties of the fuel are listed in the table 3.

Table 3- Excelsior characteristics

Fuel density (Kg/m^3)	780
Packing ratio	0.0023-0.0035-0.0046-0.0058
Fuel load (Kg/m^2)	0.2-0.3-0.4-0.5
Height (m)	0.11

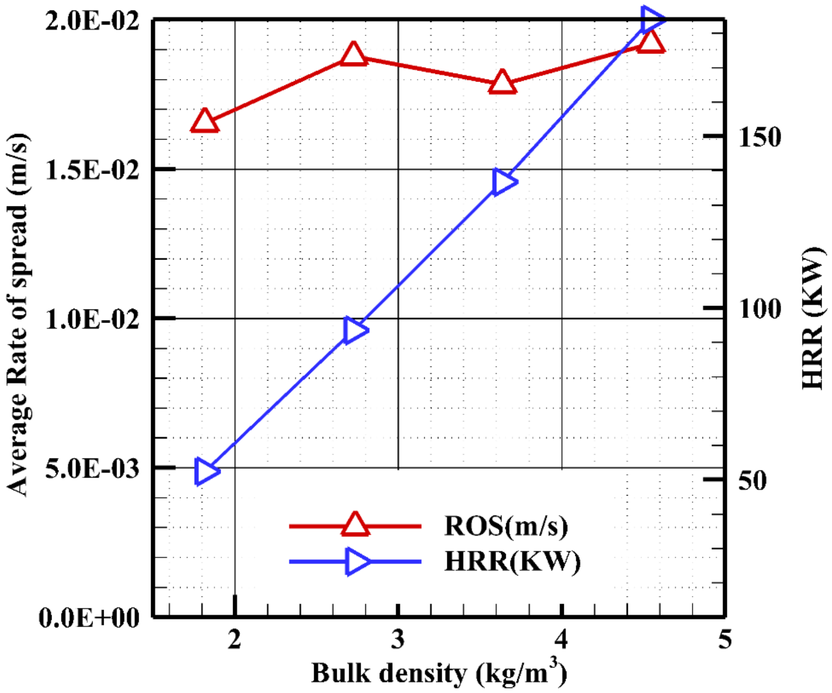

Figure 3- ROS and HRR variation in function of the bulk density for a constant fuel bed height 11 cm evaluated experimentally

The results of experimental tests are in agreement with the numerical results (Figure 3): the rate of spread barely depends of the bulk density or the fuel load when the fuel bed height remains constant. However, the fire intensity and the residence time increases with the bulk density (Figure 4).

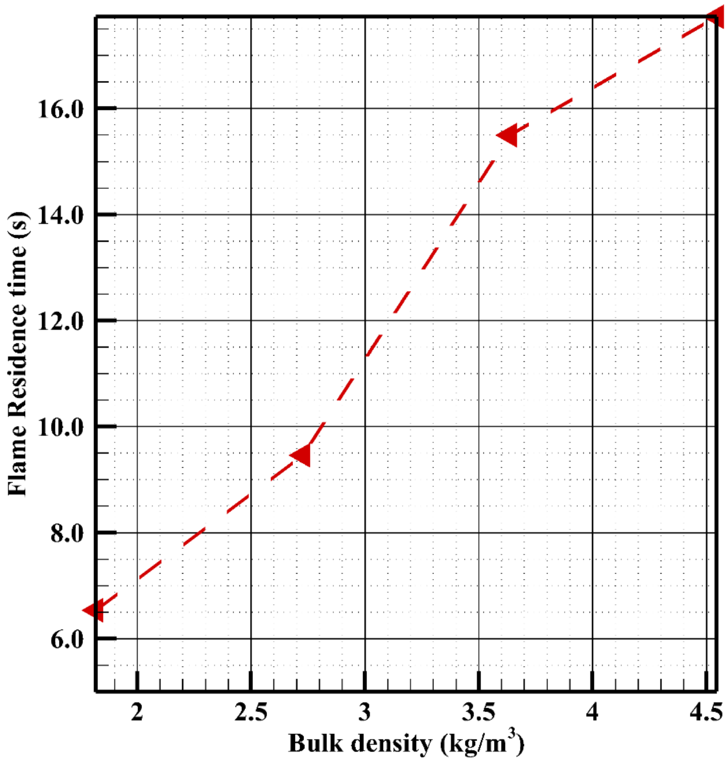

Figure 4- Flame residence time variation evaluated experimentally in function of the bulk density for a constant fuel bed height 11 cm

4. Study case (c): variable bulk density with a constant fuel load

4.1. Numerical tests

In this paragraph the fuel load remains constant or the bed height and the bulk density (packing ratio) are variables. Simulations were conducted using the grassland (table 1) under no wind no slope condition. The different configurations are represented in table 4.

Table 4 - Different configuration of grassland evaluated with Firestar2D

Packing ratio	**0.0014-0.0035**
Fuel load (Kg/m²)	0.7
Height (m)	0.3-1

Numerical results shown is figure 4 are in agreement with the tendency proposed by Rothermel [2]: the ROS reaches a maximum for an optimal bulk density (Figure 5).

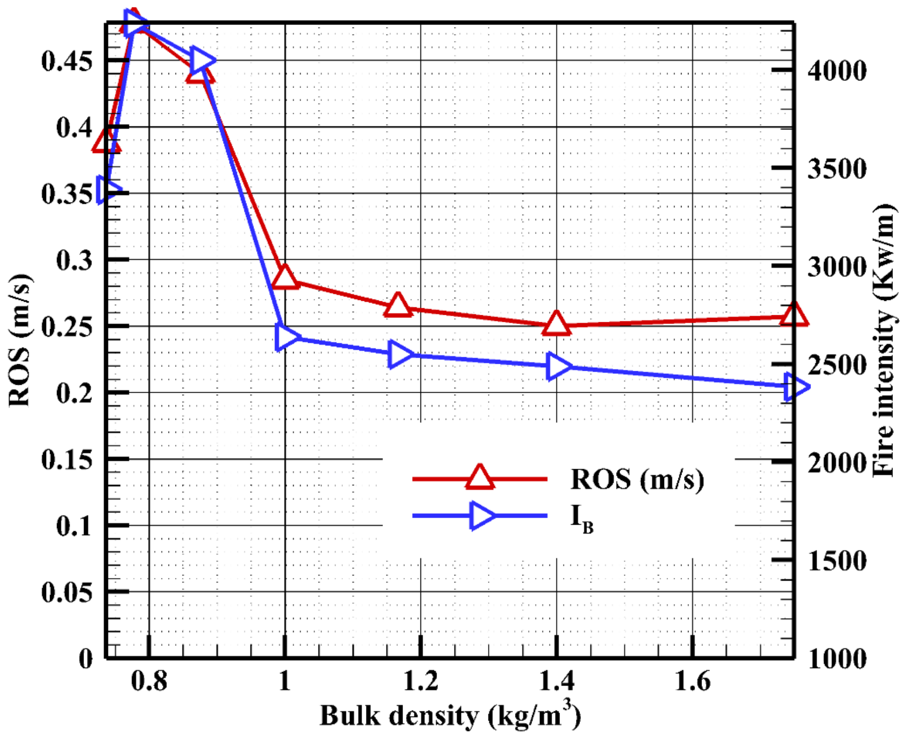

Figure 5- ROS and fire intensity variation in function of the bulk density for a constant fuel load evaluated numerically for the grass

4.2. Experimental tests

3 tests were conducted experimentally at the laboratory of the university of Corsica using the excelsior with a constant fuel load. The different configurations are represented in table 4.

Table 4- Different configuration of excelsior evaluated experimentally

Packing ratio	0.0039-0.0064-0.0017
Fuel load (Kg/m²)	0.4
Height (m)	0.13-0.08-0.03

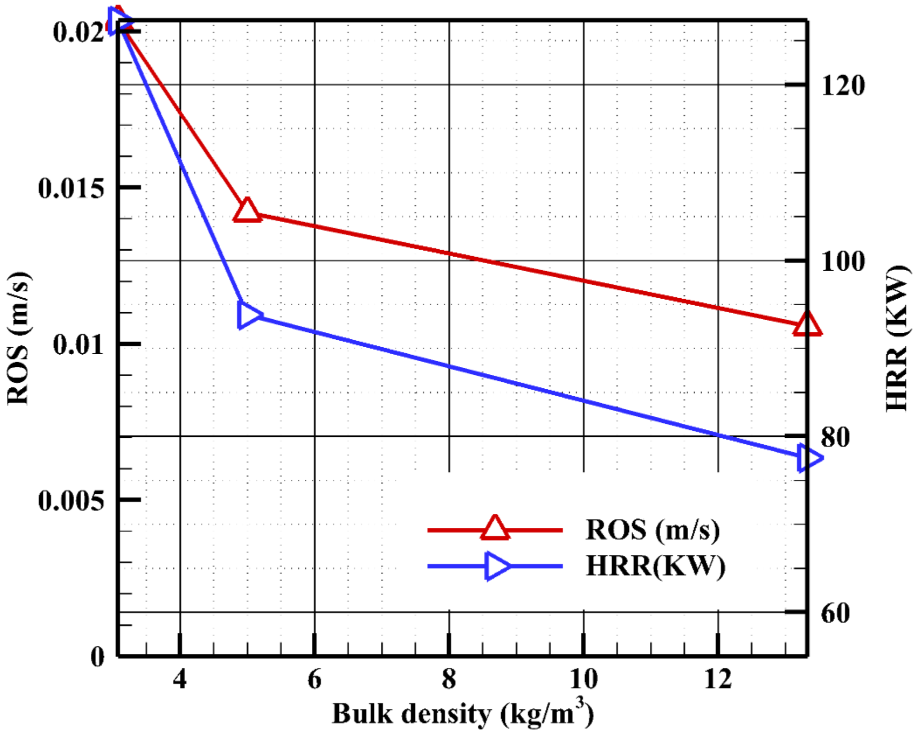

Figure 6- ROS and HRR variation in function of the bulk density for a constant fuel load evaluated experimentally for the excelsior

Figure 6 shows that the ROS and the HRR decreases with the increase of the packing ratio. In fact, this result can be explained by the fact that the packing ratio increased, the porosity of the fuel bed decreases therefore the inlet of the oxygen inside of the fuel bed also decreases. In another hand the increase of the packing ratio decreases the extinction length and therefore the total depth of the vegetation participating to the fire front propagation which explains the decrease of the HRR.

5. Conclusion

The effect of the bulk density on fire behavior is related directly to the fuel bed height and to the fuel load. For this reason, three different cases were evaluated numerically and experimentally:

(a) variable fuel load with a constant bulk density: the rate of spread increases with the fuel load or height until a specific value where it becomes independent of it; or the fire intensity increases with the increase of the fuel load.

(b) variable fuel load and variable bulk density: with a constant fuel bed height, the rate of spread is barely dependent of the fuel load or the bulk density, However the fire intensity increases with fuel load.

(c) variable bulk density with a constant fuel load: the rate of spread reaches a maximum value for an optimal packing ratio depending on the surface to volume ratio of the vegetation; the same tendency was found for the fire intensity.

6. Bibliography

Awad C, Frangieh N, Marcelli T, Accary G, Morvan D, Meradji S, Chatelon F-J, Rossi J-L (2021) Numerical study of the moisture content threshold under prescribed burning conditions. Fire Safety Journal 122, In Press. doi:https://doi.org/10.1016/j.firesaf.2021.103324.

Awad C, Morvan D, Rossi J-L, Marcelli T, Chatelon FJ, Morandini F, Balbi J-H (2020) Fuel moisture content threshold leading to fire extinction under marginal conditions. Fire Safety Journal 118, 11. doi:10.1016/j.firesaf.2020.103226.

Balbi J-H, Rossi J-L, Marcelli T, Chatelon F-J (2010) Physical Modeling of Surface Fire Under Nonparallel Wind and Slope Conditions. Combustion Science and Technology 182, 922–939. http://www.tandfonline.com/doi/abs/10.1080/00102200903485178.

Balbi J-H, Rossi J-L, Marcelli T, Santoni P-A (2007) A 3D Physical Real-Time Model of Surface Fires Across Fuel Beds. Combustion Science and Technology 179, 2511–2537. http://dx.doi.org/10.1080/00102200701484449 http://www.tandfonline.com/doi/pdf/10.1080/00102200701484449.

Campbell-Lochrie Z, Walker-Ravena C, Gallagher M, Skowronski N, Mueller E V., Hadden RM (2021) Investigation of the role of bulk properties and in-bed structure in the flow regime of buoyancy-dominated flame spread in porous fuel beds. Fire Safety Journal 120, 9. doi:10.1016/j.firesaf.2020.103035.

Catchpole WR, Catchpole EA, Butler BW, Rothermel RC, Morris GA, Latham DJ (1998) Rate of Spread of Free-Burning Fires in Woody Fuels in a Wind Tunnel. Combustion Science and Technology 131, 1–37. doi:10.1080/00102209808935753.

He Q, Liu N, Xie X, Zhang L, Lei J, Zhang Y, Wu D (2022) Experimental study on fire spread over discrete fuel bed-Part II: Combined effects of wind and packing ratio. Fire Safety Journal 103520. doi:10.1016/j.firesaf.2021.103520.

Morvan D (2013) Numerical study of the effect of fuel moisture content (FMC) upon the propagation of a surface fire on a flat terrain. Fire Safety Journal 58, 121–131. doi:10.1016/j.firesaf.2013.01.010.

Morvan D, Dupuy JL (2001) Modeling of fire spread through a forest fuel bed using a multiphase formulation. Combustion and Flame 127, 1981–1994. doi:10.1016/S0010-2180(01)00302-9.

Morvan D, Dupuy JL (2004) Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation. Combustion and Flame 138, 199–210. doi:10.1016/j.combustflame.2004.05.001.

Rossa CG (2017) The effect of fuel moisture content on the spread rate of forest fires in the absence of wind or slope. International Journal of Wildland Fire 26, 24–31. doi:10.1071/WF16049.

Rossa CG, Fernandes PM (2018) An Empirical Model for the Effect of Wind on Fire Spread Rate. Fire 2018, Vol 1, Page 31 1, 31. doi:10.3390/FIRE1020031.

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. (USDA Forest Service, Research Paper INT-115, Intermountain Forest and Range Experiment Station, Ogden, Utah) doi:http://www.snap.uaf.edu/webshared/JenNorthway/AKFireModelingWorkshop/AKFireModelingWkshp/FSPro Analysis Guide References/Rothermel 1972 INT-115.pdf.

Rothermel RC, Anderson HE (1966) Fire spread characteristics determined in the laboratory. (USDA Forest Service, Research Paper INT-30, Intermountain Forest and Range Experiment Station, Ogden, Utah)

Weise David R., Zhou Xiangyang, Sun Lulu MS (2005) Fire spread in chaparral - 'go or no-go?' International Journal of Wildland Fire 14, 99–106. doi:https://doi.org/10.1071/WF04049.

Zhou X, Weise D, Mahalingam S (2005) Experimental measurements and numerical modeling of marginal burning in live chaparral fuel beds. Proceedings of the Combustion Institute 30, 2287–2294. doi:10.1016/j.proci.2004.08.022.