Wildland fires behaviour: wind effect versus Byram's convective number and consequences upon the regime of propagation

Dominique Morvan, Nicolas Frangieh

Wildland fire behaviour: wind kW meffect versus Byram's convective number and consequences on the regime of propagation

D. Morvan[A,B] *and N. Frangieh*[A]

[A]Aix Marseille University, CNRS, Centrale Marseille, M2P2, Marseille, France.
[B]Corresponding author. Email: dominique.morvan@univ-amu.fr

Abstract. With fuel moisture content and slope, wind velocity (U_W) is one of the major physical parameters that most affects the behaviour of wildland fires. The aim of this short paper was to revisit the relationship between the rate of spread (ROS) and the wind velocity, through the role played by the two forces governing the trajectory of the flame front and the plume, i.e. the buoyancy of the plume and the inertia due to wind. A large set of experimental data (at field and laboratory scale) from the literature was analysed, by introducing the ratio between these two forces, namely Byram's convective number N_C and considering the relationship between the fire ROS/wind speed ratio and Byram's number. This short note was also an opportunity to make a point on particular issues, such as the existence of two regimes of propagation of surface fires (wind-driven fire vs plume-dominated fire), the relative importance of the two modes of heat transfer (by convection and radiation) on the propagation of a fire front, and others scientific debates animating the wildland fire community.

Introduction

The propagation of wildfires is governed by various physical parameters such as the structure and state of the vegetation, topography, and atmospheric conditions such as wind, air temperature and relative air humidity, all of these potentially affecting the heat transfer between the flame and the vegetation layer, which is the basic mechanism contributing to the ignition and development of a wildfire. For many years, several questions have fed the debate of this scientific community, such as: is the propagation of the fire front driven by the heat transfer by radiation or by convection? How does the rate of spread (ROS) decrease under the action of fuel moisture content (FMC): linearly or exponentially? Can we reduce the relationship between the ROS and wind speed to a single power law formula with a unique exponent? The responses to these questions cannot be necessary unique; the relative effect of one parameter can also depend on other parameters; for example, Morvan (2013) showed using numerical simulations that the influence of FMC on ROS can depend on wind conditions, explaining in this way the variability in the relationship ROS vs FMC reported in the literature.

Because in the beginning, all depends on the heat transfer between the flame and vegetation, a great part of the answers to these questions depends on the trajectory of the flames, which can be more or less vertical or horizontal, in the vicinity or in contact with the fuel. Consequently, one of the key points in understanding the behaviour of wildland fires concerns the action of the two forces on the flame and the plume, i.e. buoyancy due to the difference of temperature between the plume and the ambient air acting vertically, and inertia due to the wind acting horizontally (Pitts 1991; Morvan 2011). Before being able to fully understand the behaviour of wildfires in complex configurations, a necessary first step is to study the problem in simpler situations, such as on a flat terrain, with a homogeneous fuel layer, under the action of a regular wind (Beer 1991). Even in these simplified conditions, the behaviour of a fire can be subject to complex phenomena resulting from the interaction between the wind and the vegetation, and the wind and the plume, which can be at the origin of hydrodynamic instabilities (Raupach 1990; Morvan 2014) that shape the fire front.

These interactions contribute partially to the variability of the exponent n summarising the relationship between the ROS of a fire front and the wind velocity (U_W), which is very often written as a power law function: ROS $\approx U_W^n$.

As indicated in many references in the literature (Beer 1991; Sullivan 2009; Morvan 2014), this exponent varies between 0.4 and 2.6. Many papers conclude that this variability is due to the fuel moisture content (Beer 1991; Pitts 1991), the surface area-to-volume ratio characterising the fuel particles (Rothermel and Anderson 1966; Rothermel 1972; Beer 1991), the magnitude of the wind velocity (Cheney *et al.* 1998; Anderson *et al.* 2015) or other factors such as the fuel load and fuel depth.

Because these explanations are based on purely statistical observations (correlation does not mean causation), they cannot be considered fully satisfying; to progress further on this subject, it is necessary to introduce a more physical approach. A great part of the answer to this question results from analysis of the basic physical mechanisms governing the heat transfer between the flame and the vegetation layer, the distance separating the flame and the vegetation and, consequently, the two forces acting on the trajectory of the flame, i.e. the inertia due to the

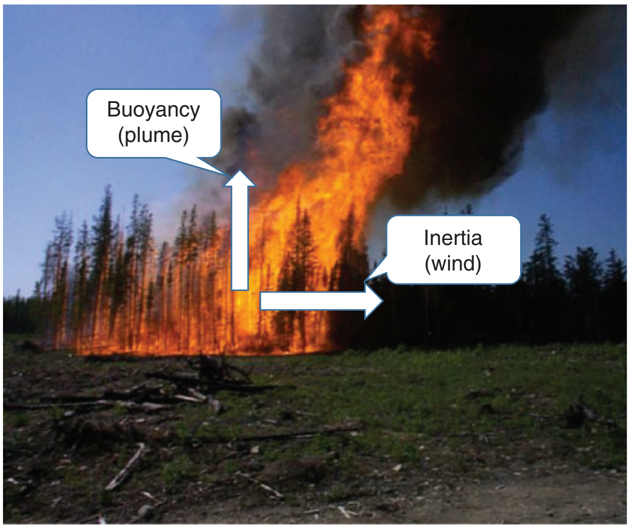

Fig. 1. Forces governing the behaviour of a forest fire.

wind and the buoyancy due to the difference of density between the plume and the ambient atmosphere (see Fig. 1). Because these two forces do not act on the flame trajectory along the same direction (horizontally for wind and vertically for buoyancy), they are in competition, and what is important in this problem is not their absolute values in terms of magnitude, but the magnitude of their ratio. This ratio can be express by introducing a comparable parameter, Byram's convective number, defined as the ratio between the power developed by these two forces (Nelson and Adkins 1988; Raupach 1990; Nelson 1993*a*, 1993*b*; Sullivan 2007):

$$N_C = \frac{2gI}{\rho C_P T_0 (U_W - \mathrm{ROS})^3}, \tag{1}$$

where g represents the acceleration due to gravity; I and ROS the fireline intensity and rate of spread of the fire; U_W the wind speed (generally defined as the 10-m open wind velocity in a zone not affected by the fire front); and ρ, C_P, T_0 the density, the specific heat and the temperature of the ambient air.

The idea of using dimensional analysis to understand the propagation of wildland fires was initially introduced by Pagni and Peterson (1973). This very interesting paper suggested that the ratio between these two forces (expressed in the paper using the Froude number: $F_r = U_W/(g\ L)^{1/2}$) (where L is the flame length) can be also at the origin of a change in the main heat transfer mechanism driven the propagation of a fire. Above a critical value of Froude number (nearly equal to 0.5), the heat transfer between the flame and the vegetation would be dominated by convection, whereas for smaller values of this parameter, radiation would be the dominant mode of heat transfer (Pagni and Peterson 1973).

A more recent paper (Nelson 2015) proposed a more refined analysis, indicating that the propagation of a fire can be mainly driven by convection if a modified Froude number $F_r = (U_w - \mathrm{ROS})^2/(g\ L)$ is larger than 1 and piloted mainly by radiation for F_r smaller than 0.25. The same author also proposed some criteria for the same threshold adapted for Byram's convective number: >10 for radiative mode and <2 for convective mode.

This transition between two modes of heat transfer has been clearly identified experimentally at a small scale in a fire wind tunnel (Beer 1991) and on a fire table (Dupuy and Maréchal 2011), and at larger scale in the field (Morandini and Silvani 2010). These experiments highlighted a significant increase in the ROS due to a corresponding increase of heat transfer by convection (resulting from an increase of wind flow or slope angle), while heat transfer by radiation seemed to stay at the same level.

As discussed by Finney *et al.* (2013*a*), currently, we cannot conclude that the discussion concerning the dominant mode of heat transfer (between radiation and convection) in a spreading fire between the flame and the vegetation can be considered closed. The only exception to this question is the situation encountered for a fire propagating on flat terrain, in no-wind conditions; in this case, the fresh air flow on both side of the fire front contributes to cooling the burned or unburned vegetation, and the only mechanism capable of contributing to the heating process is radiation.

What is shown from experimental data is that in many cases both radiation and convection play a role in the propagation of a fire front (Morandini and Silvani 2010; Frankman *et al.* 2013; Morandini *et al.* 2013) and the mechanism of propagation by flame contact and piloted ignition inside the fuel layer often cited in the literature corresponds to heat transfer by both radiation and convection (Rothermel 1972; Pitts 1991).

The transition between these two regimes of fire propagation (plume-dominated and wind-driven) is well identified in the literature (Pyne *et al.* 1996; Morvan 2011, 2013, 2014; Morvan and Lamorlette 2014); it results from a sudden change in aerology in the vicinity of a fire front: in one case, fresh air is aspirated by the plume on both side of the fire front (plume-dominated fire); in the other case, the wind flow pushes the hot gases ahead of the fire front (wind-driven fire). These two regimes of propagation have been clearly identified both numerically using detailed physical models (Morvan 2014) and experimentally in the field (Morandini and Silvani 2010). In particular, numerical simulations have highlighted that unsteady effects are more intense for plume-dominated fires compared with wind-driven fires (Morvan 2014). This feature was particularly evident in fire intensity signals and the ratio between the standard deviation and the average value. As indicated in this numerical study (Morvan 2014), this phenomenon could be attributed to the relative importance of heat transfer by radiation between the flame and vegetation, which is characterised by strong non-linearities resulting from the Stefan–Boltzmann law (the heat flux is proportional to the fourth power of the gas temperature). Experimentally, the transition between these two regimes of propagation has been identified from the correlation coefficient between the horizontal wind velocity and the gas temperature (Morandini and Silvani 2010). In these experiments, observations of the trajectory of the flames and the plume seemed to indicate that the transition between plume-dominated and wind-driven fire occurred around a critical value of Byram's convective number ranging between 17 and 26. The state of the art on this subject can be summarised as follows: for

Table 1. Some fuel and fire characteristics of data reported in Fig. 2

Fire type	Fuel	Laboratory, field	Wind speed (m s^{-1})	Fireline intensity (I, kW m^{-1})
Crown	Jack pine	Field	1.66–6.77	291–89 681
Surface	Pine needles	Field, laboratory	0.57–3.66	36–4612
Shrub	Maquis	Field	0.01–0.25	622–10 355
Shrub		Field	1.39	69–2310
Grass	Australian grass	Field	1.94–7.10	13 669–119 652
Mixed fuel	Pine needles, sticks	Laboratory	0.9–2.7	268–897
Buttongrass	Grass	Field	0.19–10.08	115–18 550
Cardboard	Artificial fuel	Laboratory	0.22–1.5	38–1808
Grass	Grass	Field	0.51–3.59	102–7824
RxCadre	Grass, shrub	Field	2–4	890–2100

plume-dominated fires, the propagation of the fire front is mainly (or exclusively in some cases) governed by radiative heat transfer, whereas for wind-driven fires, both radiation and convection contribute to the heat transfer between the flame, the hot gases and the vegetation.

One of the objectives of the present note was to revisit some experimental data obtained in various conditions (in the laboratory, in the field, for surface fires in shrubland, in grassland, for crown fires, etc.), introducing a physical analysis based on the dimensional analysis. As indicated previously, the idea is not completely new (Pagni and Peterson 1973; Nelson and Adkins 1988), but our opinion is that it was insufficiently diffused in a part of the wildland fire community, and this is the objective of this short note. The analysis was focused on the relationship between the ROS/U_W ratio and Byram's convective number (in fact, the inverse of this non-dimensional parameter).

Data analysis and discussion

A large set of experimental data was used to support this analysis, from crown fires in jack pine forests (Stocks 1987; de Groot *et al.* 2004; Taylor *et al.* 2004), surface fires in slash pine needles, litter–grass fuels and grasslands in the field and in the laboratory (Nelson and Adkins 1988), shrub fires (Baeza *et al.* 2002; Bilgili and Saglam 2003; Nelson *et al.* 2012), grass and conifer (Clements *et al.* 2015; Butler *et al.* 2016), grassland fires (Sullivan 2007) and surface fires in mixed fuel and in artificial cardboard fuel in the laboratory (Catchpole *et al.* 1993, 1998; Finney *et al.* 2013*a*, 2013*b*) to buttongrass (Marsden-Smedley and Catchpole 1995). Some fuel and fire characteristics are reported in Table 1. As can be seen, the experimental conditions cover a large spectrum, with fire intensity ranging between 36 and 119 652 kW m^{-1}.

A first step in the analysis of these results is proposed in Fig. 2, representing the evolution of the ROS versus wind velocity U_W. The curve is represented in log-log scaling to highlight the potential power law functions between these two variables. To facilitate analysis, a reference curve (ROS $= 0.01 \times U_W^3$) has been added in the representation. This curve does not represent average behaviour; it constitutes only a benchmark to evaluate how far the relationship ROS versus wind speed U_W is from linearity or not, which is generally considered standard in many experimental studies (Anderson *et al.* 2015). Despite the diversity of scale, conditions, nature of

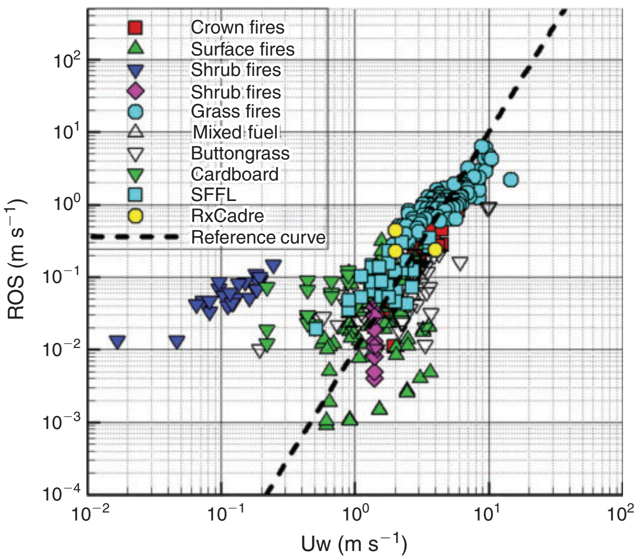

Fig. 2. Variation of the rate of spread (ROS) versus the wind speed measured for various ecosystems (experimental data and numerical results).

fuel, slope and various other parameters that can potentially affect the behaviour of fire, the data are not very dispersed. A large number of the points are grouped on both parts of the reference curve; this does not mean that the parameters (in particular the exponent) correctly fit the reality of the relationship between ROS and wind speed. This figure also reveals that many points are not aligned with this reference curve; this is not surprising when considering the great diversity of exponents found in the literature summarising the relationship between ROS and wind speed, some <1 and others >1. One of the conclusions that can be extracted from this first analysis is that to the question, 'Can the relationship between the ROS a fire and the wind speed can be restricted to a single power law function (linear if the exponent was equal to 1)?', the answer is definitively 'No!', because the physical mechanisms of propagation of a surface fire are not reduced to a single one factor (at least two have been identified) and the relative importance of these two factors is at the origin of the existence of two regimes of propagation, with a range of situations between these two limiting regimes.

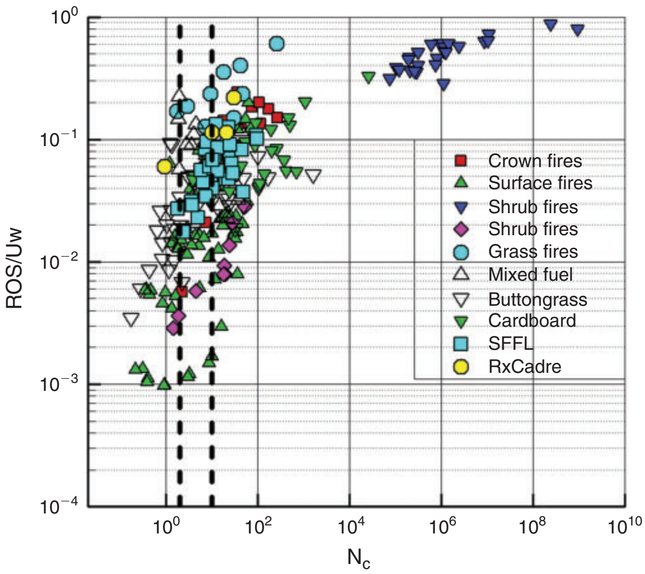

Fig. 3. Ratio rate of spread/wind velocity as a function of Byram's convective number (N_C); the two dashed lines represent the values $N_C = 2$ and 10, delimiting the two regimes of propagation, i.e. plume-dominated ($N_C > 10$) and wind-driven ($N_C < 2$).

One solution to erase these differences in burning conditions (slope, fuel structure, fuel state, etc.) is to consider that all these factors will act on the fire intensity I and therefore on one of the two forces (i.e. the buoyancy) that govern the trajectory of the flame (and the plume) and, consequently, on the interaction between the flame and the vegetation layer located just ahead of the fire front. In some sense, the variation of fuel load, fuel moisture content, slope, etc., is integrated in one parameter, namely the fire intensity I. The wind speed is one of the parameters that can be easily accessible to firefighters, so it is for this reason (and also because many experimental fires and numerical simulations have highlighted a linear relationship between these two parameters) that during a firefighting operation, the first attempt is to relate ROS to this external variable (see a general review on this subject in Morvan 2014).

For all the reasons cited above, the ratio of ROS to wind speed (ROS/U_W) (using the same set of data as in Fig. 2) have been reported (using logarithmic scales) as a function Byram's convective number (N_C) in Fig. 3. Owing to lack of data, the evaluation of Byram's convective number N_C was based on the same ambient air conditions, i.e. density $\rho = 1.171$ kg m$-^3$, specific heat $C_P = 1010$ J kg^{-1} K^{-1} and temperature $T_0 = 300$ K.

The curve shows that for values of N_C smaller than 1, many sets of data exhibits a stagnation of the ROS/U_W ratio; this is the case for surface fires, shrub fires, grassfires, i.e. fuel characterised by a quite small fuel load, not very tall, and therefore susceptible to situations corresponding to wind-driven fires. Of course, all the data did not converge towards the same ROS/U_W ratio; we can easily assume that this ratio can be affected by a parameter defining the level of stress of the vegetation, such as FMC.

This result can be understood from a dimensional analysis and the application of the Pi theorem. First, one can consider that the problem was governed by six parameters: ROS, wind speed U_W, load of water and dry fuel inside the combustible layer, and the two forces (buoyancy and inertia) piloting the trajectory of the flame and the plume, represented by the energy rate released by the fire P_f and the energy rate of the wind P_W, defined as follows (Nelson 1993*a*):

$$P_f = \frac{gI}{C_P T_0} P_W = \frac{1}{2}\rho(U_W - \mathrm{ROS})^3, \tag{2}$$

Application of the Pi theorem allows one to postulate that the problem is governed by three similitude parameters: the ratio ROS to wind speed (ROS/U_W), FMC and Byram's convective number (N_C), and that these three parameters are related by a relationship of the form:

$$\frac{\mathrm{ROS}}{U_W} = F(N_C, \mathrm{FMC}), \tag{3}$$

At the limit of wind-driven fire (N_C <<1), we can easily understand that the behaviour of the fire is not at all affected by buoyancy effects (mainly thermal convective instabilities); in this case, there is no reason for acceleration g to be considered as a relevant parameter in the dimensional analysis and consequently the ratio ROS/U_W converges towards a state independent of Byram's convective number and becomes only a function of FMC:

$$\frac{\mathrm{ROS}}{U_W} \underset{N_C \ll 1}{\longrightarrow} F(\mathrm{FMC}), \tag{4}$$

whereas for larger values of N_C, the curve representing the evolution of the ratio ROS/U_W (at least the general trend) is characterised by a sharp evolution from 10^{-3}–10^{-2} to values ranging between 0.1 and 1. This ultimate value of 1 must not to be viewed as an impossible limit; a fire can propagate even if the wind speed tends to zero.

Beside the main cluster of points (Fig. 2), we also noticed that a set of experimental results (shrub, with blue triangles) (Bilgili and Saglam 2003) did not fit the general trend compared with the others. These experimental fires were conducted in maquis fuel, characterised by a quite high fuel load (the data reported in the paper indicate a fuel consumption ranging between 1.3 and 4.4 kg m^2, between 3 and 10 times larger than the values measured for grass fires in Australia; Sullivan 2007). Moreover, these fires were carried out under very low wind conditions (ranging between 0.05 and 0.24 m s^{-1}); the consequence of these two factors (high fuel density and low wind speed) was a quite high value of Byram's convective number (larger than 10^4) in comparison with the other experimental data. Therefore, under these conditions, it was not really surprising that the behaviour of these fires differed from the others (Fig. 3).

Because experimental fires in the field are more difficult to conduct under strong wind conditions (mainly for safety reasons), a great part of the experimental data reported here can be classified as plume-dominated ($N_C > 10$), or at least transitional between wind-driven and plume-dominated ($2 < N_C < 10$), as can be seen in Fig. 3. Even if plume-dominated fires are very often encountered in wildfire-affected forests, we must keep in mind that in some ecosystems characterising the wildland–urban interface (WUI) (shrubland for example), which represents one of the major problems for fire safety engineering, fires are very often driven in shrubland by quite strong wind conditions (mistral in south-eastern France, Santa Ana in south California). Consequently, particular effort must be given in the future to improving basic knowledge for wind-driven fires, from experimental fire campaigns (if possible) to direct observations of real wildfires.

Conclusions

Various experimental data obtained for experimental fires conducted under a large set of conditions (grassfires, shrub fires, crown fires, fires in fuel litter, etc.) have been merged in a single analysis to study the effect of the wind speed on ROS. The analysis highlighted that the exponent associated with the relationship ROS versus U_W was correlated with the regime of propagation of the fire (wind-driven or plume-dominated), which itself depends on the relative importance of the two forces governing the trajectory of the flame and the plume, i.e. the buoyancy difference between the hot gases above the fire and the ambient air and the inertia forces due to the wind. The study was completed with a similitude analysis and through the relationship between the ratio ROS/U_W as a function of the inverse of Byram's convective number N_C. At small values of N_C (wind-driven fires), the ratio ROS/U_W tends towards a constant value, a function of FMC. In contrast, for large values of N_C (plume-dominated fires), the ROS/U_W ratio reached its maximum value. In conclusion, even if plume-driven fires are not characterised by inevitably strong wind conditions, because these kinds of fire are driven by non-linear heat transfer mechanisms (namely by radiation), they are less predictable than wind-driven fires (which tend towards a linear relationship between ROS and U_W) and, therefore, they can potentially be more dangerous to operational people in charge of firefighting or prescribed burning operations.

References

Anderson WR, Cruz MG, Fernandes PM, McCaw L, Vega JA, Bradstock RA, Fogarty L, Gould J, McCarthy G, Marsden-Smedley JB, Matthews S, Mattingley G, Pearce HG, van Wilgen BW (2015) A generic, empirical-based model for predicting rate of fire spread in shrublands. *International Journal of Wildland Fire* **24**, 443–460. doi:10.1071/WF14130

Baeza MJ, DeLuis M, Ravenstos J, Escarré A (2002) Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. *Journal of Environemental Management* **65**, 199–208. doi:10.1006/JEMA.2002.0545

Beer T (1991) The interaction of wind and fire. *Boundary-Layer Meteorology* **54**, 287–308. doi:10.1007/BF00183958

Bilgili E, Saglam B (2003) Fire behavior in maquis fuels in Turkey. *Forest Ecology and Management* **184**, 201–207. doi:10.1016/S0378-1127(03)00208-1

Butler B, Teske C, Jimenez D, O'Brien J, Sopko P, Wold C, Vosburgh M, Hornsby B, Loudermilk E (2016) Observations of energy transport and rate of spreads from low-intensity fires in longleaf pine habitat – RxCADRE 2012. *International Journal of Wildland Fire* **25**, 76–89. doi:10.1071/WF14154

Catchpole EA, Catchpole WR, Rothermel RC (1993) Fire behavior experiment in mixed-fuel complexes. *International Journal of Wildland Fire* **3**, 45–57. doi:10.1071/WF9930045

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

Cheney NP, Gould JS, Catchpole WR (1998) Prediction of fire spread in grasslands. *International Journal of Wildland Fire* **8**, 1–13. doi:10.1071/WF9980001

Clements CB, Lareau NP, Seto D, Contezac J, Davis B, Teske C, Zajkowski ThJ, Hudak AT, Bright BC, Dickinson MB, Butler BW, Jimenez D, Hiers JK (2015) Fire weather conditions and fire–atmosphere interactions observed during low-intensity prescribed fires – RxCADRE 2012. *International Journal of Wildland Fire* **25**, 90–101. doi:10.1071/WF14173

de Groot WJ, Bothwell PM, Taylor SW, Wotton BM, Stocks BJ, Alexander ME (2004) Jack pine regeneration and crown fires. *Canadian Journal of Forest Research* **34**, 1634–1641. doi:10.1139/X04-073

Dupuy JL, Maréchal J (2011) Slope effect on laboratory fire spread: contribution of radiation and convection to fuel bed preheating. *International Journal of Wildland Fire* **20**, 289–307. doi:10.1071/WF09076

Finney MA, Cohen JD, McAllister SS, Jolly WM (2013*a*) On the need for a theory of wildland fire spread. *International Journal of Wildland Fire* **22**, 25–36. doi:10.1071/WF11117

Finney MA, Forthofer J, Grenfell IC, Adam BA, Akafuah NK, Saito K (2013*b*) A study of flame spread in engineered cardboard fuelbeds. Part I. Correlations and observations. In 'Proceedings of 7th International Symposium on Scale Modeling (ISSM-7)', Hirosaki, Japan, 6–9 August. (International Scale Modeling Committee: Hirosaki, Japan)

Frankman D, Webb BW, Butler BW, Jimenez D, Forthofer JM, Sopko P, Shannon KS, Hiers JK, Ottmar RD (2013) Measurement of convective and radiative heating in wildland fires. *International Journal of Wildland Fire* **22**, 157–167. doi:10.1071/WF11097

Marsden-Smedley JB, Catchpole WR (1995) Fire behavior modelling in Tasmanian buttongrass moorlands: II Fire behavior. *International Journal of Wildland Fire* **5**, 215–228. doi:10.1071/WF9950215

Morandini F, Silvani X (2010) Experimental investigation of the physical mechanisms governing the spread of wildfires. *International Journal of Wildland Fire* **19**, 570–582. doi:10.1071/WF08113

Morandini F, Perez-Ramirez Y, Tihay V, Santoni PA, Barboni T (2013) Radiant, convective and heat release characterization of vegetation fire. *International Journal of Thermal Sciences* **70**, 83–91. doi:10.1016/J.IJTHERMALSCI.2013.03.011

Morvan D (2011) Physical phenomena and length scales governing the behaviour of wildfires. *Fire Technology* **47**, 437–460. doi:10.1007/S10694-010-0160-2

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 (2014) Wind effects, unsteady behaviors and regimes of propagation of surface fires in open fields. *Combustion Science and Technology* **186**, 869–888. doi:10.1080/00102202.2014.885961

Morvan D, Lamorlette A (2014) Impact of solid fuel particles size upon the propagation of a surface fire through a homogeneous vegetation layer. *Fire Safety Sciences* **11**, 1326–1338. doi:10.3801/IAFSS.FSS.11-1326

Nelson RM, Jr (1993*a*) Byram's derivation of the energy criterion for forest and wildland fires. *International Journal of Wildland Fire* **3**, 131–138. doi:10.1071/WF9930131

Nelson RM, Jr (1993*b*) Byram's energy criterion for wildland fires: units and equations. USDA Forest Service, Intermountain Research Station, Research Paper INT-415.

Nelson RM, Jr (2015) Re-analysis of wind and slope effects on flame characteristics of Mediterranean shrub fires. *International Journal of Wildland Fire* **24**, 1001–1007.

Nelson RM, Jr, Adkins CW (1988) A dimensionless correlation for the spread of wind-driven fires. *Canadian Journal of Forest Research* **18**, 391–397. doi:10.1139/X88-058

Nelson RM, Jr, Butler BW, Weise DR (2012) Entrainment regimes and flame characteristics of wildland fires. *International Journal of Wildland Fire* **21**, 127–140. doi:10.1071/WF10034

Pagni PJ, Peterson ThG (1973) Flame spread through porous fuels. *Proceedings of the Combustion Institute* **14**, 1099–1107. doi:10.1016/S0082-0784(73)80099-2

Pitts WM (1991) Wind effects on fires. *Progress in Energy and Combustion Science* **17**, 83–134. doi:10.1016/0360-1285(91)90017-H

Pyne SJ, Andrews PL, Laven RD (1996) 'Introduction to wildland fire.' (2nd edn) (Wiley: New York, NY, USA)

Raupach MR (1990) Similarity analysis of the interaction of bushfire plumes with ambient winds. *Mathematical and Computer Modelling* **13**, 113–121. doi:10.1016/0895-7177(90)90105-V

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-RP-115. (Ogden, UT)

Rothermel RC, Anderson HE (1966) Fire spread characteristics determined in the laboratory. USDA Forest Service, Intermountain research station, Research Paper INT-30.

Stocks BJ (1987) Fire behavior in immature jack pine. *Canadian Journal of Forest Research* **17**, 80–86. doi:10.1139/X87-014

Sullivan AL (2007) Convective Froude number and Byram's energy criterion of Australian experimental grassland fires. *Proceedings of the Combustion Institute* **31**, 2557–2564. doi:10.1016/J.PROCI.2006.07.053

Sullivan AL (2009) Wildland surface fire spread modelling, 1990–2007. 2. Empirical and quasi-empirical models. *International Journal of Wildland Fire* **18**, 369–386. doi:10.1071/WF06142

Taylor SW, Wotton BM, Alexander ME, Dalrymple GN (2004) Variation in wind and crown fire behaviour in a northern jack pine spruce forest. **34**, 1561–1576.