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ON WIND AND FIRE
Revisiting the classics

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Abstract: The interaction between wind and fire has been addressed by several authors in classical fire literature, from George Byram (1959) and Richard Rothermel (1972) in the U.S. Forest Services to Tom Beer (1991) in CSIRO Australia. In this paper, we revisit the early approaches taken by these pioneers and propose a new conceptual model based on their findings. In this new conceptual model, the effect of wind on fire spread is reduced by the indrafts created by fire intensity and the resulting convection. The model is successfully applied to data on experimental fires compiled by Catchpole et al. (1998).
Keywords: Wind, Fire, Interactions, Convection, Fire Spread

SOBRE O VENTO E O FOGO: Revisitando os clássicos.
Resumo: As interações entre vento e fogo têm sido estudadas por diversos autores da literatura clássica sobre fogos, desde George Byram (1959) e Richard Rothermel (1972) nos Serviços Florestal dos EUA a Tom Beer (1991) no CSIRO da Australia. Neste artigo revisitamos as abordagens destes pioneiros e propomos um novo modelo conceptual baseasdo nesses primeiros estudos. Neste novo modelo conceptual o efeito do vento na propagação do fogo é reduzido pelo efeito do vento contrário à propagação criado pela convecção associada à intensidade do fogo. O modelo foi aplicado com sucesso aos dados de fogos experimentais disponibilizados por Catchpole at al. (1998).
Palavras-Chave: Vento, Fogo, Interação, Convecção, Propagação do fogo

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Introduction

The purpose of this paper is to review some early fundamental works that tackle the interaction between wind and fire, starting by the fundamental work of George BYRAM (1959), based on physics, comparing the "Power of the Wind with the "Power of the Fire". Secondly, we look at the work of Richard ROTHERMEL (1972), based on laboratory experiments, who proposed an empirical model for the effect of wind in fire spread rate. Thirdly, we review the work of BEER (1991) who studied the airflows from convection resulting from fire.

In this sequence, we propose a conceptual model, based in convection, to assess to fire-induced wind in front of the fire front, and we include some numerical simulations, based on published equations of BYRAM (1959) and PUTMAN (1965) to estimate the indrafts of the fire wind. We use simulations with data from 357 experimental fires reported by CATCHPOLE *et al.* (1998) to exemplify the use of the model. The results are in line with the hypothesis that fireline intensity creates a convective flow and the corresponding indrafts that can reduce very significantly the effect of ambient wind on fire propagation.

Revisiting the Physics of Wind and Fire in the work of George BYRAM (1959)

George M. Byram (1909-1996) worked for the U.S. Forest Service since 1932. Byram studied physics at the University of California in Berkeley, and viewed fire in the perspective of energy. He published his major findings in a very important book (BYRAM 1959).

One of Byram´s most influential contributions was the introducing of the concept and the term fireline Intensity, often termed Byram´s fireline intensity (I_B) to quantify the heat release rate in the active combustion zone per unit length of the fire front, calculated as:

$$I_B = h_c \, w \, R$$

where:

I_B is the Byram´s fireline intensity (kW m^{-1});
h_c is the low heat of combustion of the fuel (kJ kg^{-1});
w is the amount of fuel for flaming combustion (kg m^{-2}), and
R is the rate of fire spread (m s^{-1}).

BYRAM (1959) also used the concept of fireline intensity in the derivation of his energy criterion to compare the strength of the buoyancy of the convective fire plume with the power of the horizontal ambient wind. He suggested a ratio between the power of the convective fire plume (P_f) and the power of the wind (P_w). With:

$$P_f = g\, I_B / (C_{pa}\, T_a)$$

$$P_w = (1/2)\, \rho_a\, (U_a - R)^3$$

The dimensionless ratio between the "Power of the Fire "(P_f) and the "Power of the Wind" (NELSON 1993) was then termed the Byram´s convective number (N_c), as:

$$N_c = P_f / P_w = (2\, g\, I_B) / [\, \rho_a\, C_{pa}\, T_a\, (U_a - R\,)^3]$$

where:

g is gravity (9.8 m s^{-2});
I_B is the Byram´s Fireline intensity (kW m^{-1});
ρ_a is the density of air (around 1.2 kg m^{-3});
C_{pa} is the specific heat of dry air at constant pressure (around 1.005 J kg^{-1} K^{-1});
T_a is the absolute air temperature (K);
U_a is the horizontal wind speed (m s^{-1}); and
R is the forward rate of fire spread (m s^{-1}).

Byram used this energy criterion to distinguish two types of fires. Larger values of N_c correspond to fires that are dominated by the upward forces associated with large and vertical convective plumes. Smaller values of N_c correspond to fires that are primarily driven by the ambient wind, with the fire plume deflected in the direction of the wind flow.

The experimental approach by Richard ROTHERMEL (1972)

Richard Rothermel initial degree in 1953 was in aeronautical engineering at the University of Washington and received his master degree in mechanical engineering at the University of Colorado, Fort Collins, in 1971. He served in the U.S. Air Force as a special weapons aircraft development officer from 1953 to 1955, then joined the Douglas Aircraft Co. and the General Electric Co. in the aircraft nuclear propulsion department at the National Reactor Testing Station in Idaho. In 1966, Rothermel joined the Northern Forest Fire Laboratory, where he has been engaged in research on the mechanisms of fire spread leading different units and projects as a research engineer since 1966 at the Northern Forest Fire Laboratory in Missoula, Montana.

With his engineering background, Rorhermel worked with Hal Anderson in the Missoula Laboratory, and they published together an important paper with their first results with experimental fires (ROTHERMEL AND ANDERSON 1966). Subsequently, ROTHERMEL (1972) published his mathematical model for predicting fire spread that has since been the basis of most applications around the world. With his background in aeronautical engineering, Rothermel developed a semi-empirical model.

From the energy conservation approach, Rothermel kept the equation for rate of spread for the no-wind, no-slope conditions (R_0) as:

$$R_0 = (I_p)_0 \;/\; (\rho_{be}\, Q_{ig})$$

where:

R_0 is the rate of spread of the fire in the no-wind no-slope conditions (m s^{-1});
$(I_p)_0$ is the propagating heat flux for the no-wind no-slope conditions (kW m^{-2});
ρ_{be} is the effective bulk density (kg m^{-3}); and
Q_{ig} is the heat of pre-ignition (kJ kg^{-1}).

The effects of wind and slope were then added with the formula:

$$R = R_0\,(1 + \varphi_W + \varphi_S)$$

where:

φ_W is an empirically derived wind coefficient, dependent on a fuel bed property, the packing ratio β, and the fuel particle size σ, and

φ_S is an empirically derived slope coefficient, based on the slope of the fuel bed $\tan(\varphi)$.

The mathematical model of ROTHERMEL (1972) includes the effect of ambient wind speed in a multiplication factor with empirical coefficients derived from experiments. However, the model does not explicitly addresses the processes of heat transfer, or the interaction between wind and fire. From the figures, it is apparent that Rothermel recognizes the importance of heat transfer through the fuel bed by internal radiation and convection, and the existence of indrafts in the no-wind no-slope situation. However, from the same work (Figure 1), it is apparent that Rothermel sees radiation as the primary process of heat transfer in wind-driven fires, and indrafts are not represented. However, several studies and computational fluid dynamics simulations at finer scale (e.g. Morvan et al. 2011) indicate that these airflow patterns do exist and that, close to the fire, inflows from both sides replace the outflow air that moves upwards in the convection plume (Figure 1).

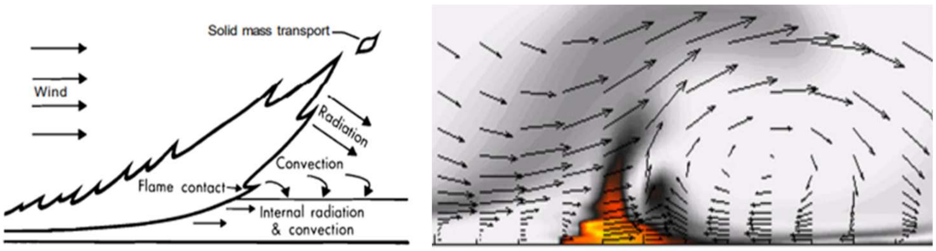

Figure 1 - Left: Representation of the processes involving wind and convection in the work of ROTHERMEL (1972). Right: Airflow patterns around a fire front driven by wind according to computatuional fluid dynamics simulations (after Morvan et al. 2011).

The physics behind the Rothermel model was based on the conservation of energy principle and the heat balance approach well established to understand fire spread through porous fuels (FRANDSEN 1971). However, as ANDERSON (1964, 1969) had already recognized, the heat transfer by internal radiation and convection through the fuel bed was not enough to fully predict fire spread. Therefore, several other authors focused in more depth on modelling radiative flux from the flame and its contribution to the spread of fires (e.g. THOMAS 1965, Telitsyn 1973). However, it was soon understood that convection was the most important process to consider in the presence of significant wind (PAGNI AND PETERSON 1973).

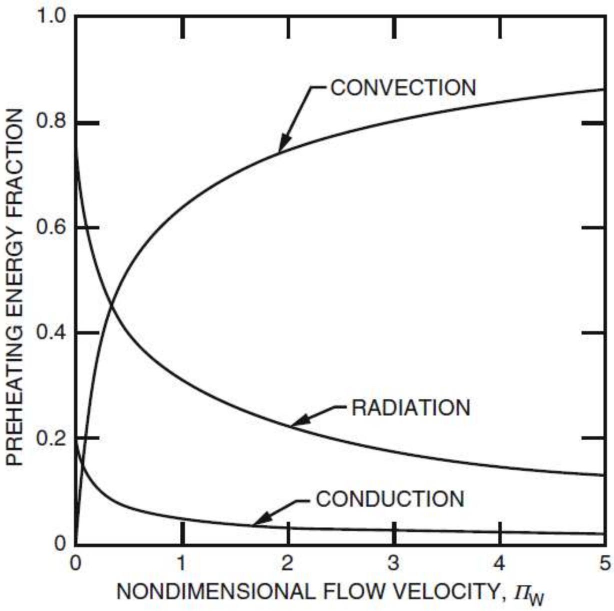

Figure 2 - Relation of the preheating energy fractions of the three processes of heat transfer (conduction, radiation and convection) as a function of a nondimnsional flow velocity, a gradient of ambient wind speed and fire rate of spread (PAGNI AND PETERSON 1973).

From these analyses, it became apparent that the energy conservation approach is best applied when heat is transferred in porous fuels through the combustion zone by conduction and radiation, but it is difficult to apply when the main process involved is convection.

The Fire Wind from Australia by BEER (1991)

In Australia, working as a research scientist for the Commonwealth Scientific and Industrial Research Organization (CSIRO), Tom Beer made important contributions for the understanding of the interactions between wind and fire.

BEER (1991) took a different approach, using the balance of the volume of air entering and leaving the fire zone. First, applying stoichiometry, and knowing that there is a relatively constant value for the volumetric air requirement per kilogram of fuel consumed (G around 4.3 m^3 kg^{-1}) he proposed the calculation of a stoichiometric flux per meter of the fireline (SF in $m^3s^{-1}m^{-1}$) as:

$$SF = G\ w\ R$$

where, as before, w is the fuel load (kg m^{-2}) and R is the fire spread rate (m s^{-1}).

He then defines a Fire Wind (U_f) as the velocity of air entering the fire. If the height of this fire wind is considered equivalent of the flame height (H in m), then, because inflow comes from both sides of the flame, the velocity of the fire wind (U_f in ms^{-1}) is:

$$U_f = (G\ w\ R)\ /\ (2\ H)$$

The diagrammatic representation of the calculations to estimate the fire-induced wind from stoichiometry is shown in figure 3.

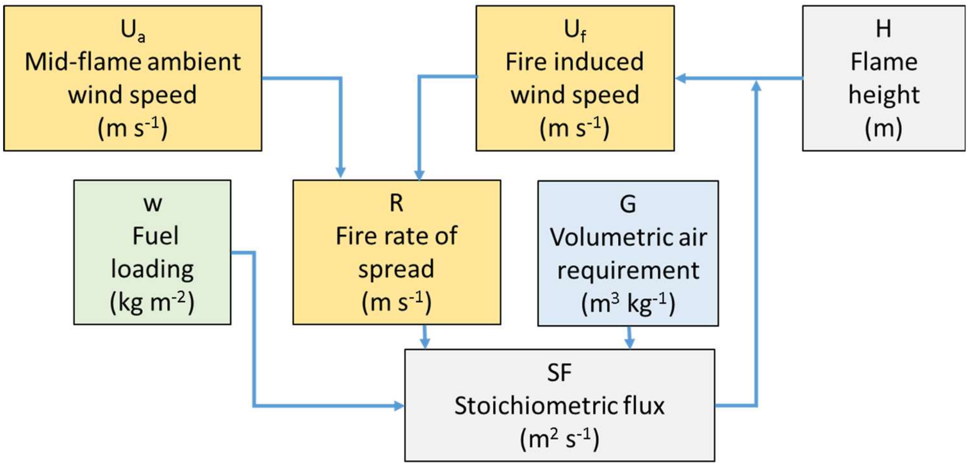

Figure 3 - The variables associated with the stoichiometric calculation of the fire-induced wind according to BEER (1991).

This model indicates the minimum requirements for a sustained fire, and this stoichiometric flux is always less than the actual convective flux originated by the fire.

The estimate of the convective air velocity was provided by the work of another Australian, Raupach (1990) who used similarity analysis to propose an equation to predict the updraft vertical velocity above the fire (U_v) as a function of Byram´s Fireline intensity (I_B):

$$U_v = 1.66\ [\ (\ g\ I_B\ )\ /\ (\rho_a\ C_{pa}\ T_a)\ ]^{1/3}$$

where:

U_v is the upward velocity of the fire plume (m s^{-1});
g is gravity (9.8 m s^{-2});
I_B is the Byram´s Fireline intensity (kW m^{-1});
ρ_a is the density of air (around 1.2 kg m^{-3});
C_{pa} is the specific heat of dry air at constant pressure (around 1.0 J kg^{-1} K^{-1});
T_a is the absolute air temperature (around 300K).

Simplifying, we have the approximate equation:

$$U_v = 0.5\ I_B^{\ 1/3}$$

The visual representation of this process is in Figure 4.

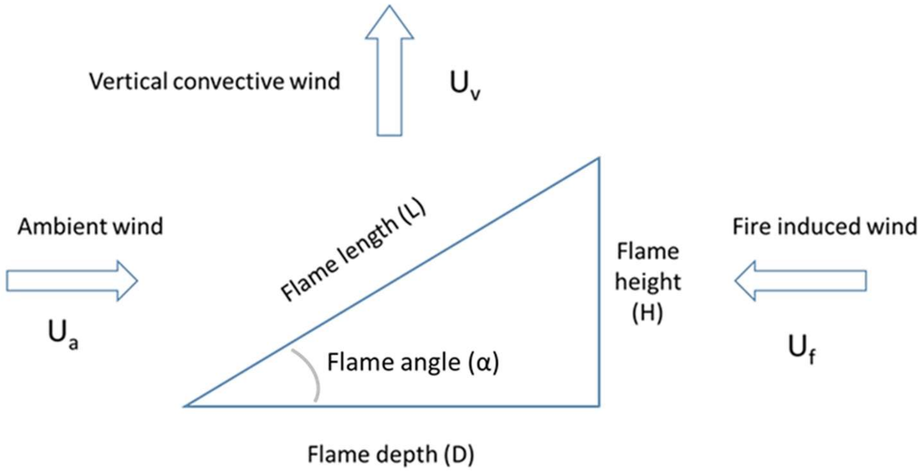

Figure 4 - A visual display of the simplified geometry of the flame and the type of winds involved in the process of fire propagation dominated by convection. The geometry of the flame is represented by flame length (L), flame height (H), flame depth (D) and flame angle (α). The type of winds are the horizontal ambient wind (U_a), the vertical convective wind (U_v), and the fire induced wind (U_f).

Finally, as in BEER (1991), if we consider that the air in the updraft flow has to be replaced by air coming equally from indrafts from the two sides of the flame, we can approximate the velocity of fire wind (U_f in ms^{-1}), as:

$$U_f = U_v D / (2H)$$

However, it is known that the process is not so simple as air can come differently from the two sides and flame height (H) is also a function of the ambient wind speed (U_a) and the subsequent inclination of the flame.

A Conceptual Model

Using the concepts already presented, we hypothesize that, in wind-driven fires where convection is the dominant process on fire behavior, the convective flow originated by the fire itself reduces the influence of ambient wind on fire spread.

The conceptual model follows processes explained in a few steps. First, the ambient wind tends to increase fire spread and therefore fireline intensity. Subsequently, the intensity of the fire creates a vertical convective flux above the flame. The inclination of the flame is dependent on the balance between ambient wind and the convective wind. The air required to replace the volume lost in convection has to come from both sides of the flame through the vertical height of the flame. The fire-induced wind from indrafts at the front of the fire counteracts the influence of the ambient wind on fire spread. This negative feedback creates a control system that has to be in balance in a steady-state situation of fire propagation. The diagram of Figure 6 illustrates the model.

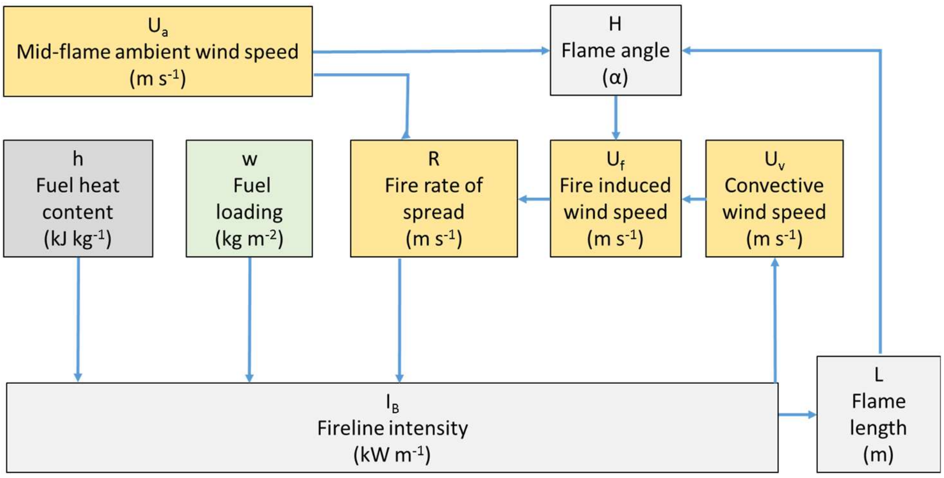

Figure 6 - The conceptual model proposed with the different variables and their relations.

In this simple model, the balance between the upward airflow and the air inflows from both sides, that do not necessarily have to be equal, is:

$$(U_a + U_f)\ H = U_v\ D$$

As $H\ /\ D = \tan(\alpha)$ the equation can be solved for U_f as:

$$U_f = U_v\ /\ \tan(\alpha) - U_a$$

Simulations with empirical equations and data from CATCHPOLE *et al.* (1998)

The solving of the previous equation for H_f requires knowing U_a and estimates of U_v and $\tan(\alpha)$. And some authors have established equations to estimate U_v and $\tan(\alpha)$ from Byram´s fireline intensity. The first is the already shown equation by Raupach (1990):

$$U_v = 1.66\ [\ (\ g\ I_B\ )\ /\ (\rho_a\ C_{pa}\ T_a)\ ]^{1/3}$$

The estimation of the flame angle and therefore $\tan(\alpha)$ requires two steps:

The first step is to estimate flame length (L in m) from fireline intensity (I_B in kW m^{-1}), as proposed by BYRAM (1959):

$$L = 0.0775\ I_B^{\ 0.46}$$

This equation has since been widely used as in BEHAVE and in subsequent fire behavior systems.

The second step is to estimate $\tan(\alpha)$ from flame length (L) and ambient wind (U_a). Flame angle is difficult to evaluate in experimental fires in forest fuels. However, from experimental fires with natural gas flames it was possible to derive a theoretical model to estimate flame angles from flame length and ambient wind speed (PUTMAN 1965). This model was subsequently parameterized (WEISE AND BIGING 1996) and produced the equation:

$$\tan(\alpha) = (g\ L)^{1/2}\ /\ (1.4\ U_a\ ) = 2.24\ L^{1/2}/\ U_a$$

Finally, if we consider that the air in the updraft flow has to be replaced by air coming equally from the two sides of the flame, we can compute the velocity of fire wind (U_f in ms^{-1}), as indicated before:

$$U_f = U_v / \tan(\alpha) - U_a$$

This indicates that, for the same flame angle, the fire-induced wind increases with convective winds resulting from fireline intensity and decreases with ambient wind speed. This agrees with the results of simulations made by ROXBURGH AND REIN (2008) who used a computational fluid dynamic model of fluid flows driven by fire (MCGRATTAN et al. 2007).

The work of CATCHPOLE *et al.* (1998) provided very important data on 357 experimental fires burning in a large wind tunnel. As the fires are all well described for their characteristics it is possible to apply the above model to these fires and estimate the fire-induced wind.

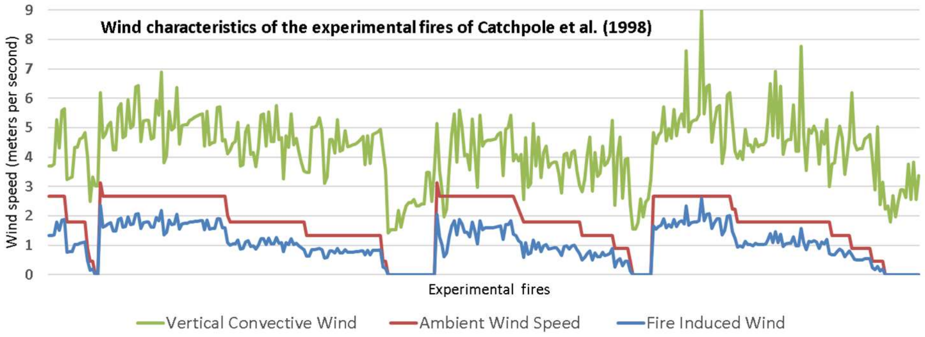

Figure 7 - Simulations with the proposed model using data from CATCHPOLE *et al.* (1998).

The estimates of the fire-induced wind are smaller than the given ambient wind speeds but follow tem closely.

Rearranging the former empirical equations to have U_f as a function of U_a and I_B we have the approximate formula:

$$U_f = (0.8\ I_B^{\ 0.1} - 1)\ U_a$$

This equation shows that as fireline intensity increases the larger is the ratio between the fire induced wind and the ambient wind. A graphical representation of the influence of fireline intensity in the ratio between the induced fire wind and the ambient wind is shown in Figure 8.

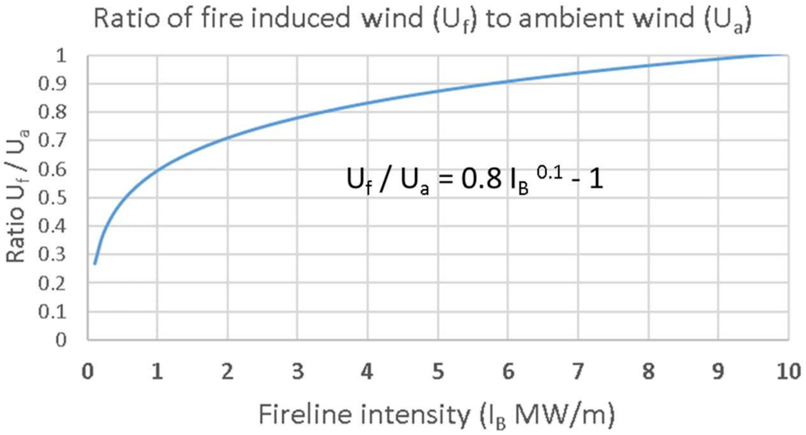

Figure 8 - Using the conceptual model and the empirical equations presented, the fire-induced wind (U_f) approaches the ambient wind (U_a) for large fireline intensities.

In spite of the results obtained are derived from empirical equations, some general conclusions can be drawn from the simulations performed.

First, the results are in line with observations and simulations that indicate that indrafts increase with fireline intensity.

Secondly, results are in line with the known characteristic that the effect of wind in fire spread is much higher fires in light fuels, with lower fuel loads and therefore lower convection, than with higher fuel loads, as represented in the study of ROTHERMEL (1972), shown in Figure 9.

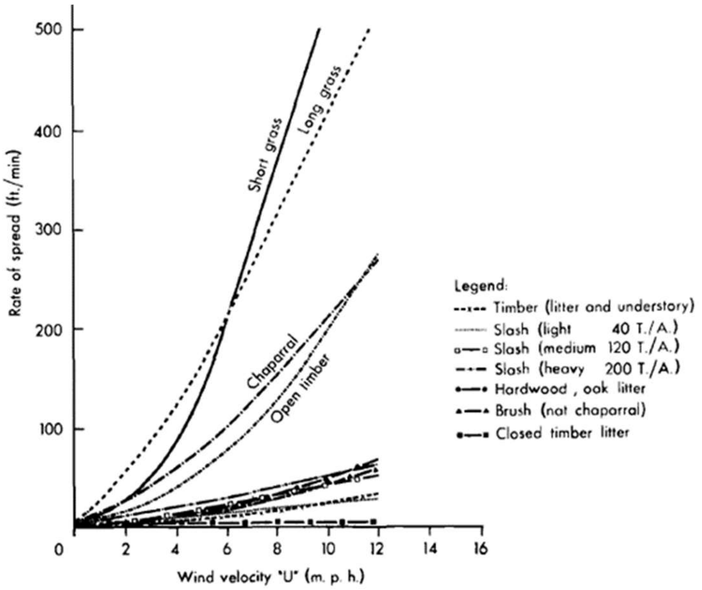

Figure 9 - The different effect of wind in different types of fuel that have different fuel loads (ROTHERMEL 1972).

Thirdly, the results seem to confirm the hypothesis of the negative feedback of indrafts created by convection that counteract the effect of ambient fire on fire spread. The larger the fireline intensity, the larger the ratio between the wind induced by the fire and the ambient wind. For very large intensities, the ratio is very close to unity and fires will spread very slowly.

The proposed model and simulations are attempts to better clarify the processes involved in the interaction between wind and fire and the main relations of the different types of wind, from ambient wind to those generated by fire itself.

A possible approach to predict fire rate of spread exemplified with data from CATCHPOLE *et al.* (1998)

From the above sections, we are able to combine the different approaches. We can use the principle of the conservation of energy to estimate the rate of spread in a no-wind no-slope situation, and then use a multiplication factor to include wind and slope in the equation, as did ROTHERMEL (1972).

The ratio between the heat source, the heat release rate (HRR in kJ m^{-2} s^{-1}), and the heat sink, the heat of pre-ignition (HP in kJ m^{-3}), is an estimate of the potential rate of spread (PR, in m/s) based on the principles of conservation of energy:

$$PR\ (m/s) = HRR\ (kJ/m^2/s)\ /\ HP\ (kJ/m^3)$$

Heat Release Rate (HRR, $kJ/m^2/s$) is the net release of energy from fuel combustion. The average value of 18000 kJ/kg, commonly used, takes into account the heat content of dry forest fuels (around 18600 kJ/kg) decreased by the energy required to increase a unit weight of dry fuel from initial temperature to ignition temperature (around 600 kJ/kg). Also, we have to consider the losses due to the energy required to raise the initial temperature of a unit weight of the moisture to boiling temperature, to vaporize that water, and to increase the resulting water vapour to ignition temperature, which is around 3000 kJ per kg of water. If we use the ratio between moisture and dry fuel (M_f, non-dimensional) and consider the dry fuel loading (F, kg/m^2) and the residence time (T_p, in seconds) the heat release rate is:

$$HRR\ (kJ/m^2/s) = (\ 18000\ kJ/kg - M_f\ 3000\ kJ/kg\ ) * F\ (kg/m^2)\ /\ T_p\ (s)$$

Heat of Preignition (HP, kJ/m^3) is defined as the energy required to bring a unit volume of fuel to ignition. The calculations are based on the energy required to increase a unit weight of dry fuel from initial temperature to ignition temperature (around 600 kJ/kg), and the energy required to raise the initial temperature of a unit weight of water to ignition temperature (around 3000 kJ/kg). Therefore, using the value of the moisture content of fuel particles (M_f), and taking into account that the mass of fuel per unit volume of the fuel bed (the bulk density of the fuel (B in kg/m^3) we compute HP as:

$$HP\ (kJ/m^3) = (600\ kJ/kg + M_f * 3000\ kJ/kg) * (B,\ kg/m^3)$$

We can now use again data from CATCHPOLE *et al.* (1998) to develop an equation that includes the potential rate of spread (PR), the effects of wind and the effect of convection to estimate rate of spread (R).

In the previous sections, we saw that the negative feedback wind caused by convection is related to fireline intensity. If we want to estimate rate of spread we cannot use it as predictor. As fireline intensity already includes rate of spread in its calculations, we have to use another measure of intensity. In this case we use Reaction Intensity, or Heat Release Rate, as a proxy of convection and therefore of the negative feedback indrafts. We propose the equation:

$$R = a\ PR^{\,b} * \exp(c\ U_a - d\ HRR)$$

The first part of the equation is based on the potential rate of spread (PR, in m/s) derived from the principle of the conservation of energy. The second part of the equation is related with the action of the ambient wind (U_a in m/s) and the negative feedback created by the convection caused by fire itself, as measured by the heat release rate (HRR, in kJ/m²/s). The model is represented in Figure 10.

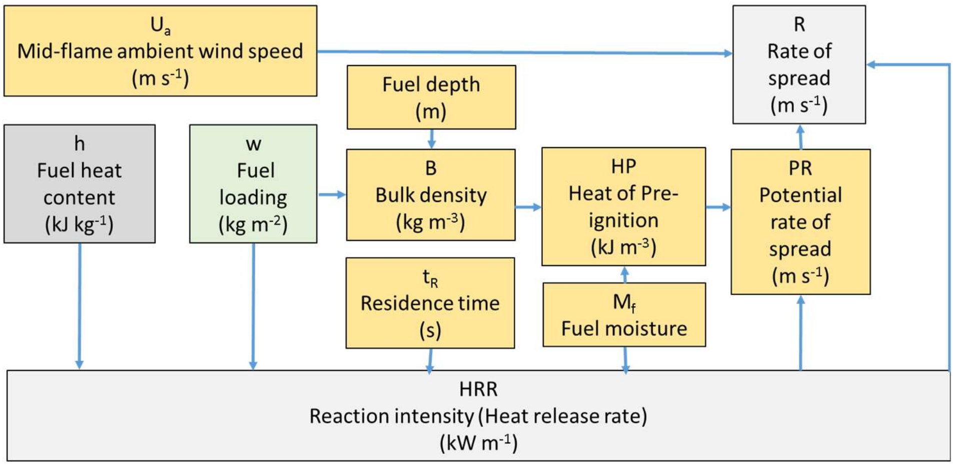

Figure 10 - Representation of the model proposed to estimate fire rate of spread (R) from potential rate of spread (PR), ambient wind (U_a) and heat release rate (HRR) showing some of the most important variables associated.

Using the equation above, we fitted this equation to the data set provided by CATCHPOLE *et al.* (1998) who describe the results of 357 experimental fires conducted in an environmentally controlled large wind tunnel, including fires burning over a range of particle sizes, fuel bed depths, moisture contents and windspeeds. We used 338 of those experiments as we excluded those with a very small fuel depth (less than 2.5 cm) that the authors considered suspicious.

The final equation to predict fire rate of spread (R in m/s) was established through a non-linear regression approach with the resulting parameters estimated as:

$$R = 0.145\ PR^{\,0.59} * \exp(0.49\ U_a - 0.00066\ HRR) \qquad R^2 = 0.835 \qquad n = 338$$

The match between observed and predicted rates of spread is obvious in Figure 11.

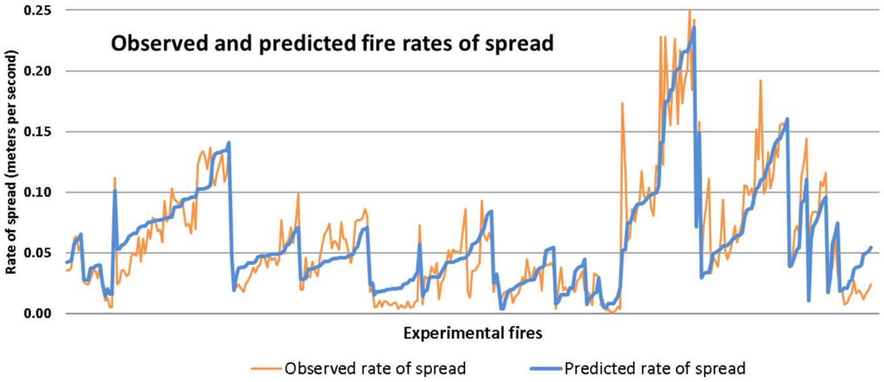

Figure 11 - Comparison of the good agreement between observed and predicted rates of spread using the model proposed applied to 338 experimental fires reported by CATCHPOLE et al. (1998).

The negative effect of heat release rate counteracting the effect of wind is particularly interesting. These results seem to confirm empirically that the convection updraft created by fire has important consequences in the indrafts it originates and on fire spread. From these results, it is possible to estimate that a heat release rate of around 740 kJ/m^2/s counteracts an ambient wind of 1 m/s.

The proposed model and its good fit to the experimental data illustrates the potential of using a semi-empirical model combining the principles of conservation of energy in the estimation of a potential rate of spread with the concept that the effect of wind decreases with the intensity of fire.

LITERATURE CITED:

ANDERSON, H.E. 1964. Mechanisms of fire spread. Research Progress Report No. 1. Res. Pap. INT-8. Ogden: USDA Forest Service Intermountain Forest and Range Experiment Station.

ANDERSON, H.E. 1969. Heat transfer and fire spread. Research Paper INT-69. Ogden: USDA Forest Service Intermountain Forest and Range Experiment Station.

BEER, T. 1991. The interaction of wind and fire. Boundary-Layer Meteorology, 54(3), 287-308.

BYRAM, G.M. 1959. Combustion of forest fuels. In K. Davis (Ed.). Forest fire: Control and use. New York. McGraw-Hill.

CATCHPOLE, E.R., CATCHPOLE, E.A., BUTLER, B.W., ROTHERMEL, R.C., MORRIS, G.A. AND LATHAM, D.J. 1998. Rate of Spread of Free-Burning Fires in Woody Fuels in a Wind Tunnel. Combust. Sci. and Tech. Vol. 131. Pp.1-37.

FRANDSEN, W.H. 1971. Fire spread through porous fuels from the conservation of energy. Comustion and Flame 16: 9-16.

MCGRATTAN, K, KLEIN, B., HOSTIKKA, S. AND FLOYD, J. 2007. Fire Dynamic Simulator (version 5) User´s Guide, NIST Special Publication 1019-5.

NELSON, R.M. Jr. 1993. Byram´s derivation of the energy criterion for forest and wildland fires. Int. J. Wildland Fire 3(3): 131-138.

PAGNI, P.J., AND PETERSON, T.G. 1973. Flame spread through porous fuels. In International Symposium on Combustion 14(1): 1099-1107. Elsevier, Amsterdam.

PUTMAN, A.A. 1965. A model study of wind-blown free-burning fires. In Proceedings, 10th Symposium (International) on Combustion. Combustion Institute, Pittsburgh, Pa., 17-21 Aug. 1964. University of Cambridge, Cambridge, U.K. pp. 1039-1046.

ROTHERMEL, R.C., AND ANDERSON, H.E. 1966. Fire spread characteristics determined in the laboratory. Res. Pap. INT-30. Ogden: USDA Forest Service Intermountain Forest and Range Experiment Station.

ROTHERMEL, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden: USDA Forest Service Intermountain Forest and Range Experiment Station.

ROXBURGH, R. AND REIN. G. 2008. Study of wildfire in-draft flows for counter fire operations. WIT Transactions on Ecology and the Environment, 119:13-22.

THOMAS, P.H. 1965. The contribution of flame radiation to fire spread in forests. Fire Research Note 594. Boreham Wood: Joint Fire Research Organisation.

WEISE, D.R., AND BIGING, G.S. 1996. Effects of wind velocity and slope on flame properties. Can. J. For. Res. 26: 1849-1858.