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Fire spread near the attached and separated flow transition, including surge and stall behaviour

John Dold[a]

[a]*School of Mathematics, University of Manchester, M13 9PL, U.K.*
Email: John.Dold@manchester.ac.uk

Abstract: Some fires are observed to spread in what might be called a *surge-and-stall* manner, spreading quickly when wind dominates any buoyancy effects (at low burning intensity) but slowly when intensity is high and buoyancy causes a flow separation. Other fires in light, easily flammable dry vegetation are said to spread at speeds that are not very substantially slower than the wind. Scalings associated with plume dynamics suggest a simple relationship at the separation-attachment transition, similar to a formula of Byram (1959), at which an equilibrium fire spread rate would grow strongly with the wind speed, especially for easily ignitable light fuel loads. Simulations show that this equilibrium becomes unstable for fuels with a sufficiently delayed engagement between ignition (at the fire's arrival) and the release of heat. Under these conditions surge-and-stall behaviour arises, being oscillatory at its onset but also showing the potential for chaotic dynamics at strongly delayed intensity generation.

In more detail, there are two key physical processes that underlie these conclusions.

The first is that fireline intensity I (having the units $\mathrm{kW\,m^{-1}}$) is accumulated as a fire spreads over any new vegetation, being determined by the rate at which chemical energy is released behind a unit length of fireline, from the point where burning begins to the point where the fire burns out. The size of this region (the flame depth) varies with time if the spread rate R of the fire front is not constant. Also, the energy release rate through the flame depth is not necessarily constant since lighter fuel components become engaged first in the flaming with heavier components entering later on to contribute differently to the rate at which pyrolysis and oxidation occur. This can be expressed mathematically in the form of an integral

$$I = \frac{Qm}{\tau_\mathrm{b}} \int_0^{\tau_\mathrm{b}} \psi(\tau)\, R(t-\tau)\, \mathrm{d}\tau \tag{1}$$

in which the fuel load is $m\ \mathrm{kg\,m^{-2}}$ with a combustion energy of $Q\ \mathrm{kJ\,kg^{-1}}$, burning at a non-constant rate of $\psi(\tau)/\tau_\mathrm{b}\ \mathrm{s^{-1}}$ where τ is the elapsed time from the moment burning begins at any location and τ_b represents the overall burnout time. The factor $\psi(\tau)$ serves as a weighting function, normalised so that $\int_0^{\tau_\mathrm{b}} \psi(\tau)\, \mathrm{d}\tau = 1$, to allow for variations in the rate of energy release from the time of ignition ($\tau = 0$) to the time of burnout ($\tau = \tau_\mathrm{b}$). If the spread rate is constant then the steady energy balance formula $I = QmR$, attributable to Byram (1959), is reproduced. In unsteady fire spread Byram's formula does not hold true and the more involved formula (1) is a more physically appropriate representation.

The second physical process comes from the recognition that, when driven by a steady wind w, a transition between attached flow through the fire (at low intensity) and a separated buoyant plume flow (at high intensity) arises around a critical intensity $I_\mathrm{c}(w)$. These different forms of air flow through the fire lead to different spread rates R. Most importantly, the enhanced convective heat transfer that is present in attached flow must lead to an increased spread rate at low enough intensities (below I_c). An equilibrium spread rate near this transition is possible if the spread-rate intensity relationship $R = \mathcal{R}(I)$ intersects Byram's formula $I = QmR$ near $I = I_\mathrm{c}$, something that is most likely to happen in light dry vegetation (e.g. cured grass) with strong enough winds. By examining a suitable spread-rate intensity relationship that captures this feature, simulations show that the equilibrium spread rate becomes unstable, leading to surge-and-stall fire spread, for a sufficient degree of delayed energy release, as represented by the weighting function $\psi(\tau)$.

Keywords: Fireline intensity, Fire plume, Wind driven fire spread, Fire in attached or separated flow. Unsteady fire spread, surge and stall fire spread.

1 INTRODUCTION

It is sometimes seen that firelines advance in an unsteady manner, having a spread rate R and intensity I that do not remain in proportion to each other. Eruptive or blowup fires as highlighted, amongst others, by Viegas (2005, 2006, 2009) are a case in point (Dold & Zinoviev, 2009; Dold, 2010). But these are not the only examples. A report on Project Vesta (Gould et al, 2007) includes the description:

> *As the wind speed increases there are surges in forward spread that ignite an area of fuel behind the head and increase the convection over the burnt ground. If the ambient wind speed is light, this convection can be strong enough to block the wind from reaching the flame front. The front will burn as a backing fire for a minute or so until the fuel behind the flame front has burnt out and the convection weakened to a point where the wind can again penetrate to the leading edge of the fire and blow the flames forward again as a heading fire.*

That is: a low (backing) spread rate was observed at large flame depth and high intensity when the fire was seen to wane or diminish; a high (heading) spread rate was observed at small flame depth and low intensity when the fire waxed or intensified; the burnout time τ_b of the fire in these experiments was around a minute or so.

This *surge-and-stall* advancement of a fire front raises several interesting issues in the nature of fire spread, actually helping to unify a number of concepts, as will be explained here. These are

- that intensity develops through an accumulation process as a fire spreads, being related to the history of spread rates over the past burnout time and the rates at which different parts of the vegetation, ignited earlier, continue to release fuel vapour into the flames over the burnout time
- that spread rate is a function of intensity since the latter determines, at least in part, how quickly energy can be fed into the vegetation ahead of the fire
- that this dependence of spread rate on intensity can have a bimodal form in the presence of wind, depending on whether or not the buoyancy of the fireline is strong enough to overcome the wind

The manner in which fireline intensity depends on earlier spread rates has been formulated in previous publications (Dold *et al.*, 2009; Dold, 2010; Dold *et al.*, 2011) and this formulation will be used here. In essence, the intensity is given by the weighted integral formula (1) over earlier spread rates that has already been described in the abstract.

When this formula for intensity evolution is applied to spread rate dependences on intensity that characterise attached and separated transitions, simulations show that not all vegetation layers would be able to generate surge and stall advancement of a fireline. It is found that the process of energy release from any small area of vegetation needs to increase with elapsed time, to some degree, from the moment of engagement in the burning, so that the weighting function $\psi(\tau)$ reflects some degree of delay in the release of energy. Physically, this might be achieved, for example, by initial engagement of a relatively low mass of light vegetation components, with a greater mass of slightly thicker vegetation components following on to deliver the bulk of the energy during a later stage of the active burning process.

2 CRITERION FOR SEPARATED OR ATTACHED FLOW AT A FIRELINE

The theory connected with line plumes (Gebhart *et al.*, 2003) can be used to identify criteria that can help to predict the type of air flow that arises around a wind-driven fireline of a high enough intensity.

2.1 Plume considerations

The basic idea is that strong buoyancy associated with a high intensity fire or low wind-speed must make the air flow separate at a fireline, causing air to rise upwards, entraining or drawing in surrounding ambient air from both the upwind and downwind sides; this represents *a plume dominated fire, having separation of the air flow* at the fireline. On the other hand, stronger winds or lower intensity fires that do not generate sufficient buoyancy to overcome the wind, would lead to an air flow that penetrates through the fireline and continues to flow forwards ahead of it, representing *a wind dominated fire having attached air flow*. This duality in the type of air flow, dominated either by the plume or by the wind, was already identified by Andrews and Chase (1989) and is implicit in some of the work of Byram (1959) even though he was not explicitly considering plume flow near ground level.

A steady buoyant line plume rising vertically above a long line fire in neutrally stratified air can be characterised by its mean vertical velocity $v(z)$, mean density $\rho(z)$ and mean horizontal thickness $b(z)$, all depending on vertical height z as illustrated in Figure 1. Treated using a top-hat formulation (Gebhard *et al.*, 2003) the properties are taken to be uniform across the plume and the buoyancy force is determined using Archimedes principle. In the simplest (Boussinesq) approach, fresh environmental air of density ρ_e and temperature T_e is taken to be entrained into both sides of the plume at the transverse velocity $v_e = \alpha v$ for an entrainment constant α that has a value of $\alpha \approx \frac{1}{8}$ (*ibid*). Conservation of mass, energy and momentum as they flow upwards then take the respective forms

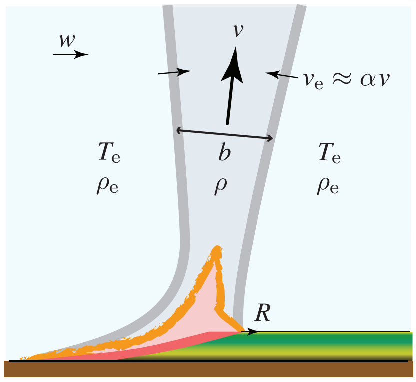

Figure 1: Sketch of a buoyancy dominated plume above a line fire, spreading at speed R in a wind of speed w.

$$(b\rho v)_z = 2\alpha\rho_e v \qquad (bv)_z = 2\alpha v \qquad (b\rho v^2)_z = b(\rho_e - \rho)g \tag{2}$$

after some simplification, including use of the isobaric gas law $\rho T = \rho_e T_e$ where $T(z)$ is the temperature in the plume at height z. The first two of these equations can be combined to show that $\big(b(\rho_e - \rho)v\big)_z = 0$ which means that the 'buoyancy flux' $F_b = b(\rho_e - \rho)gv$ stays constant in the plume. Moreover, this quantity can be estimated from the fireline intensity as $F_b = b(\rho_e - \rho)gv = gI/(c_p T_e)$, for a specific heat of c_p, where the mean density ρ just above the flames is taken to be much less than ρ_e, as it should be.

Solutions of equations (2) approach a self-similar form as z increases, in which v stays constant and b increases linearly with height, having

$$b \to 2\alpha(z + z_0) \qquad v^3 \to \frac{F_b}{2\alpha\rho_e} \qquad \rho \to \rho_e - \left(\frac{\rho_e F_b^2}{4\alpha^2}\right)^{1/3} \frac{1}{g(z + z_0)} \tag{3}$$

where z_0 is a constant (representing a downward vertical displacement). It can be noted that the Richardson number approaches a value of 2α. That is, in the plume

$$\mathrm{Ri} = \frac{b(\rho_e - \rho)g}{\rho_e v^2} = \frac{F_b}{\rho_e v^3} \to 2\alpha \qquad \text{so that} \qquad v^3 \approx \frac{gI}{2\alpha\rho_e c_p T_e} \tag{4}$$

which shows that the mean velocity of rise in the plume scales with the cube root of the intensity.

In a plume rising vertically above the moving fireline, the entrainment velocity $v_e = \alpha v$ must be supplied by the incoming wind w relative to the spread-rate R, at least on one side, so that $w - R \approx v_e$. It follows that $(w - R)^3 \approx \alpha^2 gI/(2\rho_e c_p T_e)$ in such a plume. For a wind satisfying this relation, the plume rises almost vertically in a reference frame that moves with the fireline. Any stronger wind must push the plume towards the vegetation, causing flow attachment when the wind is strong enough.

Without further investigation, an order of magnitude estimate for the wind-intensity relation at the stage where a transition from separated to attached flow should occur, can be deduced as having the form

$$(w - R)^3 \approx \frac{gI_c/A}{\rho_e c_p T_e} \qquad \text{or} \qquad I_c \approx A\,(w - R)^3 \rho_e c_p T_e/g \approx A \times \left(\frac{w - R}{\mathrm{km/h}}\right)^3 \mathrm{kW/m} \tag{5}$$

in which A is an as yet unknown order one factor; the first of these relations (with $A = 1$) is Byram's estimate for the transition between wind and intensity dominance of the fire. As shown here, if realistic values for environmental properties are inserted into the formula and $w - R$ is evaluated in $\mathrm{km/h}$ then $A \times (w - R)^3$ numerically estimates the value of I_c in $\mathrm{kW/m}$. Thus, for example, the transitional intensity at a value of $w - R \approx 10$ km/h would be estimated at around A MW/m.

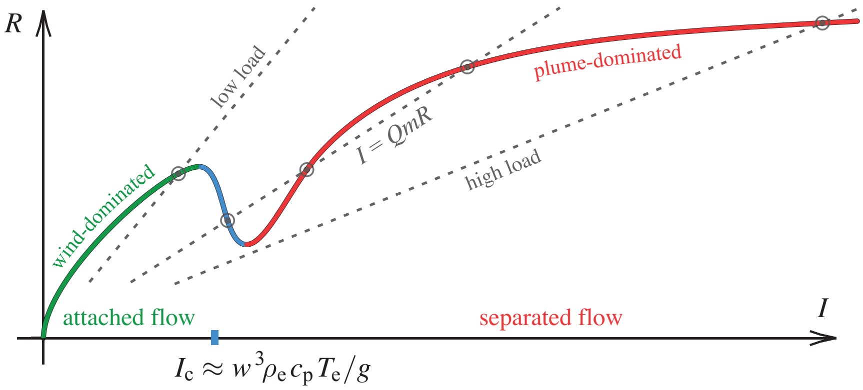

Figure 2: The solid curve is a qualitative illustration of the general *unsteady* variation of spread rate R with intensity I, having separated or plume dominated flow for $I > I_c$ (coloured *red*), attached or wind dominated flow for $I < I_c$ (*green*) and transitional flow for $I \approx I_c$ (*blue*). Wind and fuel conditions would tend to change the shape of the spread-rate variation $R = \mathcal{R}(I)$, with increased wind shifting the solid curve to the right and probably also upwards, at least for $I < I_c$. Steady fire spread (marked by the *circles*) is only possible where the general spread-rate variation intersects the line along which Byram's formula for steady fireline intensity $I = QmR$ applies, with at least three different situations arising (illustrated by *dotted lines*) depending on the available combustion energy in the fuel load Qm, which may be called the *energy load*. For a low enough energy load only one steady spread rate is possible in either attached or intermediate flow. For a high enough energy load steady spread is only possible in separated flow. For an intermediate energy load three forms of steady spread are possible, two in separated flow and one in transitional flow.

At this time, because the constant factor A in these estimates needs further investigation to be determined fully, these formulae provide trends rather than precise numerical values.

2.2 Steady fire spread near the attached-separated transition point

There is potential here for a relatively simple spread rate formula for certain kinds of fireline. If attachment leads to increased spread rates (because of enhanced convective heat transfer) and separation leads to reduced spread rates, a steady spread rate $R = R_c$ might arise at or close to the transition point. The intensity associated with such a spread rate would be $I_c = QmR_c$ so that the transition criterion becomes a formula (a cubic equation) that can be solved for the spread-rate R_c

$$R_c \approx \frac{A\rho_e c_p T_e}{Qmg}(w - R_c)^3 \qquad \text{or} \qquad R_c \approx A \times \frac{\mathrm{kg/m^2}}{m} \times \left(\frac{w - R_c}{15\ \mathrm{km/h}}\right)^3 \mathrm{km/h} \tag{6}$$

in which the second version is based on a rough estimate of $Q \approx 20\,000\ \mathrm{kJ/kg}$ for the combustion energy, so that a fuel load of $1\ \mathrm{kg/m^2}$ and a spread rate of $R_c = A\ \mathrm{km/h}$ would arise for a wind-speed of $w \approx A + 15\ \mathrm{km/h}$. This represents a relatively large difference between w and R_c if A is around one in value, but at lower fuel loads and higher wind speeds the spread rate R_c would increase very significantly becoming a much larger fraction of the wind speed w.

2.3 Unsteady fire spread around the attached-separated transition point

For unsteady fire spread, the rate of spread R at any moment depends on the fireline intensity I at that time and the heat transfer processes. Around the critical intensity I_c, reducing the intensity I should lead to greater convective heat transfer and so an increase in R. As I is decreased further the flow must become more fully attached, but ultimately the heat transfer will decrease as the intensity is decreased towards zero. Similarly, if the intensity I is increased through I_c and above, the flow becomes more separated, initially decreasing the heat transfer and the spread rate. But, ultimately, the heat transfer must increase again as radiative transfer begins to grow with increased flame length and flame thickness.

A qualitative sketch of the relationship $R = \mathcal{R}(I)$ that can be envisaged between R and I is given in Figure 2, showing the various possibilities. As can be seen, steady solutions in which $I = QmR$ become possible only for separated flow, only for one case with either attached or transitional flow, or for cases with transitional and separated flows, depending on the wind and fuel details in any particular case. For a fixed wind speed, steady spread in attached, wind dominated flow is encouraged by light fuel loads, or rather *energy loads* Qm, while steady spread in separated, plume dominated flow is favoured at high loads. For a fixed energy load, steady spread in attached flow would be encouraged by strong winds, with steady spread in separated flow encouraged by light winds.

Situations in which a transitional steady solution is possible are potential candidates for surge and stall fire spread.

3 UNSTEADY EVOLUTIONS

Using the integral formula (1) to simulate the variation of fireline intensity with time, for the dependence of spread rate on intensity shown in the top left diagram of Figure 3, a number of evolutions were obtained for different weighting functions $\psi(\tau)$. Four of these are also presented in Figure 3.

The dependence of spread rate on intensity $R = \mathcal{R}(I)$ shown in Figure 3 involves three possible steady spread rates, identified by the circled intersections of the line of steady fire spread, $I = QmR$, with the curve of $\mathcal{R}(I)$. For the simulations carried out, one of these steady fire spreads is close to the transitional spread rate at $I = I_{\rm c}$, with both of the other two occurring in separated flow. The arguments presented in Dold (2010) show that the lower intersection in separated flow, at which the gradient of the function $\mathcal{R}(I)$ exceeds the gradient of the line $R = I/(Qm)$ should be unstable: starting, for example, with a slightly increased spread rate and intensity, the formula (1) would then cause intensity to increase further, with the relation $\mathcal{R}(I)$ then ensuring that the spread rate also increases further. For analogous reasons, the furthest intersection where the gradient is less than that of $R = I/(Qm)$ should be stable.

Simulations carried out with the constant weighting function $\psi(\tau) \equiv 1$ revealed that the lowest intersection, near $I = I_{\rm c}$, was also stable. This finding was reproduced in a wide variety of qualitatively similar examples of the spread-rate dependence $\mathcal{R}(I)$ with a wide range of negative gradients of $\mathcal{R}(I)$ at the point of steady fire spread. Stability is only lost if the weighting function $\psi(\tau)$ has a sufficient level of bias towards later energy release within the burnout time $\tau_{\rm b}$. The example seen in Figure 3 with the most gentle gradient of $\psi(\tau)$ is very close to the point of marginal instability.

Increasing this gradient by a relatively small amount leads firstly to oscillatory, surge and stall fire spread, with intensity and spread rate varying out of phase with each other as described in the Project Vesta report (Gould *et al.*, 2007). The period of this oscillation is seen to be very close to the burnout time $\tau_{\rm b}$ in these examples. The amplitude of the oscillation is found to increase if the gradient of $\psi(\tau)$ is increased further and the period of oscillation is also found to increase. Strong delays in energy release, as employed in the final example shown in Figure 3, can lead to fully chaotic fire spread, with no repetition to be found in the uneven intensity and spread rate cycles.

4 CONCLUSIONS

Arguments based on plume dynamics for a transition between attached flow (a wind dominated fire) and separated flow (a plume dominated fire) are found to replicate, within an as yet unknown order one constant, Byram's arguments concerning the power of the fire and the power of the wind (Byram, 1959). In his article of 1959, Byram stated that plume dynamic arguments could be used to arrive at the same result although he did not present any of them—plume theory was relatively new at the time. The main physical conclusion is that the flow becomes attached (wind dominated) at reduced intensity and separated (plume dominated) at higher intensity.

The fact that increased convective heat transfer occurs in attached flow must also mean that spread rates increase as intensity is reduced below the transition region, although it is not yet possible to quantify the degree to which this happens. The details must depend intimately on the wind speed, moisture content, fuel structure, etc., but a spread rate dependence on intensity that is qualitatively of the nature sketched in Figure 2 must be expected. Whether or not a steady fire spread (stable or unstable) arises near the transition region then depends on the fuel load and the steady relation $I = QmR$ between intensity and

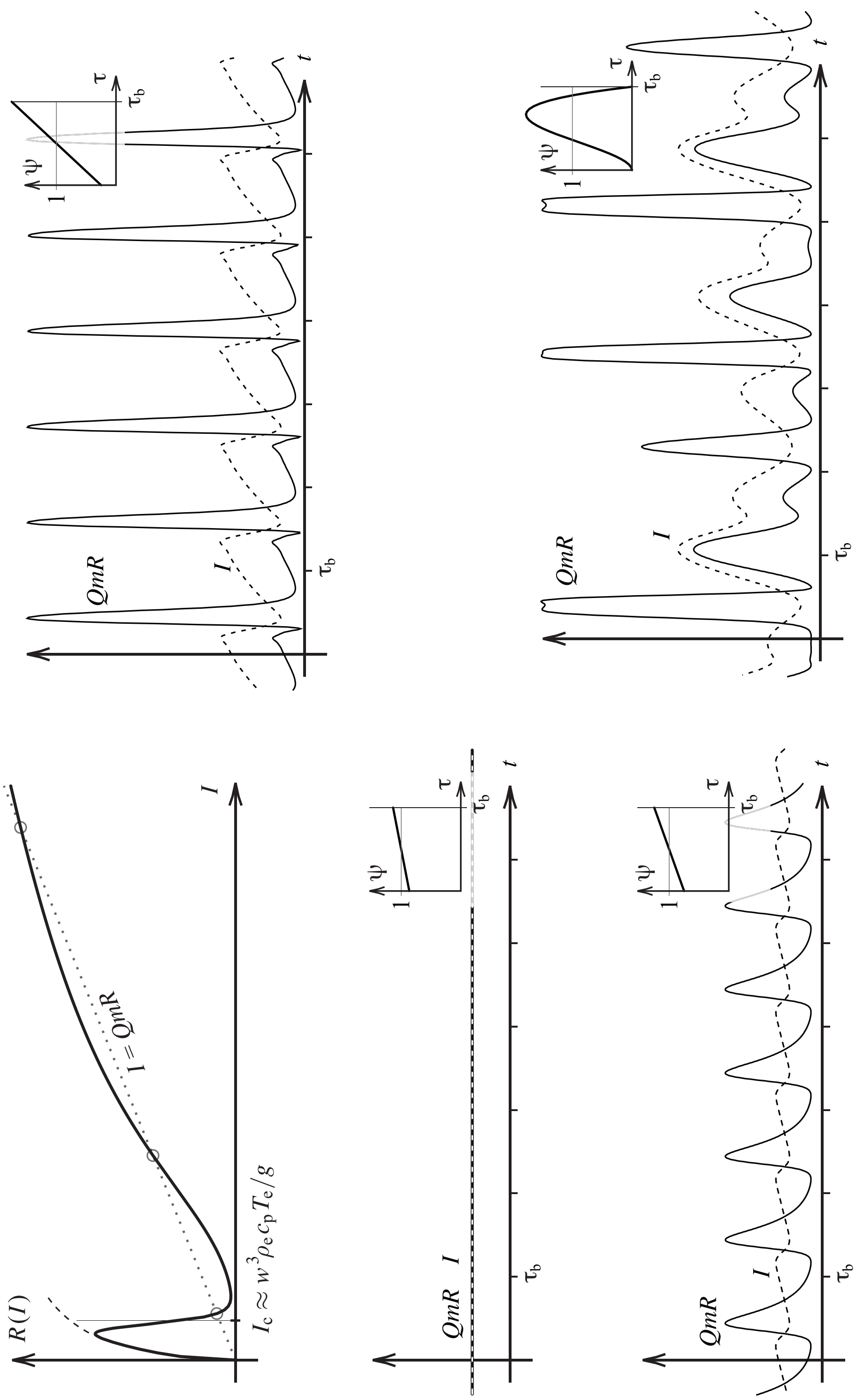

Figure 3: Using the spread-rate relation sketched in the top-left diagram (when viewed in landscape orientation), simulations employing the weighting functions $\psi(\tau)$ shown in the subfigures lead to the evolutions plotted for the fireline intensity I and spread rate R (scaled as QmR) in four separate examples. The steady fire spread at $I \approx I_c$ loses stability and generates surge and stall fire behaviour in the cases where $\psi(\tau)$ involves a sufficient degree of delay in the generation of fireline intensity. The strong delay operating in the final example leads to fully chaotic spread rate and intensity interactions.

spread rate.

Using the integral formulation (1) for the unsteady accumulation of fireline intensity, and suitable spread rate relations $\mathcal{R}(I)$ of the qualitative nature of Figure 2, then allows unsteady fire behaviour to be simulated. It is found that surge and stall fire behaviour is indeed reproduced, but only if there is also a sufficient level of delay in the energy release rate after burning first begins in any part of the vegetation.

This is a vindication, to a degree, of the arguments presented here and the physical reasoning (Dold *et al.*, 2011) that underlies the use of equation (1) along with a suitable spread rate relation $\mathcal{R}(I)$ to model unsteady fire behaviour, including blowup or eruptive fire growth (Dold & Zinoviev, 2009). The arguments surrounding the plume dominated and wind dominated transition raise further interesting issues: for example, can the constant A in equations (5) be determined? To what degree does the curve of $\mathcal{R}(I)$ vary near to, as well as away from the transition region for any given vegetation type? Is there a steady, wind-driven fire spread relation of the form of (6) for some types of vegetation in dry enough conditions, corresponding to a suitable intersection of the form seen in Figure 2? If the conditions for this can be determined then fire-spread predictions using (6) would be relatively easy and practicable.

Further investigation is clearly needed in order to address these questions more quantitatively.

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