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Simulation of spot fire coalescence with dynamic feedback

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Abstract: Under certain situations, high densities of viable firebrands can ignite closely-spaced spot fires downwind of a fire front. The manner in which these spot fires coalesce determines the overall heat release rate. Here, we simulate the merging and interaction of multiple spot fires to assess the time taken to merge and determine fire intensity curves to assess maximum power output during the coalescence process. The growth of the spot fires is governed by a rate-of-spread model coupled with a pyrogenic model simulating the inflow of air to high intensity regions within the fires. The inflow is governed by a Poisson equation for a pyrogenic potential with a forcing term, α, proportional to the local fire intensity. The gradient of this pyrogenic potential gives the velocity field for the inflow of air.

The effect of increasing the spot fire density and magnitude of the forcing term on the non-dimensionalised intensity I' is shown in Fig. 1. For a fixed number of spot fires, increasing the forcing term, α, results in a higher peak intensity profile (Fig. 1a). The profile has been corrected by subtracting the linear intensity trend for a single spotfire (Fig. 1b). The peak of the intensity profile scales with the number of spot fires, N, per area (Fig. 1c). Crucially, above a certain spot density, all simulations taking into account inflow of air generated by the fire result in higher peak intensities over simulations without inflow. Models of coalescence without this attribute are therefore likely to underestimate the maximum fire intensity. These results may provide a better understanding of the dynamics of mass spot fire coalescence events and lead to improved predictive models.

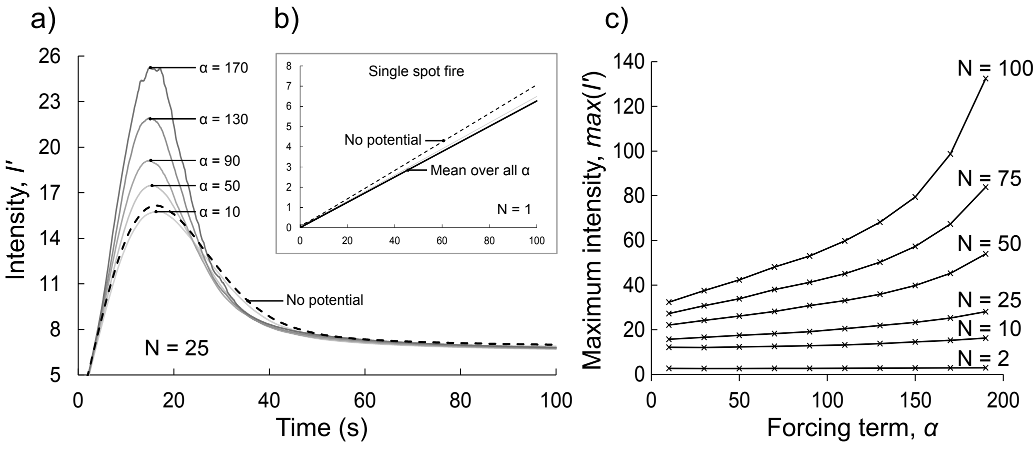

Figure 1. a) Non-dimensionalised intensity against time for 25 spot fires of 2 cm radius placed randomly within a 2 m × 2 m area coalescing for different forcing values, α. Each curve is the average of 100 simulations with randomised spot spatial placements. Dashed curve shows intensity profile without pyrogenic potential model. b) Single spot fire showing monotonic increase in fire line intensity as the fire grows under constant conditions both with (solid line) and without (dashed line) pyrogenic potential model. c) The maximum intensity as a function of number of spots N (for a fixed area of 2 m × 2 m) and forcing term α.

Keywords: *Wildfires, energy release, modelling*

1 INTRODUCTION

Fire behaviour in dry eucalypt forests in Australia (and in many other vegetation types to a lesser extent) is characterised by the occurrence of spot fires, which are new fires ignited by the transport of burning debris such as bark downwind of an existing fire. Under most burning conditions, spot fires play little role in the overall propagation of a fire, except where spread is impeded by breaks in fuel or topography and spotfires allow these impediments to be overcome. However, under conditions of severe bushfire behaviour spot fire occurrence can be so prevalent that spotting becomes the dominant propagation mechanism and the fire spreads as a cascade of spot fires forming a pseudo front (Luke and McArthur, 1978).

It has long been recognised that the presence of multiple individual fires affects the behaviour and spread of all fires present. The coalescence of separate individual fires into larger fires can lead to rapid increases in fire intensity and spread rate and can result in deep flaming and rapid breakdown of coherent suppression action. As such, there is a need to be able to accurately model spot fire coalescence and in understanding the effects it can have on pyroconvective dynamics. This is a challenging task since spot fire coalescence is characterised by distinctly dynamic modes of fire spread, that are driven by pyroconvective interactions between the individual fires.

Existing operational fire behaviour models assume that a fire will burn at an approximately constant (quasi-steady) rate of spread for a given set of environmental conditions. While recent work has showed that an individual fire starting from a point accelerates to this quasi-steady state, little research has been undertaken into the behaviour of multiple simultaneous adjacent ignitions under wildfire conditions or the effects of the dynamic feedbacks involved. No operational fire spread models currently account for the various forms of dynamic fire spread that are known to occur. In particular, there are no models that account for fire-fire interactions, like those that occur when spot fires coalesce.

The inability to accurately predict the behaviour of mass spotting events and the interactions of multiple adjacent fires has a number of consequences for fire management. For example, it is possible that the local dynamic enhancement in rates of spread, which occur as multiple spot fires coalesce, could result in a significant increase in the peak power emanating from a fire. This could in turn significantly affect the dynamics of the plume, and in particular the likelihood of pyrocumulonimbus development. Of course, a quasi-steady model cannot capture the dynamic enhancement in the local rates of spread and so cannot offer any practical guidance on these possibilities.

In this paper we use a newly developed fire spread model that accounts for pyroconvective interaction between individual spot fires. The model is used to assess the effect that the local dynamic enhancement in fire intensity has on the overall power output from a fire as multiple spot fires coalesce. The results from this model are contrasted with those from a quasi-steady fire spread model to provide insight into whether or not the dynamic nature of spotfire coalescence has a significant effect on the power output of a fire, beyond that which would be expected if spot fires coalesced independently; that is, without any pyroconvectve interaction.

2 METHODOLOGY

2.1 Fire propagation model

Fires were simulated using a perimeter propagation model in which the interface between un-burnt and burnt regions is represented as a one-dimensional perimeter within a two-dimensional domain. The perimeter is assumed to grow outward with a rate of spread r dependent on factors such as local environmental conditions (such as wind and temperature) as well as fuel parameters (such as available fuel). Despite the considerable simplification of fire dynamics, such two-dimensional models have been found to successfully replicate the behaviour of a fire perimeter at both large (km) scales and small (m) scales (Hilton *et al.*, 2016).

There are several computational approaches for implementing perimeter propagation models, including raster based level set and cellular automata methods as well as vector-based front-tracking approaches (Sullivan, 2009). Here, we use the level set method (Sethian, 2001) which has a number of advantages over other methods, including the ability to handle the merging of any number of fire perimeters without additional computational effort or bookkeeping. This is a major benefit for this particular study, which models multiple coalescing spot fires. The model was implemented within the Spark framework [1], a GPU-based perimeter propagation system allowing new fire behaviour models to be easily added.

[1] http://research.csiro.au/spark/

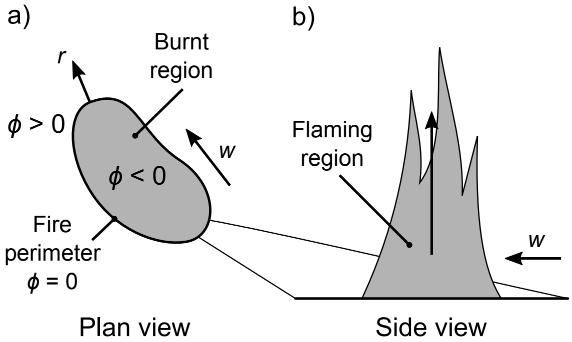

Figure 2. Schematic diagram of pyrogenic model. a) The fire perimeter (solid black closed curve) moves outward at a rate r depending on local conditions such as fuel and local wind vector $\mathbf{w}$. The perimeter is represented in the level set model as the zero set of the distance ϕ from the perimeter. b) The flaming region is treated as a vertical sink in the horizontal plane with strength proportional to the fire line intensity. The fire line is modelled using a smoothed Dirac delta function $\delta_s(\phi)$.

The level set method is based on updating the closest distance ϕ to the perimeter over the two-dimensional domain. The perimeter is not stored, but identified by finding the set of distance points for which $\phi = 0$. A schematic view of the model with the fire perimeter and burnt area is shown in Fig. 2a, where ϕ and example outward spread values r are shown. The time evolution of the distance function ϕ is given by:

$$\frac{\partial \phi}{\partial t} + r|\nabla \phi| = 0 \tag{1}$$

where r is the outward speed of the interface. For wildfire modelling the speed can be determined from empirical models based on fuel and weather conditions. In this current study, however, we use a basic model which only considers outward growth of the perimeter and movement in the direction of a background wind field:

$$r = u_0 + u_1 \max(\hat{\mathbf{w}} \cdot \hat{\mathbf{n}}, 0) \tag{2}$$

where $\hat{\mathbf{w}}$ is the background wind vector and $\hat{\mathbf{n}}$ is the normal vector to the perimeter. The maximum operation in Eq. (2) restricts the speed to positive values to ensure only outward growth of the fire perimeter occurs. Further details on the model and examples are given in Hilton *et al.* (2016).

2.2 Dynamic feedback

This study considers dynamic feedback effects during coalescence caused by the inflow of air to a fire. This flow acts as a perturbation, or correction, to the local wind vector to account for the presence of the fire. This air flow is modelled using the pyrogenic potential model, full details of which will be published in a longer study. Essentially, the pyrogenic potential model considers only the flow of air in the two-dimensional ground plane of the fire and treats the fire line as a vertical sink, as shown schematically in Fig. 2b. Assuming the air is incompressible and irrotational (in the ground plane) allows the correction $\Delta\mathbf{w}$ to be represented as the gradient of a potential $\Delta\mathbf{w} = \nabla\psi$. The potential is determined from the Poisson equation $\nabla^2\psi = \nu$ (Batchelor, 1967).

The forcing term in the Poisson equation, ν, represents the strength of the sink or outflow of air from the ground plane. This is governed by the vertical acceleration of air at the fire line which, in turn, is related to the intensity of the fire line. This is defined by Byram (1959) as $I = Hwr$, where I is the fire line intensity in kW m^{-1}, H is the heat of combustion in kJ kg^{-1}, w is the fuel load in kg m^{-2} and r is the rate of the spread of the fire line in m s^{-1}. Byram's equation only holds for a one-dimensional fire line. To mathematically extend this definition to a one dimensional fire line Γ in a two-dimensional domain the formula can be expressed as:

$$I(\mathbf{x}) = \int_\Gamma Hwr(\mathbf{x}')\delta(|\mathbf{x} - \mathbf{x}'|)d\Gamma \tag{3}$$

where $\mathbf{x}$ is a point in the two-dimensional domain, $\mathbf{x}' \in \Gamma$ and $\delta(\phi)$ is the Dirac delta function. Using the identity (Towers, 2007):

$$\int_\Gamma f(\mathbf{x}')d\Gamma = \int_\Omega f(\mathbf{x}')\delta(\phi(\mathbf{x}'))|\nabla\phi(\mathbf{x}')|d\Omega \tag{4}$$

where $\phi(\mathbf{x})$ is the distance function at point $\mathbf{x}$ and Ω is the two-dimensional domain gives:

$$I(\mathbf{x}) = Hwr(\mathbf{x})\delta(\phi(\mathbf{x}))|\nabla\phi(\mathbf{x})| \tag{5}$$

where we have used $f(\mathbf{x}') = Hwr(\mathbf{x}')\delta(|\mathbf{x} - \mathbf{x}'|)$ in Eq. (4). The distance function ϕ is calculated automatically in the level set function making computation of (5) very straightforward. For numerical computations the delta function must be expressed in a smoothed form with the same properties under integration. Here we use the smoothed delta function:

$$\delta_s(\phi) = \lim_{\kappa\to\infty} \frac{2\kappa}{(e^{\kappa\phi} + e^{-\kappa\phi})^2} \tag{6}$$

where κ is a smoothing parameter with dimensions m^{-1}. The value of $1/\kappa$ effectively controls the the distance the delta function is smoothed over. Here, we choose to smooth over a single grid cell so $\kappa = 1/\Delta$, where Δ is the grid spacing. The smoothed form of the delta function results in the intensity reaching a maximum at the interface as $\phi \to 0$. We make the assumption $\nu \propto I$, giving the final expression for the forcing term as:

$$\nu(\mathbf{x}) = \alpha\frac{I(\mathbf{x})}{Hw} = \alpha r(\mathbf{x})\delta_s(\phi(\mathbf{x}))|\nabla\phi(\mathbf{x})| \tag{7}$$

where we have removed the dependence on the H and w terms and introduced a constant of proportionality, α. The heat of combustion and fuel load are considered constant here over the domain but could easily be modified in the computation for heterogeneous conditions. Solving the Poission equation gives the pyrogenic potential ψ, the gradient of which gives the correction to the local wind vector.

It should be noted that Byram's equation is the fire line intensity of a fire spreading at an equilibrium rate of spread r and alternate expressions exist for non-steady fire spread (Dold et al., 2009). However, in this initial study we assume that this expression for equilibrium fire line intensity holds. The method detailed here can straightforwardly be extended to expressions for non-steady fire line intensity.

2.3 Spot fire simulations

The coalescence of N spot fires was modelled, in which the fires were ignited simultaneously on flat ground with and without the pyrogenic potential model. The domain size was 10 m by 10 m at a resolution of 1 cm. Within this area N spots of radius 2 cm were randomly spatially distributed over the 2 m by 2 m central area using the Python uniform random generator. The rate of spread model given in Eq. (2) used coefficients of $u_0 = 0.01$ m s^{-1} and $u_1 = 0.02$ m s^{-1} with a wind vector $\mathbf{w}$ of bearing 180° degrees (upward in the images) and strength 0.1 m s^{-1}. The parameter α was varied between 10 and 200 for different simulations. All values used in the simulation were chosen to illustrate the effect of the feedback and behaviour transition and are not currently related to physical parameters. This calibration will be carried out in a future study.

The Poisson equation was solved using a multigrid method (Brandt, 1977). Dirichlet boundary conditions of $\psi = 0$ (no source terms) were imposed over the edges of the domain. Two sets of simulations were performed, one using the pyrogenic model to provide dynamic feedback and one without to provide a comparison without interaction. The fields were saved at regular intervals, as well as the total non-dimensionalised fire line intensity over the domain given by:

$$I' = \frac{1}{\alpha u_0}\int I(\mathbf{x})d\mathbf{x} \tag{8}$$

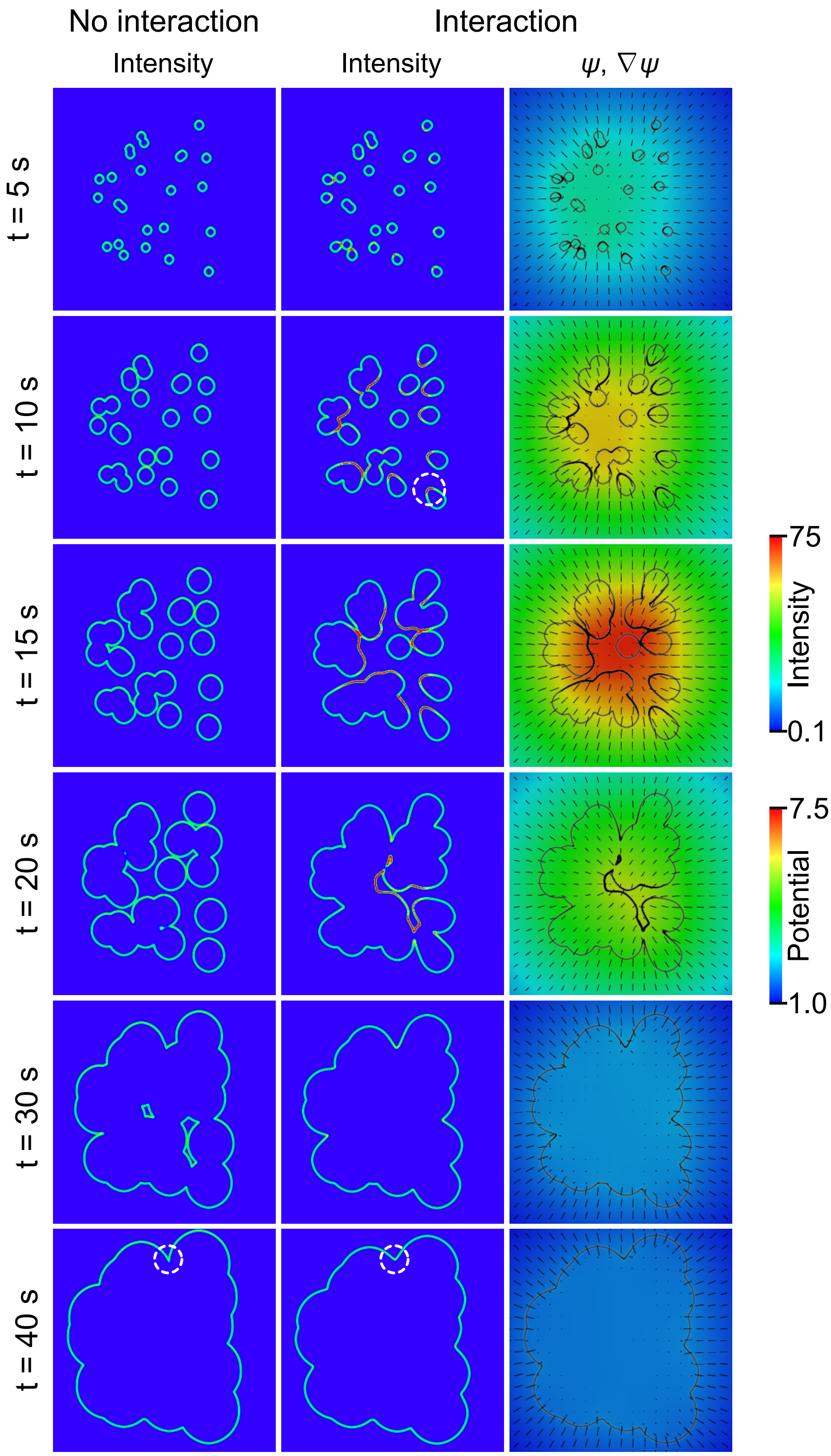

Figure 3. Coalescence of 25 spots without and with interaction over time shown in the left and central columns, respectively. The pyrogenic potential and corrective wind vector is shown in the right column. The simulation used the parameters $\alpha = 100$ and $\kappa = 100$.

As the intensity profile varied depending on the initial spot locations, simulations were repeated multiple times to assess the mean behaviour. The results are presented in the following section.

3 RESULTS

A set of results demonstrating the dynamic behaviour of spot fires with and without the pyrogenic model is shown in Fig. 3. This simulation has $N = 25$, $\alpha = 100$ and $\kappa = 100$. The figure shows a plan view of the spot fire intensity, pyrogenic potential and corrective wind field. The first and second columns are coloured by the fire line intensity, and the final column is coloured by the potential with the forcing terms superimposed in black. The corrective wind field is also superimposed over this image as a set of vectors.

This example clearly illustrates the effect of pyrogenic interaction both on the individual spot fires and after all spot fires have coalesced. It can be seen in the early stages of development (t $\sim$ 5-15 s) the individual spot fires are forced into the centre of the group by the corrective wind. This results in the stretching of the fires into an elongated 'teardrop' shape and increased fire line intensity, as can be seen on the leading edges of the spot fires (dashed circle at t = 10 s). The feedback also has the effect of closing 'V' shaped intersections between merged spot fires resulting in gaps within the centre of the spot fires closing more rapidly when interaction between the fires was taken into account. The pyrogenic model also had the effect of closing 'V' intersections between merged fire lines slightly faster (dashed circles at t = 40 s). It can be seen from the corrective wind field that the net flow is inwards, towards the centre of the spot fires, throughout the simulation. Notably, when the fire has coalesced into a single perimeter this wind correction serves as an inward pressure slowing outward growth of the fire perimeter (t $\sim$ 30-40 s).

The total fire line intensity, I', is plotted against the number of initial spot fires in Fig. 4. These simulation used the parameters $\alpha = 100$ and $\kappa = 100$. Simulations were repeated ten times for each case, with different random initial placements of spot fires. The main feature shown by the plots is a peak in fire line intensity as the spots coalesce for $N > 5$, which becomes more prominent for higher values of N. For a single spot, the intensity monotonically increases with as the perimeter of the spot grows over time. When two spots coalesce, their perimeter merges and the total intensity after coalescence is reduced as the total perimeter of the fire is smaller. Hence, for the cases without interaction, the initial gradient of the intensity is proportional to the number of spots. As these coalesce, the intensity is reduced until finally there is a single perimeter increasing monotonically in intensity. The maximum of the intensity represents the time at which all the spots have coalesced. The case with interaction is similar, but the spots are forced together by the corrective wind towards each other. This means the spots coalesce together faster, as can be seen from the the plots where the maxima have been shifted earlier in time compared to the cases without interaction. The corrective wind also increases the rate of spread of the fires resulting in a higher maximum intensity.

To investigate the effect of the forcing parameter α on the peak intensity, simulations were run for varying N and α. An example set of curves for $N = 25$ is shown in Fig. 1a. The linear trend associated with long-term behaviour was removed by running a simulation of a single spot and calculating a linear regression. The regression line is shown as a dashed line in Fig. 1b, superimposed over the normalised simulation results for varying α. This linear trend was subtracted from all data sets with $N > 1$. As can be seen in Fig. 1a the long-term trend after these processing steps results in a constant intensity value for all α. To assess the mean behaviour, 100 simulations were run for each case and averaged.

The maximum intensity as a function of the forcing parameter α and number of spots is shown in Fig. 1c. It can be seen that the maximum intensity increases for both density of spot fires as well as the forcing parameter. Interestingly, the plot does not collapse when divided by the number of spot fires, likely due to the number of contact points between a random spatial distribution of spot fires being a non trivial function of the spot fire number, similar to circle packing problems.

4 CONCLUSIONS

We have simulated the coalescence of multiple spot fires and shown that the peak fire intensity scales with the spot density. Furthermore, incorporation of a model accounting for air flow resulted in a higher and earlier mean peak intensity. This pyrogenic potential model showed, under the basic assumptions used, that spot fires coalesce faster due to feedback effects from the inflow of air towards the centre of the spot fires. The peak intensity scales with both the spot density and strength of the coupling between the fire intensity and air inflow.

The simulations used highly idealised rate of spread models and a simplified feedback effect based on two-dimensional ground level air flow. Furthermore, spot fires would likely have a distribution of sizes and ignition

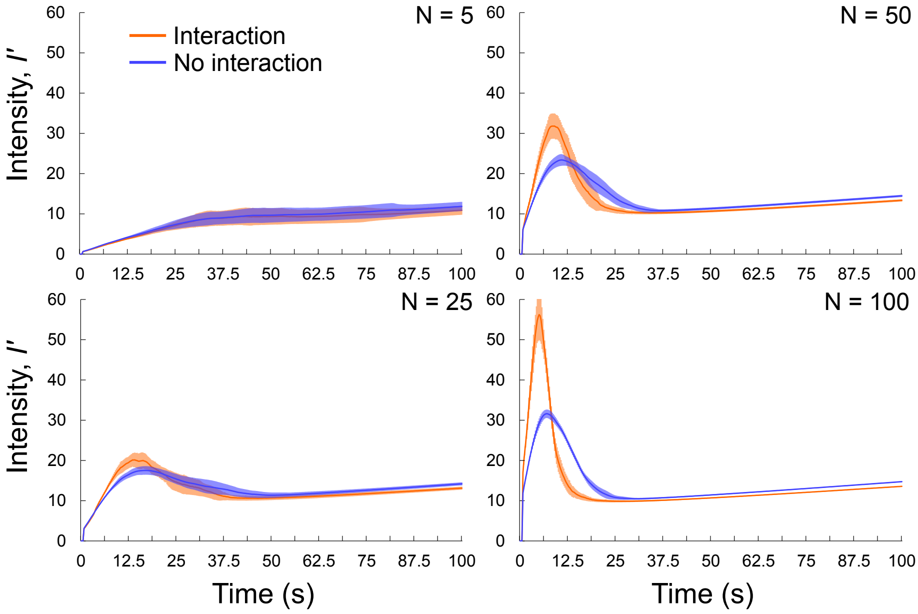

Figure 4. Power profile for coalescence as a function of number of spots. The lines show the mean value over ten simulations and the confidence band shows one standard deviation.

times. However, the dynamic models used here have been shown to agree with experimental fires at small to medium scales. The analysis presented should give a reasonable indication of the magnitude of the effect that dynamic modes of fire propagation can have on the overall energy release from a fire.

The results indicate that not considering the influence of dynamic enhancement of rate of spread that accompanies spot fire coalescence can lead to a significant underestimate of the convective potential of the fire, particularly in low wind regimes. This means that the potential for fires to develop into violent pyroconvective events could be under-appreciated if quasi-steady fire spread models are employed to assess the power emanating from a fire.

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