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Generalized Byram's formula for arbitrary fire front geometries

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ABSTRACT

The expression proposed a half century ago by Byram allowing the estimation of wild land fire front heat flux was extensively used in fire research and by firefighters. However, this formula does not account for wild land fuel heterogeneity and local weather changes. Its validity is limited to stationary spreads, and fails in describing the behavior of curved fronts and non-spreading fires. A new formula is derived to generalize heat flux estimation to any fire front with arbitrary geometry. Heat flux is found to depend on the front local radius as well as its convexity/concavity. The front curvature induces also a quadratic dependence on the rate of spread. The derived equation is validated by numerical simulations using the small world network model for line and curved fronts. Extensions of generalized Byram formula including fractal dimension of the front and wind speed effect are also proposed.

1. Introduction

Millions hectares of vegetation are burned each year because of wildland fires [1]. Control methods to be implemented against forest fires depend on their intensities which are divided into several classes [2]. In the late 50s, Byram proposed an empirical equation to estimate the intensity of a fire front [3]. This law is now widely used both by scientists for laboratory or field experiments, and by operational fire managers. It indicates that the heat flux ϕ (kW/m) delivered per meter of fire front is related to the consumed fuel load m (kg/m^2), the combustion heat or enthalpy H (kJ/kg) and the rate of spread v (m/s) by

$$\phi = m \times H \times v \tag{1}$$

The heat of combustion (enthalpy) H used here is a proportionality constant assuming a linear dependence of the heat released rate on the fuel load. In case of a nonlinear dependence, the mass load m appears with a nonlinear exponent in (1). This relationship, valid for stationary propagation, has two major disadvantages: firstly it is not predictive, as the rate of spread cannot be estimated beforehand, and secondly it does not account for the fuel heterogeneity (wild land-urban interfaces, highways, fuel breaks etc.), non-stationary spreading fronts, as well as non-spreading fires ($v = 0$). The rate of spread strongly fluctuates from a zone to another one in heterogeneous fuel beds, and depends on the combustion region. This strongly decreases the accuracy of the fire intensity estimation, which moves from a risk class to another. In 1976, Tangren [4] noticed that (1) was introduced for a line front and that the rate of spread is in fact the ratio of the front width to fire residence time ($v = w/t_c$, w being the front thickness). He raised the problem of the spread direction (the main or the lateral direction). A curved geometry of the front could influence significantly fire intensity, and may be felt differently by operational fire managers.

A reformulation of (1) is thus necessary to make it predictive and to account for other important parameters involved in the spread such as a curved and non-stationary spreading front. In this paper, a new formula of fire intensity is derived for various geometrical aspects of the front. The estimated intensity from this new formula is compared to fire spread simulations using the *small world network model* [5]. Such simulations were realized under various ignition outbreaks and wind conditions (circular or elliptical fronts for point like outbreaks and a line front for line outbreaks). Its behaviour is also compared to experimental data. Further improvements of the derived expression introduce the fractal dimensions of the front perimeter and area as well as the

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wind speed instead of the rate of spread.

2. Derivation of Byram formula

The intensity per unit length expressed by Byram's formula (1) is derived from the heat released from the unit length perimeter of the front. This energy depends on the front width, its perimeter, the fuel load and the heat of combustion. The idea in this paper is to estimate the heat released from the front by the use of satellite images whose resolution analysis (size effect) allows the dependence of this energy on the fractal dimension of burning area of the fire front or a portion of it in which important changes of curvature or fuel load may occur.

Time resolution of images is here assumed to be sufficient to determine the front rate of spread, necessary for the heat flux estimation. Satellite images currently available do not have sufficient time resolution (for example image rates of less than one per minute and a space resolution of 20 m are necessary for a front spread rate of 0.3 m/s). The price of satellite images being still high, the use of aerial images (aircrafts and UAVs) would solve this problem. Although the formula we derive here can be used in the general case, it will be validated in stationary propagation situations, which overcomes this problem of time resolution.

Let us consider an L-sized square heterogeneous fuel system, with a fire front spreading in y direction (Fig. 1). The system heterogeneity may be geometrical (i.e. randomly distributed fuel through the system) and/or a fuel heterogeneity (fuel of different nature). Assuming that the fuel is of the same kind, the enthalpy (H) is constant. The energy released per unit length in the lateral (x) direction is given by:

$$\frac{\mathrm{E(t)}}{\mathrm{L}} = \frac{\mathrm{H}}{\mathrm{L}} \iint \mathrm{m(x,y,t)} \times \mathrm{P(x,y,t)dxdy} \tag{2}$$

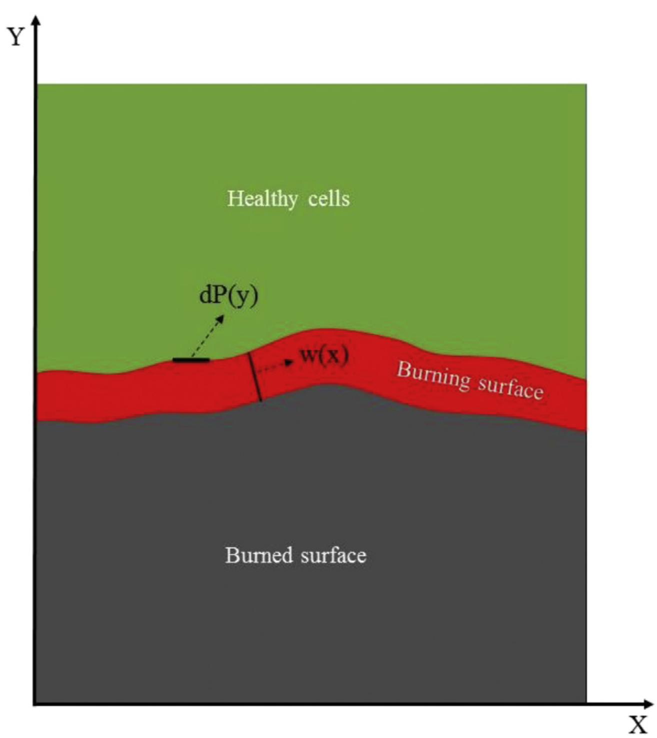

Fig. 1. Fire spread representation at a given time with unburned fuel (green) and fire front (red). Burned area is represented in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As char cannot contribute to fire spread, the consumed mass load $m(x,y,t)$ used in (1) is the effective fuel mass load per unit surface (i.e., the mass load without char and other unburned fuel). The function $p(x,y,t)$ appearing in (2) defines the probability distribution to find a surface element $dx \times dy$ of fuel burning at time t centered at position (x,y). Using the fire front surface element ($dS = \mathrm{dwdP} = \frac{\mathrm{dw}}{\mathrm{dx}} \frac{\mathrm{dP}}{\mathrm{dy}} \mathrm{dxdy}$) of width dw(x,t) and perimeter dP(y,t) (Fig. 1), Equation (2) can be rewritten as

$$\frac{E}{L} = \frac{H}{L} \iint m(x,y,t) \frac{\partial w(x,t)}{\partial x} \frac{\partial P(y,t)}{\partial y} \, dxdy \tag{3}$$

The integral Equation (3) includes a product of 3 functions of time and space. Deriving (3) with respect to time yields the heat flux per unit length released by the system, $\phi = \frac{1}{\mathrm{L}} \frac{\mathrm{dE(t)}}{\mathrm{dt}}$ (the system size L being fixed) reads

$$\begin{aligned} \phi(\mathrm{L,t}) &= \frac{1}{L} \frac{dE}{dt} \\ &= \frac{H}{L} \left(\iint \left(\frac{dm(x,y,t)}{dt} \right) \frac{\partial w(x,t)}{\partial x} \frac{\partial P(y,t)}{\partial y} dxdy \right. \\ &\quad \left. + m(x,y,t) \left(\frac{d}{dt} \left[\frac{\partial w(x,t)}{\partial x} \frac{\partial P(y,t)}{\partial y} \right] \right) dxdy \right) \end{aligned} \tag{4}$$

Time derivatives in (4) involve partial derivatives $\left(\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{\partial x}{\partial t} \frac{\partial}{\partial x} + \frac{\partial y}{\partial t} \frac{\partial}{\partial y} = \frac{\partial}{\partial t} + \vec{v} \cdot \vec{\nabla} \right)$. Thus (4) becomes

$$\begin{aligned} \phi(\mathrm{L,t}) = \frac{H}{L} \times & \left(\iint \left(\dot{m}(x,y,t) + \vec{v} \cdot \vec{\nabla} m(x,y,t) \right) dS + \iint m(x,y,t) d\dot{S} \right. \\ & \left. + \iint m(x,y,t) \left(\frac{v_x}{\rho_x} \frac{\partial P(y,t)}{\partial y} + \frac{\partial w(x,t)}{\partial x} \frac{v_y}{\rho_y} \right) dxdy \right) \end{aligned} \tag{5}$$

Here $\dot{m} = \partial m / \partial t$ and $\dot{S} = \partial S / \partial t$, the surface element being $dS = dP \times dw = \frac{\partial \mathrm{w}}{\partial \mathrm{x}} \frac{\partial \mathrm{P}}{\partial \mathrm{y}} \mathrm{dxdy}$. The third term of (5) corresponds to the part $\vec{v} \cdot \vec{\nabla}$ of the time partial derivative. The gradient part of the time partial derivative yields the second derivatives of the front width and perimeter, defining the radius of front curvature in x and y directions ($\partial^2 P / \partial y^2 = 1/\rho_y$) and ($\partial^2 w / \partial x^2 = 1/\rho_x$)). Equation (5) is much more complicated than the initial Byram's law (1). In the first term of this equation appears the rate of mass loss $\dot{m}$ (describing the local fuel combustion), and its spatial variation. The second terms of this equation reveals the dependence of the heat release rate on the non-stationary behavior of the burning area (where the burning surface is time varying). The geometrical aspects of the front (the lateral (ρ_x) and longitudinal (ρ_y) curvature radius appear in the third term. Note here that the radius appearing in the third term has an algebraic value. It is negative in case of a concave front leading to the decrease of the heat release, and positive for a convex one increasing of the heat release rate. The heat flux dependence on the rate of spread is here much more complicated than (1), since both its lateral and longitudinal parts are weighted by the mass gradient (first term) and the front curvature (last term).

Firefighters are usually looking at the head of the front mainly in the spreading direction (y), neglecting the lateral part. Furthermore, it is difficult to estimate the mass load gradient and the non-stationarity of the front spread from satellite or aircraft images. In the following, the fuel is assumed to be uniformly distributed with a load density depending only on time (m(t)). The surface coverage rate is the doping parameter (p). This parameter has values smaller than unity in heterogeneous mediums and is $p = 1$ for homogeneous ones. Obviously, during fire spread there is a mass load difference between the forward and backward positions of the front,