LIHTFire: A high-resolution 1D physics-based wildfire spread model

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Abstract

We describe the development and performance of a dynamical one-dimensional (1D) model of fire spread (LIHTFire, Linear Ignition and Heat Transfer). The model resolves burning rates, heat transfer, and ignition at cm-scales with explicit accounting of heterogeneous fuels and time-varying weather. An empirical convective heating method speeds computation compared to CFD methods. Heating, drying, pyrolysis, ignition, and solid phase combustion of fuel with varying sizes and shapes is represented by a particle model that captures within-particle gradients. The heat transfer, burning behaviors, and fire spread characteristics (spread rate, flame length, and flame zone depth) are compared with experiments of particle heating and fire behaviors from laboratory and field studies. The 1D model rapidly simulates spreading line fires over domains of ~10^2 m and reveals strong coupling of physical processes involved in producing fire spread, spread thresholds, and non-steady and nonlinear behaviors including acceleration and damped oscillation. The model is intended for generalized use in wildland fire spread predictions, either as a stand-alone simulation for understanding the interplay of fire and environmental conditions but also for use in 2D and 3D simulation systems.

1. Introduction

Many physical models of wildfire spread have been developed (Sullivan 2009). Physics-based models have potential advantages over empirical modelling systems, including reducing model-related error in predictions (by contrast to error introduced from data or users) and explaining rather than just correlating fire behaviours. Physics-based models are also expected to better predict phenomena outside the range of current empirical models, such as spread/no spread thresholds, acceleration/deceleration, fluctuating wind conditions, discontinuous and heterogenous fuel beds, and conditions outside current lab and field datasets (very strong winds, large flame dimensions, etc.). The need for such models is also driven by the increasingly large and destructive wildfires for which current models are sometimes insufficient to predict or inform proactive management approaches.

Differences among physical models derive from two factors. First, there is uncertainty as to how basic processes operate. Heat transfer by radiation and convection, heating/drying/ignition of fuel particles, and fuel burning rates are still not settled (Cruz et al. 2018). Second, it is difficult to formulate these fine-scale processes in a computationally practical model for large wildfire domains. For example, Baines (1990), Cohen and Finney (2022) indicate that much of the heat transfer responsible for igniting fuel particles in a spreading fire act at cm scales, yet many 3D physics-based models (e.g., Mell et al. 2007, Linn et al. 2002, Morvan et al. 2009) often operate at meter scale. Despite having coarse spatial resolution, assumed thermally thin behaviour of fuel particles, and parameterized "sub-grid" burning rate and heat transfer these models cannot simulate large fires (say 10,000+ acres) fast enough for operational use (Clark et al. 2003).

Alternatively, high resolution can be maintained at low computational cost by limiting the domain to one-dimension (Fons 1946) and approximating fluid flow using simplified methods. A reprise of this approach was presented by Finney et al. (2021) based on research of fine-scale fuel burning rates, convection heat transfer, and heating and ignition of fuel particles. The model simulates dynamic wildfire behaviours as the fire spreads over domains of 10^2 m, resolving fuel heterogeneity on cm-scale resolutions and heat transfer and thermally thick heat and moisture dynamics of individual fuel particles. Here we describe an improvement of this 1D wildfire simulation that utilizes an advanced particle model to represent burning rate as a function of the particle's thermal and oxygen environment.

2. Model Description

The LIHTFire model is a one-spatial dimension (1D) linear domain of arbitrary length that is oriented in the direction of fire spread. The model simulates the spread of a heading fire along this line by incorporating heat transfer by radiation and convection and the heating/drying/ignition/combustion of individual fuel particles (Figure 1). An important guiding principal of the model is that it should spatially and temporally resolve heat transfer processes at the leading edge of the fire front, as it has been demonstrated experimentally that fire spread rate is highly sensitive to its accurate representation (Baines 1990, Cohen and Finney 2022). The model describes heading fire spread through a single-layer fuel bed of discrete particles based on physical processes and their coupling. It makes no assumptions about a steady rate of spread, but rather computes the time evolution of the fire spread. And so nonlinear dynamical feedbacks are implicit in the formulation and consequently the fire may accelerate, decelerate, or extinguish. It can also respond to fluctuating winds and variable fuel properties along the bed.

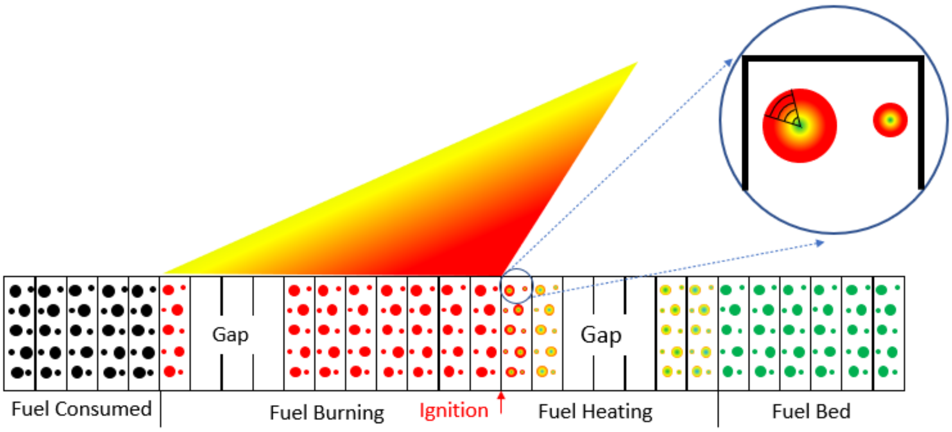

Figure 1. Schematic side view of the 1D model domain showing a fuel bed composed of cells with discrete particles of specified size and properties or voids (which form fuel gaps). Particle heat and moisture dynamics are calculated ahead of the flame zone as a 1D particle model shown in the inset.

The 1D domain is discretized into 'cells' which each hold an arbitrary number of fuel particles of differing size, shape, and thermophysical characteristics (including moisture content). For computational efficiency, it is assumed that each type of fuel particle in a cell has the same state, so only one particle for each type is tracked. For these particles, the model calculates changes in temperature, moisture, thermal decomposition, and combustion. Cell resolution is somewhat subjective but is typically on the order of 10^{-2} m to represent the variation in fuel structure along the fuel bed and to resolve heat transfer gradients that occur ahead of the burning fuel. Convective and radiant heat transfer is calculated at the resolution of the cells.

A critical piece of any fire model is how fuel particles are represented. LIHTFire uses a finite volume method to simulate 1D conduction of heat perpendicular to the surface of a particle (i.e., thermally thick behaviour). This detailed representation avoids the bias of thermally thin assumptions (no thermal or moisture gradients). Experiments in spreading fires show that gas temperature dynamics occur at scales of centimetres with steep temperature gradients and strong velocities near the flaming edge (Finney et al. 2020). This convective behaviour leads to large temperature and moisture gradients in even fine fuel particles (~1 mm) that determine drying, ignition and burning.

Here the particle model developed by Ahmed et al. (*this conference*) is used. The model allows for three fuel particle shapes: sphere, cylinder, and slab (flat leaf-like) and describes the heating, drying, and pyrolysis as well as the solid phase combustion of residual char. Two modes of pyrolysis are included in the model: purely thermal degradation, and combined thermal and oxidative degradation. This mechanistic approach to pyrolysis and char combustion means that energy release rate of a given fuel particle is a function of its near-environmental conditions (thermal and oxygen boundary conditions). Primary benefits are that the burning rate of fuel beds is independent of empirical flame residence time correlations (Anderson 1969, Mell et al. 2007) which work for simple, single size class fine fuel beds but not for mixed size and mixed property (moisture, live/dead, thermal properties) beds. Heat flux and oxygen concentrations drive the thermal and oxidative pyrolysis of the fuel particles (Ahmed et al. this conference). Oxygen concentrations within the burning zone are obtained from empirical relations from data showing depletion to 3% during flaming phases, rising slowly to ambient during solid phase combustion. Heat flux in the burning zone is determined by radiation and convection proportional to the size of flames and flame zone.

Radiation heat transfer forward of the flame zone is calculated using a method adapted from Koo et al. (2005). Both radiation from the flames and from the glowing solid fuels in the flaming front are included using relatively simple and computationally cost-effective calculations. The flame radiation to the fuel particles forward of the flaming front utilizes a view factor-based calculation assuming a flame sheet tilted by the wind and with uniform temperature and emissivity. The emissivity varies with flame length using an empirically derived effective total absorption coefficient to account for thin flames. The radiation calculation from glowing solids in the direction forward of the flame zone uses an exponential decay function to account for blocking and absorption of radiation as it travels through the bed.

Convection heat transfer from the flaming zone forward of the fire is calculated using an empirical gas temperature profile based on the flaming zone geometry, intensity, wind speed, and slope (Finney et al. 2020). The temperature and velocity are decoupled from energy transfer with the fuel particles (meaning gas/velocity distributions are not influenced by the particles). This simplified approach greatly reduces the computational cost compared to computational fluid dynamics-based approaches. The convective surface heat flux to a particle is computed using the prescribed gas temperature and velocity, the particle surface temperature, and its shape based on commonly used empirical correlations.

3. Model Behaviours

Under the simplest uniform fuel and wind conditions, the model illustrates dynamcial behaviors of acceleration from igniton to steady state (Figure 2a). The fuel bed consisted of 1 millimeter diameter cylindrical shaped fuel particles uniformly distributed at a loading of 0.5 kg m^{-2} at a depth of 0.1 meters. The particles started at a moisture content of 5% and used thermophysical properties of wood. Wind was constant at 1 m/s. Calculations of this type take on the order of tens of seconds to compute on standard laptop computers. With increasing loading, the longer burning time of the fuel bed introduces non-linear oscillations prior to steady spread (Figure 2b). The thresholding behaviors of fire spread are demonstrated (Figurte 2c) for combinations of wind speed and fuel moisture content, where a high wind is required at higer moisture content for spread to occur. Similar non-steady spread and intensity dynamics are illustrated for fuel beds with gaps or discontinuities (Figure 2d) which produce jumps and delays in spread across the void spaces.

4. Conclusions

We described a 1D approach to modelling wildland fire spread that incorporates the physical processes of combustion, heat transfer, and ignition at high resolution. The model is applicable to spatially and temporally heterogeneous domains extending to hundreds of meters and is computationally efficient, requiring run times of seconds to 10’s of seconds depending on resolution and input conditions. The intent of the model is to capture dominant dynamical behaviours of spreading line fires in a way that is sensitive to the fine-scale properties of fuel beds and variable weather for inclusion, in some form, in large-scale wildfire simulation systems.

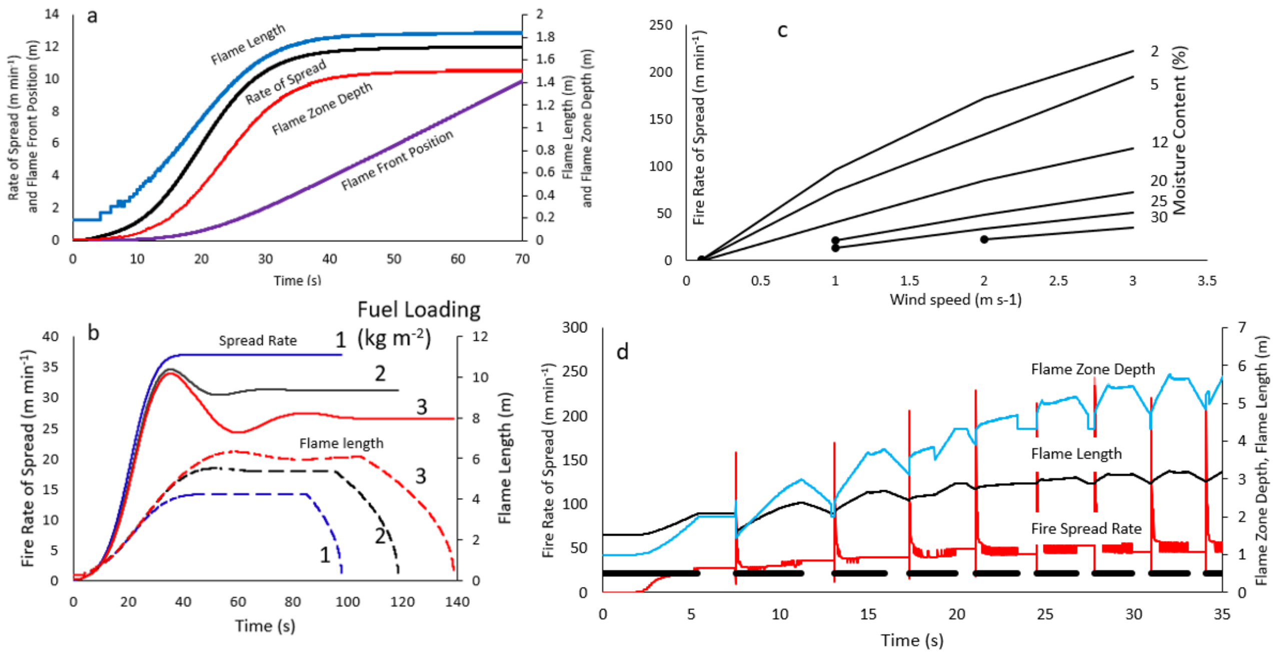

Figure 2. Behaviours of head fires modelled by LIHTFire show a) acceleration of fire characteristics from ignition to steady state, b) dynamical oscillations of spread rate (solid lines) and flame length (dashed lines) for fuel beds with different loadings, c) joint effects of wind speed and fuel moisture content on spread rate and thresholds for spread (dots), and d) non-linear dynamics of fire spread in discontinuous fuels (bold black line indicates fuel locations and gaps as leading edge encounters them).

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