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Spread vector induced cellular automata model for real-time crown fire behavior simulation

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ABSTRACT

Cellular automata (CA) approaches in wildfire modelling are computationally more efficient than vector-based methods. Despite this advantage, these methods suffer from the lack of physical basis and distortion in simulated fire shapes. To overcome these drawbacks and to perform a real-time interactive crown fire simulation for training use, a new CA model is proposed in which a new spread mechanism is introduced based on the physical equations of reaction and radiation. Then, through a series of crown fire simulations in uniform and heterogeneous synthetic fuel beds, the functional validation of the model and the sensitivity analyses on vegetation parameters are performed. Finally, a case study is discussed to illustrate the application of the model with real-world data. Without any mathematical correction, this method is intrinsically free from the distortion problems found in several CA approaches.

1. Introduction

Forest fires play a dominant role in the renewal of plant communities and ecosystem regeneration (Jpa et al., 2007). However, uncontrolled forest fires are a critical natural hazard worldwide and cause enormous ecological destruction, economic losses and significant casualties (Sun et al., 2013), and their intensity has increased in recent years (Jellouli et al., 2016). Therefore, these human and socioeconomic damages increase the demand to improve knowledge of fires (Collin et al., 2010), particularly the modelling and simulation of forest fire behaviours.

Before and after the disaster, the simulation models could determine the fire risk of local artificial situations and evaluate the effects of different fire-fighting policies, based on historical data in the given area (Dunn, 2007). Fire-suppression tactics could be deployed by water-dropping helicopters and air-tankers (particularly seawater planes) (Alexandridis et al., 2011), but the inefficient use of aviation resources leads to an increase in suppression costs (Thompson et al., 2013). Additionally, firefighting trainings could be realized in safe simulated environments with low costs to improve the efficiency of outfires in actual forests. Hence, a real-time interactive crown fire behaviour model is needed.

In recent decades, with the increasing capabilities in remote sensing, geographical information systems (GIS) and computing power, several simulation models have been developed to better understand the behaviours and effects of forest fires. The most important models of wildland fire behaviour have been summarized and classified in studies by Perry (1998), Pastor et al. (2003) and Sullivan (2009a). The classification of these models is listed below.

According to the fire types:

Ground fire models. The combustible target of the ground fire model is the vegetal stratum below the surface litter layer, which is formed by fermentation and humus layers.

Surface fire models. The surface fire spreads through surface fuels consisting of small trees, bushes, herbaceous vegetation and fallen trunks, which are less than 2 m high.

Spotting fire models. The spotting fire model comprises pieces of burning material transported by a convection column and carried beyond the main perimeter of the fire.

Crown fire models. The fuel bed of crown fires is formed by surface and aerial vegetation strata. In particular, an active crown fire is defined when the fire front spreads through the two strata as a unit, and a passive crown fire is that in which tree crowns are individually ignited by the surface fire. Compared to other types of fires, crown fires lead to high fire intensity and bring great destruction to forests.

According to the variables studied:

Fire spread models. These models focus on variables that directly influence the propagation of fire perimeters. Fire spread rate, fire line intensity and fuel consumption are three important variables addressed in most of the models.

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Software availability

Name of the software SVICA simulator
Developer Yuxuan Liu
Contact information yuxuan.liu@buaa.edu.cn
Hardware required General-purpose computer with standalone graphics card
Software required Unity 5.2.3 or higher
Programming languages C#
Availability Contact the developer
Year first available 2017

Fire front properties models. At the local scale, the geometric and physical features of flames are studied, such as flame height, temperature, etc.

According to the nature of mathematical functions:

Physical models. Derived from laws of combustion, heat transfer and fluid dynamics, a physical model attempts to simulate both the physics and chemistry processes of wildland fires. Although physical models are widely studied, two major drawbacks are inevitable. First, many input data of the model could not be measured in the field (Chandler, 1983), thus the validation and numerical simulation of the model are extremely difficult to propose. Second, the lack of knowledge on the complex chemicophysical processes still limits the development of the physical models.

Quasi-physical models. Developed from general and theoretical physics equations and completed by laboratory-based or field-based experimental data, a quasi-physical model represents only the physical processes. One of the quasi-physical models widely used in wildfire spread rate prediction is that developed by Rothermel (1972). Although the difficulty in input data acquisition is reduced to some degree compared with physical models, many of the simulations adopting the quasi-physical model have directly converted the one-dimensional spread model to that of a two-dimensional planar model.

Empirical models. Involving no physical or chemical mechanism, an empirical model comprises statistically and mathematically analogous descriptions from experimental or historical fire data. However, the lack of physical basis restricts the implementation of the model in different environments, suggesting that the fuel bed conditions should be validated prior to application of the model.

Quasi-empirical models. Based on the physical framework, a quasi-empirical model is also built by statistical approaches. Different from empirical models, physical framework is embedded so that the interaction between the fire model and external factors (i.e., water dropped from helicopter) during the simulation is feasible. Nevertheless, geographical restrictions of the model still exist due to the dependence on the statistical data of fire behaviours in the given area.

According to the representation of the fire:

Vector-based models. In vector-based models, the fire front line is considered as a closed curve of linked vertices, described in the literature as a vector implementation. Huygens' wavelet principle proposed by Richards, 1990, 1995 is applied in the propagation of the fire perimeter in which each vertex is considered as a potential source of independent elliptical expansion. Using Huygens' principle as the fire growth model, The FARSITE Fire Area Simulator developed by Finney (1998) incorporated existing fire behaviour models simulates past, active and potential fires (Finney and Andrews, 1999). As a software tool in fire front prediction, FARSITE is widely used in many studies to verify the simulated fire shape and evaluate the performance (Peterson et al., 2009; Trunfio et al., 2011; Avolio et al., 2012; Ghisu et al., 2014, 2015). To predict actual firing borders instead of burned area front lines, the reaction models (or equations) are additionally required for existing vector-based models.

Raster-based models. In raster-based models, fires are treated as a group of globally contiguous cells in a grid, described in the literature as a raster implementation. Several states are defined to each cell, so that the propagation of fire is then transformed into the successive state transitions of cells in a raster grid. As one of the most used raster implementations, the Cellular Automata (CA) approach is computationally less intensive than that of the vector-based method and has strong adaptability in heterogeneous fuel and meteorological conditions.

Level-set models. In the level-set model, the fire front line, similar to that in vector-based models, is regarded as a closed curve, whose horizontal projection interface corresponds to the zero-level set of one evolving function ϕ. The expanding problem of the interface is then transformed to the evolution of ϕ in time (Adalsteinsson and Sethian, 1995). Tiziano Ghisu et al. (2014) presented a level-set algorithm for simulating wildfire spread, compared with raster-based models, whose results show high accuracy in fire front prediction without any distortion. Similar to the vector-based models, based on supplementary reaction models (or equations), the burning time for each ignited cell could be easily determined. Therefore, both the firing and burned out front lines could be simulated.

In the models summarized above, aiming at surface fire spread modelling, many researchers have proposed vector-based or raster-based methods with equations ranging from the purely physical to the purely empirical in which the formulation of fire front properties has been simplified or replaced by statistical analogues (Sullivan, 2009b, 2009c). Therefore, these models are focused on the prediction of propagation, and a unique model describing full chemicophysical processes of forest fire is still not computationally feasible (Collin et al., 2010). Moreover, compared with surface fire, other types of wildland fire are less studied (Pastor et al., 2003), and in much of the literature, wildfires were not classified.

To construct the interactive simulated environment for forest firefighting training, based on the classification listed above, the wildland fire behaviour model should be featured as:

A crown fire model
A fire front properties model
A quasi-empirical model
A raster-based model

Active crown fire is targeted as the modelled fire type in the present study, due to its intense destruction of forests. The model should contain enough fire properties, including the fire spread rate and front shape, to realize additional interactions needed in future applications. Considering the difficulty in full chemicophysical modelling and initial data collection, a quasi-empirical framework is applied. Finally, from the viewpoint of application, the discrete nature of raster-based models makes the implementation on digital computers easier than that of vector-based models. Additionally, compared with level-set models and vector-based models, raster-based models have the potential to embody the physical framework of forest fire propagation, which has been demonstrated by Collin et al. (2010). To comprehensively fill in the blanks concerning the real-time simulation of crown fire behaviours, the CA approach appears to be an appropriate alternative. Thus, the feasibility and necessity of a new CA approach are discussed below with a detailed review of previous works employing the CA method in fire modelling.

First introduced by Karafyllidis and Thanailakis (1997), the CA approach in forest fire spread prediction was broadly applied and considerably developed. Based on the CA model by Karafyllidis and Thanailakis (1997) and the modified fire spread model of Rothermel (1972), Berjak and Hearne (2002) proposed an improved CA model in a spatially heterogeneous Savanna system. Extended from the model of Karafyllidis and Thanailakis (1997) and Berjak and Hearne (2002), A. Hernández Encinas et al. (2007a) introduced a new method to calculate the propagation factor from a diagonal adjacent cell. However, the simulated fire shapes of these CA models under constant wind and homogeneous landscape conditions suffer from significant distortion,