Environmental Modelling & Software 92 (2017) 163–168

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Simulating wildfires backwards in time from the final fire perimeter in point-functional fire models

S. Monedero [a, *], J. Ramirez [b], D. Molina-Terrén [c], A. Cardil [a]

[a] Tecnosylva, Parque Tecnológico de León, 24009 León, Spain
[b] Technosylva, UCSD Calit2 Qualcomm Institute, La Jolla, CA 92037, United States
[c] University of Lleida, 25198 Lleida, Spain

A R T I C L E I N F O

Article history:
Received 21 September 2016
Received in revised form
13 February 2017
Accepted 20 February 2017

Keywords:
Empirical fire models
Backwards in time
Ignition locations
Wildland fire
Fire modeling

A B S T R A C T

Fire propagation models simulate wildfires forward in time from a set of ignition locations, but are usually unable to be used backwards if only a final fire perimeter is available. This approach is useful to search fire ignition points, reconstruct past fire events, adjust fire simulators and other purposes. This study proposes three different algorithms: a short time range backwards in time simulation from the perimeter, a statistical analysis related to the likelihood of a fire ignition location over the domain, and an analysis aiming to multiple ignition locations. The methods presented are fast to be solved and may be used with any empirical fire propagation model as a core engine as long as the ROS is locally defined and the model is not coupled to the weather.

1. Introduction

Wildfires cause substantial global losses in ecosystems and assets, such as houses, private lands, electrical lines or other infrastructure (Bracmort, 2012; Cardil and Molina-Terren, 2013). Fire modeling provides an analytical framework to characterize and predict fire behavior and spread in several and complex fire environments (Albini, 1976; Finney, 1998, 2002). In this context, fire management agencies rely on fire propagation simulation models to conduct prescribed fires, assess the effectives of fuel treatments, develop suppression strategies, etc. (Anderson et al., 2009; Cruz, 2010; Pimont et al., 2016). Today's empirical fire propagation simulators are the result of decades of intense fire modeling research and experimentation (Sullivan, 2009a, 2009b, 2009c). Many fire modeling systems such as Farsite (Finney, 1998), Nexus (Scott, 1999), FlamMap (Finney, 2006), BehavePlus (Andrews, 2014), ForeFire (Balbi et al., 2009), Wildfire Analyst (WFA; Ramirez et al., 2011) and others have been developed. Given variables like the ignition location, wind, fuel moisture, slope, aspect, elevation and vegetation inputs, they simulate fire behavior and some of them like WFA, FlamMap or Farsite provide the future position and fire perimeter shape together usually with the Rate of Spread (ROS), flame length and intensity with significant degree of accuracy.

Fire propagation models simulate forward in time from an ignition point or line but are usually unable to use a final fire perimeter as an input to model backwards past fire incidents. A first implementation of this model can be found in WFA (Ramirez and Monedero, 2011), together with some other propagation modes (Evacuation, Adjust and Probabilistic). This is a very desirable analysis for searching fire ignition points, modeling past fire events, adjusting fire simulators to different input data, creating an approximated fire history to start fire-weather coupled models from a given fire perimeter, and other purposes (Kondratenko, 2015).

In the context of the level set method and coupled models Kondratenko et al. (2011) computed an artificial fire history inside of a given perimeter by linear interpolation of the arrival times at the perimeter and the ignition location. This simple approach was later improved by Mandel et al. (2014) by constructing a level set function taking into account the rate of spread and using Sussman et al. (1994) reinitialization equation. In the context of Huygens (front tracking) based time evolution models like Farsite (Finney, 1998), Heathfield et al. (2015) proposed a spread vector rotation scheme to simulate fire backwards in time and seek for ignition locations. In the context of Minimum Travel Time evolution

* Corresponding author.
E-mail address: smonedero@tecnosylva.com (S. Monedero).

http://dx.doi.org/10.1016/j.envsoft.2017.02.023
1364-8152/

algorithms, Mandel et al. (2014) and Kondratenko (2015) proposed a reverse time, backtracking implementation which was tested in a real fire with great success. Along a similar line to these works, this paper presents three algorithms for computing the ignition location: a direct *Backwards in Time* propagation from an outer perimeter, an enhancement over the first method implemented in WFA in 2011, a *Single Ignition Location Search* method aiming to provide the likelihood of an ignition location over the domain, and a *Multiple Ignition Location Search* method to search for multiple ignition locations. The direct Backwards in Time simulation is very similar to the one proposed by Mandel et al. (2014) and Kondratenko (2015) and it is basically shown for completeness in the presentation. The other two methods are innovative and are specifically developed to search for ignition locations in the landscape.

2. Study cases

A perimeter obtained from a simulated fire with WFA serves to test the algorithm (Fig. 1 Left), and an actual wildland fire perimeter is used for validation (Fig. 1 Right; Cardona Fire). The 2005 Cardona Fire occurred in the province of Barcelona (Spain) (lat. 41°54′ N, long. 1° 40′ E) on 8th July 2005 and both ignition point and fire perimeter were provided from Catalonian firefighters. The fire started at 02:45 p.m. and spread until approximately 07:45 p.m. when firefighters controlled it. It burned 1400 ha of *Pinus pinaster* Aiton. and *Pinus halepensis* Mill.forest. The understory vegetation was very thick due to the lack of fuel management. Dominant species were *Erica Arborea* L., *Genista multiflora* Aiton., *Cistus monspeliensis* L., *and Cistus albidus* L. The continuous fuel with very high load provided a high rate of spread and long flame lengths. Weather data from Santa Coloma of Farners meteorological station located 12 km away from Cardona fire starting point were used as input in the fire simulator (WFA). The model required temperature, wind direction and speed and relative humidity. Dead fuel moisture was calculated using Nelson's equation (2000) and live fuel moisture was set considering both the plant species and weather scenario. All weather variables were constant spatially updated every 30 min. Fire weather was adverse with 30 °C maximum temperature, 30% minimum relative humidity in air and 23 km/h southern winds. Both, high atmospheric instability and the development of a pyrocumulus cloud effect of the wildland fire environment caused extreme fire behavior (Werth et al., 2011) that included active crown fires. Fire spread was monitored by firefighters in real time and both the main fire runs and perimeters were recorded (Fig. 1 Right). The fire initially spread under southwestern winds but the wind shifted southerly 2 h later. This altered fire behavior in the west flank (left flank) which became a head fire, developing new fire runs.

3. Methods

Three methods are presented: a direct *Backwards in Time* propagation, a *Single Ignition Location Search* method and a *Multiple Ignition Location Search* method. The direct Backwards in time simulation from an outer perimeter is mathematically expected to give accurate results (fire arrival times and any other model output like flame length or intensity) if the mathematical fire propagation model perfectly mimics real fire behavior and no multiple ignition locations are present. In a real case, however, where small inaccuracies are expected to be found along the simulation, the method may be used in short time period analysis, but it is not recommended to be used to seek for ignition location (i.e., long time range analysis). This is because as the fire shrinks down to the ignition location inaccuracies from any part of the simulation tend to build up and may have a direct effect on the ignition location. This is different to what happens in a standard simulation spreading

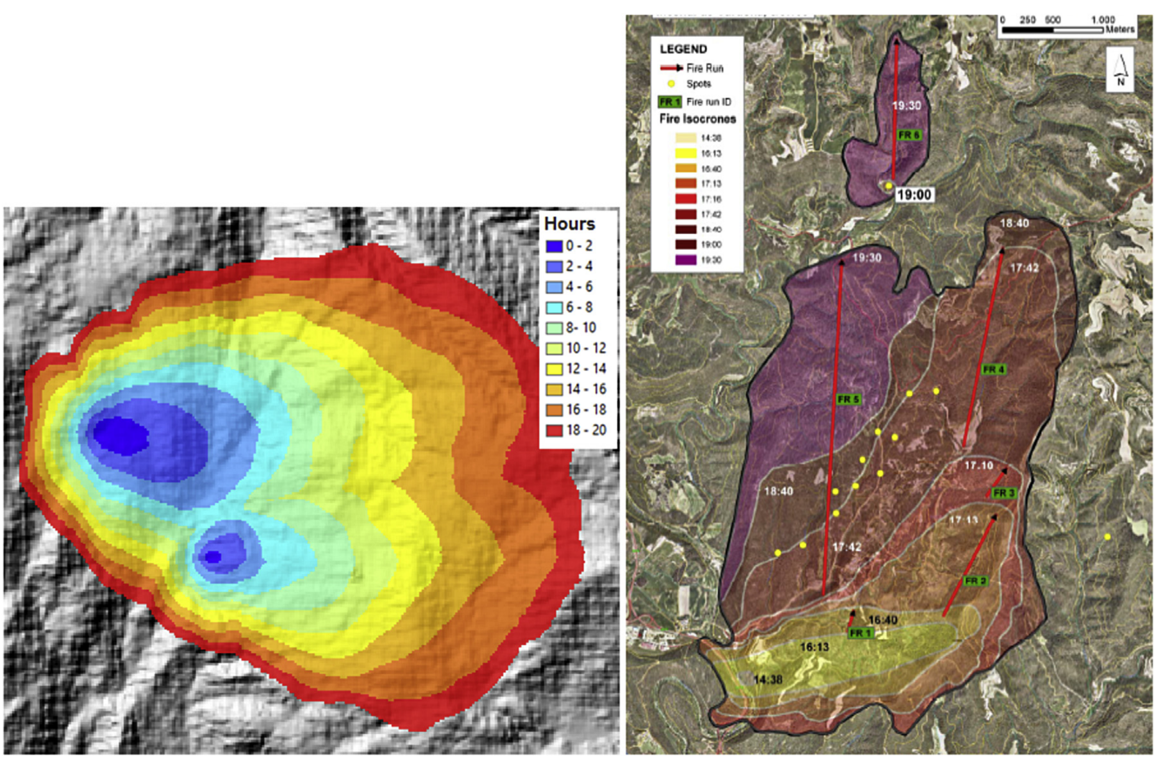

Fig. 1. A 20 h fire simulation with a 1 h delay secondary source that resulted in the final perimeter (left). Fire runs and Cardona's fire perimeter (right) (Catalonian Department of Interior, Fire suppression section, and GRAF firefighters team).