An Improved Wildfire Simulation Engines

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***Abstract*—Wildfire simulation is implemented mainly by raster-based methods, with cellular automata (CA) being among the most widely used, due to their computational efficiency and easy implementation. However, most of the CA-based models often cause spatial distortions and artifacts, arising from the discrete nature of time and space in the simulation engine. Limited access to crucial environmental information in real time can further reduce their accuracy. In this work, we present an improved CA-based method which applies a perimeter shape correction mechanism during the simulation, so as to enhance wildfire simulation, by incorporating not only local transition rules, but also actions in the macroscopic level, leading to a more realistic representation of fire spread, The performance of the enhancement is validated using a wildfire test case scenario based on real-world wildfire data.**

***Index Terms*—Wildfire Simulation, Cellular Automata, Wildfire Shape, Natural Disaster**

I. Introduction

Among the various modeling approaches proposed in the literature, the class of methods based on Cellular Automata (CA) is gaining more and more attention. This class of models has received a substantial body of publications and has been adopted in both scientific and operational, real-world applications. Although CAs are not, in themselves, predictive models of wildfire dynamics – this role is fulfilled by fire-spread models (like Rothermel's surface spread model [1], a distinct subclass of wildfire simulation frameworks [2] – they provide an effective formalism for representing and visualizing local interactions among the physical and environmental components that govern fire propagation. In CA-based wildfire models, the underlying spread model specifies the transition rules, which determine both the intensity and the spatial extent of interactions between neighboring cells. As a result, CAs serve as a computationally efficient mechanism for capturing the spatially explicit, neighborhood-driven processes that characterize wildfire spread, while delegating the quantitative estimation of fire behavior to the embedded spread model. A fire spread model usually incorporates environmental readings with forestry fuel characteristics and topography in order to quantify (usually in a single dimension) wildfire spread characteristics like fire line intensity, Rate of Spread (ROS), flame length, etc. The forestry fuel composition can be derived from predefined fuel models [3], [4], [5] which incorporate averaged out fuel characteristics and observations of wildland fuel structures in a standardized manner.

On the other hand, CAs – like any model – are a simplification of the real word. Despite their undeniable robustness as a simulation tool, they have also been criticized [2]. Most of the criticism is driven by the discrete nature of the method itself, which fails to accurately capture the continuous spatiotemporal interactions of fire. Additionally, the inherently local nature of CA transition rules provides a rather myopic representation of the modeled world, failing to express the macroscopic nature of the evolving phenomena. As a consequence, such models suffer from limitations in capturing broader landscape-level dynamics that often play a significant role in real wildfire behavior, leading to artifacts and unrealistic spread patterns.

As part of our research effort on improving wildfire spread prediction in the field, by combining pre-existing information, such as maps and surveys, with information that becomes available as the phenomenon occurs, such as actual fire front observations, we are developing a CA-based simulator that can operate in mobile devices. In this paper, we propose a method for improving the accuracy of a CA-based simulation based on a fire perimeter shape estimation mechanism which corrects some of the artifacts produced by the grid-like nature of CA models.

The remainder of this paper is organized as follows. Section II provides an overview of CA-based wildfire simulation techniques, setting the context for the study. In Section III we describe wildfire spread at a macroscopic level and context on how to model it. Section IV describes the inherent limitations of a CA-based simulation. Section V presents an improved CA-based method for simulating wildfires. In Section VI we apply the proposed model to a past wildfire event in order to demonstrate its efficiency. Section VII concludes the paper and outlines directions for future work.

II. Typical Cellular Automata Simulator

To define a typical Cellular Automata wildfire simulator, we first need to provide the following parameters:

- **temporal resolution:** defines the duration of the simulation time step (t_α) which represents the physical time elapsed between two consecutive simulation steps.
- **spatial resolution:** quantizes the simulated area into a two dimensional square lattice (grid) consisting of square cells with a known side length (l).
- **cell states:** for each grid cell we define a set $S = \{s_1, s_2, \ldots, s_n\}$ of (usually discrete) states the cell is allowed to take during the simulation.
- **cell neighborhood:** for each cell, a number of adjacent cells forms its neighborhood. Usually that number is four cells (von Neumann neighborhood) or eight cells (Moore

neighborhood). The states of neighboring cells influence the state of the examined cell at the next simulation step, according to a set of transition rules.

- **transition rules:** a set of deterministic or stochastic functions that take as input the state of a cell and the states of the neighboring cells (according to the neighborhood definition) at the current simulation step and return the state of the cell at the next simulation step.

For simplicity, in this paper we will adopt a subset of the typical CA structure proposed by Alexandridis [6] which has served as a foundation for numerous later implementations, as described below.

A. Cell States

At each time step (t), a cell with coordinates (i, j) can be in one of the following four discrete states ($S^t_{i,j}$):

- **State 1:** empty (the cell contains material that cannot be ignited like water bodies, artificial constructions, etc.).
- **State 2:** not ignited (the cell contains combustible fuel that has not been ignited up to this time).
- **State 3:** burning (the combustible fuel inside the cell is burning for the duration a simulation time step).
- **State 4:** burned (the fire has consumed the cell's contents and cannot be reignited).

B. Transition Rules

- **Rule 1:** If $S^t_{i,j} = 1$ then $S^{t+1}_{i,j} = 1$, that is, empty cells remain empty.
- **Rule 2:** If $S^t_{i,j} = 3$ then $S^{t+1}_{i,j} = 4$, that is, a cell that is burning at time step t, will be completely burned at time step $t + 1$.
- **Rule 3:** If $S^t_{i,j} = 4$ then $S^{t+1}_{i,j} = 4$, that is, burned cells remain burned.
- **Rule 4:** If $S^t_{i,j} = 3$ then $S^{t+1}_{i\pm1,j\pm1} = 3$ with probability p_{burn}, that is, a cell under fire can propagate the fire to its neighboring cells (assuming a Moore neighborhood).

C. A probabilistic function of cell combustibility

In each time step, a cell may catch fire according to probability p_{burn} which quantifies the likelihood of the fire to propagate to that particular cell. To calculate this probability, we consider the factors influencing wildfire behavior [3], such as the type and composition of the forestry fuel, the terrain, the wind, etc. One possible formulation of p_{burn} is presented in Equation 1:

$$p_{burn} = p_h(1 + p_{veg})(1 + p_{den})p_w p_s \tag{1}$$

Where p_h is a constant probability representing the likelihood of a cell to propagate the fire to its neighboring cell under the influence of no wind and zero slope. That value is usually fine-tuned and obtained from rounds of optimization evaluating the performance of the model against past wildfire events. Terms p_{veg} and p_{den} are probability coefficients expressing the influence of vegetation type and density respectively. In most publications [6], [7], [8] vegetation types and density are categorized into distinct classes and a look-up table with the corresponding probability coefficients is provided.

The term p_w is a probability coefficient which is given as a function of wind velocity and angle in Equation 2:

$$p_w = e^{[V(c_1+c_2(\cos(\theta)-1))]} \tag{2}$$

Where c_1, c_2 are user defined parameters, V is the wind velocity and θ is the angle between the wind direction and the candidate fire-spread direction.

Finally, the p_s term expresses the impact of terrain slope in the spread of fire, since a fire moving upslope propagates faster due to the faster preheating of the available forestry fuel [9], as shown in Equation 3.

$$p_s = e^{\alpha\theta_s}, \theta_s = \begin{cases} \tan^{-1}\left(\frac{E_1-E_2}{l}\right) \text{if cells are adjacent} \\ \tan^{-1}\left(\frac{E_1-E_2}{l\sqrt{2}}\right) \text{if cells are diagonal} \end{cases} \tag{3}$$

Where α is a user specified parameter, θ_s is the slope angle formed by the cell who is burning to the one considered for propagation, l is the cell length and E_1, E_2 is the elevation (from the centroid) of the involving cells. Elevation data can be obtained from publically available raster-based Digital Elevation Models (DEM) and APIs like Copernicus DEM and NASA SRTM.

III. Wildfire Spread at the Macroscopic Level

Over the past years, many research efforts have focused on analyzing the spatial evolution of an active wildfire in order to better predict its spread across an impacted region. Several patterns have been proposed to express its shape characteristics, like the simple elliptical model, the double elliptical, the ovoid, the lemniscate shape or the tear shape pattern [10], [11] According to the literature [10], the main factors that determine the shape of a wildfire are the wind, the type of fuel involved and the terrain. In Table 1 we present an overview of the most common patterns in wildfire shapes and the conditions under which they are observed by the researchers [10], [12]. It is important to note that researchers conclude that the accuracy of models against real word fires depends primarily on the number of the observed input parameters used, rather than on the inherent geometric properties of the shapes themselves [13].

Other approaches to model the shape and the perimeter of a wildfire include deep learning and graph networks [14], the pyrogenic potential model [15] and machine learning with remote sensing [16], but since they are computationally heavy and have not been implemented in operational systems, we do not consider them in this study.

A core parameter utilized in most of these models is the length to breadth (L/B) ratio of the ellipse that contains the burned area. Many publications have proposed a relationship between wind and L/B like McArthur [17] and Alexander [10]. In the context of the proposed simulation software the general estimation of $\frac{L}{B} = 1 + 0.00120\ W^{2.154}$ will be used [10]. The above approximation relates the 10-m wind with the expected L/B ratio, and it is applicable for winds not above 50 km/h

TABLE I
COMMON WILDFIRE PERIMETER PATTERNS UNDER DIFFERENT WIND AND FUEL CONDITIONS.

Shape	Wind	Fuel	Limitation
Ellipse	Constant, unidirectional	Uniform, continuous	Simple method. Generally, the shape is governed by wind speed
Double Ellipse	More accurate on spot fires due to wind influence	Weak-intensity surface fires	Provides little gains in detail
Ovoid	Low wind speed	More widely spaced fuels	Pattern observed in the early stages of wildfire spread
Lemniscate / tear shape	Strong or changing wind directions	Heterogeneous	Primarily observed in the Australian heath

and when the direction of the wind is considered relatively steady.

In order to calculate the length of the major semiaxis of the ellipse, we need to determine the head ROS (rate of spread) and the rear ROS as well. While there are several models to predict the head ROS [1] (given weather and fuel characteristics), not much attention has been provided to the rear ROS. Some researchers assume that the rate is negligible, others that the fire spreads primarily to the front (and the flanks), due to the fact that fire suppression efforts are firstly applied directly to the rear where conditions are more favorable and others assume a fixed rate [18] in order to express a free burning scenario. A similar approach is followed by Anderson [19] where it is assumed that the ignition point of the fire is located close to the focal points (opposite to the head), so that the length of the rear fire can be derived from the geometric properties of the ellipse itself and not from the rear and head spread speeds. That approach is the most realistic, since in practice it is very hard to distinguish either the ignition point or which portion of the area along the major semiaxis is consumed by the head and which by the rear fire after some time. Hence, it is generally accepted that the fire perimeter evolves in an approximately elliptical shape, irrespective of the specific ratio between its head and rear rates of spread [20].

For the purposes of our work, the proposed simulator will implement Simard's formula [21] for rear (Equation 4) and flank (Equation 5) ROS ratios, which gives a very conservative estimation of the expected rear ROS.

$$R_r = \ e^{-0.075W} \tag{4}$$

$$R_{fl} = R_r + \ 0.000167(W \ sW) \tag{5}$$

Where R_r is the rear to front ROS ratio, R_{fl} is the flank to front ROS ratio, W the wind and sW the standard deviation of the wind.

The center offset of the theoretical ellipse from the ignition point can be found as $d = \frac{R_h - R_r}{2}t$ where R_h is front ROS, R_r the rear ROS and t the elapsed time.

This step is methodologically necessary because, although past fires are projected onto an elliptical shape post-hoc, our model must first simulate a nascent fire spreading bidirectionally from its known point of ignition and only then its perimeter can be validly projected onto an expected elliptical shape.

IV. LIMITATIONS OF CA-BASED BASED SIMULATION ENGINES

During a CA run, the simulation advances in discrete intervals determined by the simulation time step variable. Within this time interval, the model must determine how to simulate the progression of the fire at any direction, that is, decide if a cell will catch fire at this step or not. This decision is made based on the value of the p_{burn} probability, which is a combination of weighted factors like vegetation, wind and a "base probability" p_h. Despite the fact that this approach seems to address the problem of no uniform fuel and environmental conditions, it comes with some caveats too. First of all, the ROS of a wildfire is not linearly related to the fuel type and the vegetation density [1] hence, to the p_{burn} probability. Additionally, the method implies that a cell will be either completely burned or completely unburned at the next simulation step, even if the fire (according to the computed ROS) is not able to consume the whole area of the cell. Furthermore, even when the simulation time step and the spread rate of the current cell are perfectly aligned – allowing the fire to reach the horizontal or vertical boundary of a neighboring cell, as indicated by the constant probability at a given time step – this approach fails to account for fire spreading at an angle, which results in only partial consumption of the cell, meaning that it cannot reach the next neighboring cells. The limitations of the method are further amplified by the fact that, at each simulation time step, it simultaneously evaluates multiple cells with different forest fuel compositions and advances the fire-front by a grid cell, even if substantial variations in the ROS factors are detected among them.

V. AN IMPROVED CA-BASED METHOD WITH SHAPE CORRECTION

The preceding analysis demonstrates that CA-based methods may introduce additional uncertainty, spatial distortion, shapes with no normal curvature [22] and unrealistic assumptions, leading to reduced performance and accuracy. In this paper, we propose an easy to implement modification over the traditional CA simulation framework, addressing the issue of spatial distortion of the fire front due to the inherently discrete nature of this method and its potential of generating artifacts.

After the discretization of the simulation space is completed, at each time step we calculate the corresponding burn probabilities and mark any provisional cells to be burned at the next iteration. Before the start of the next iteration, we calculate how much the fire front has advanced during that iteration and use that information to obtain the rear advance, according to Equation 4. Then, the L/B ratio can be calculated from [10], and a theoretical ellipse can be constructed. If the user has access to further meteorological parameters, they can use the formula of Equation 5 to obtain the flank to ROS ratio and then obtain the L/B ratio directly. Before turning the provisional cells for burning, we examine if they lie inside the theoretical ellipse that we constructed or not. If they are outside (e.g., the model overestimates the spread of fire) we mark them as burning using a fixed probability $p_{outside}$. The same approach can be applied in the case where the model underestimates the spread and forces some cell to turn into burning if the propagation obtained from CA is not aligned with the theoretical ellipse. The following block of pseudo code outlines the proposed improvement:

```
for (t=0; t < max_time; t++)
           // for each time step
{
  for (i=0; i < N; i++)
  {
    for (j=0; j < N; j++)
    {
      if (cell[i][j] == unburned &&
  under-fire(neighborhood(cell[i][j][t])))
      {
        Pburn = (1+Pveg)*(1+Pden)*Pw*Ps*Ph;
        cell[i][j][t+1] = burning with
   probabilty Pburn;
      }
      if (cell[i][j] == burning)
      {
        cell[i][j][t+1] = burned;
      }
    }
  }
  R_head = Rothermel(envParameters);
  R_rear = exp(-0.075*W);
  LB = 1+0.0012*wind_speed^2.154;
  R_flank = getFlank(LB);
  ellipse = calculateEllipse(ignitionPoint,
    windDir,R_head,R_flank,R_rear,t);
  for each cell marked as
    burning at time == t
  {
    if (cell is outside ellipse)
    {
       cell[i][j][t+1] = burning
          with probality Poutside;
    }
  }
}
```

VI. Case study: Hymettus 2022 wildfire

A wildfire event took place at Hymettus mountain, in the southern Athens suburb of Glyfada, Greece, at the 4th of June 2022 around 12:50 pm local time. It led to a Copernicus EMS activation with ID: EMSR576. According to the Copernicus EMS report, about 432.2 ha of land usage was affected. That particular event was quite severe, since it took place in the wildland-urban interface zone between the vegetation of Hymettus mountain and its adjacent residential areas.

To evaluate the CA-based simulator, we tested our implementation against that event. The initial burned area was retrieved in JSON format from the Copernicus incident page. Within the fire perimeter, some internal gaps were present, representing unaffected areas. These gaps were subsequently filled, because their irregular shapes could not be adequately represented by the square-grid framework employed by the algorithm, so a fair comparison could not be conducted. As a consequence, the burned area slightly increased to 447 ha. The implementation of the software was purely in JavaScript, since we aim to create a portable and lightweight simulator able to adapt to various use cases, including mobile computing scenarios. Elevation data were gathered from NASA SRTM (3-arc-second / 90 m) HGT tiles, while the meteorological conditions during the event were retrieved from weather stations from National Observatory of Athens. On the other hand, forestry fuel data were estimated by examining the Corine Land Cover (CLC) 2018 100-m dataset and manual interpretation of the vegetation types from satellite photographs. The estimated by the Copernicus Repot burned area and the land usages from CLC are depicted in Fig. 1.

After loading the different fuel (in GeoJSON format) and topological data to the user's browser, a square lattice of user-definable size was constructed, while intersecting geometry was calculated utilizing the turf.js library. The resulting map in our simulation tool is shown in Fig. 2.

TABLE II
Mapping of CLC 2018 Codes to probability coefficients

CLC Code	Type	p_{den}	p_{veg}
111	Continuous urban fabric	-1	-1
112	Discontinuous urban fabric	-1	-1
121	Industrial /commercial units	-1	-1
231	Pastures	-0.25	-0.20
242	Complex cultivation patterns	0.15	0.35
312	Coniferous forest	0.75	0.70
323	Sclerophyllous vegetation	0.30	0.40
324	Transitional woodland shrub	0.40	0.40
333	Sparsely vegetated areas	0.10	0.30

TABLE III
Simulation parameters

Parameter	Value	Parameter	Value
p_g	0.60	α	0.078
c_1	0.045	l	45 m
c_2	0.131	$p_{outside}$	0.25

Two simulation runs were conducted, with and without shape correction. The vegetation classes along the burned area estimation and the simulation parameters used are given in Table II and Table III, respectively.

The estimated burned area for both simulation scenarios is illustrated in Fig. 3, with the left side showing the results

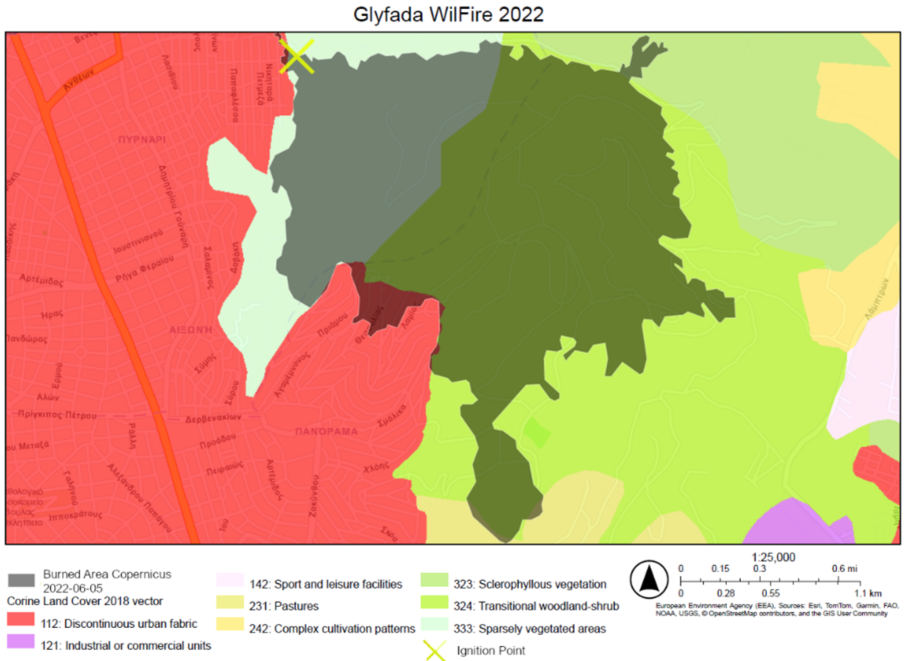

Fig. 1. Hymettus Mountain wildfire in 2022. Affected area (gray color) estimation using data from EMSR576 Copernicus Activation Report. Land Usages from CLC 2018.

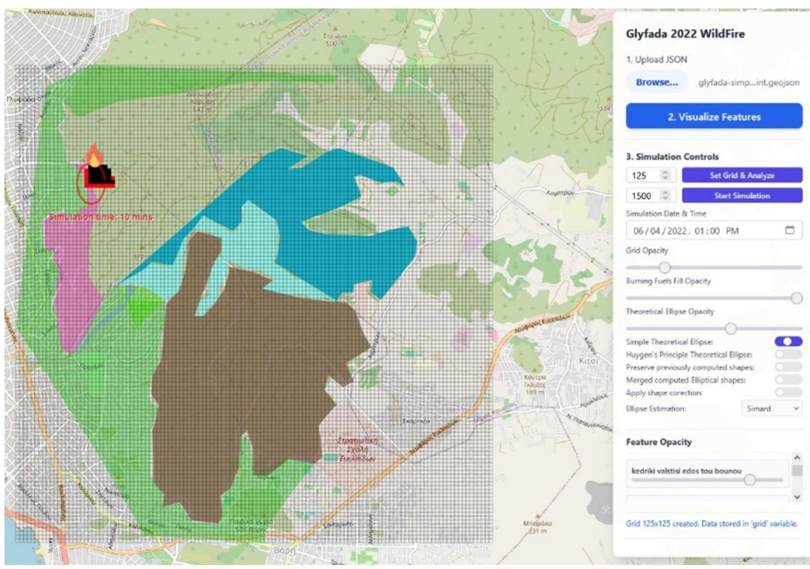

Fig. 2. Web interface of the simulator while running the Hymettus Mountain wildfire scenario of 2022. Grid lines and fuel geometry opacity can be modified by appropriate UI controls. The shape correction mechanism is computed either using Simard's or Anderson's estimation.

without shape correction and the right side when our shape correction method is employed. In the estimation provided by the Copernicus report, the actual affected area is approximately 447 hectares. The first simulation run, which did not apply any shape-correction mechanism, overestimated the burned extent by 20,13%, yielding a total of 537 hectares. When the shape correction procedure was activated and all other parameters were kept the same, the cellular automata model produces a revised burned area estimate of 399 hectares, which underestimates the ground truth by only 10,73%.

It should be noted that the study area is characterized by significant elevation variability, which further increases the complexity of the simulation. In addition, the model used does not incorporate firefighting suppression actions, despite the fact that such interventions were implemented during the actual wildfire event due to the proximity of the area to residential houses. The model we adopted, which is based on a simple and straightforward cellular automata implementation, is not sufficiently advanced to accurately represent complex wildfire behavior. Because each cell can only either ignite its neighboring cells or not, statistically a CA model tends to overestimate the burned area. The proposed correction scheme mitigates that problem to some extent. However, when the computed burned area is found to be less than the expected

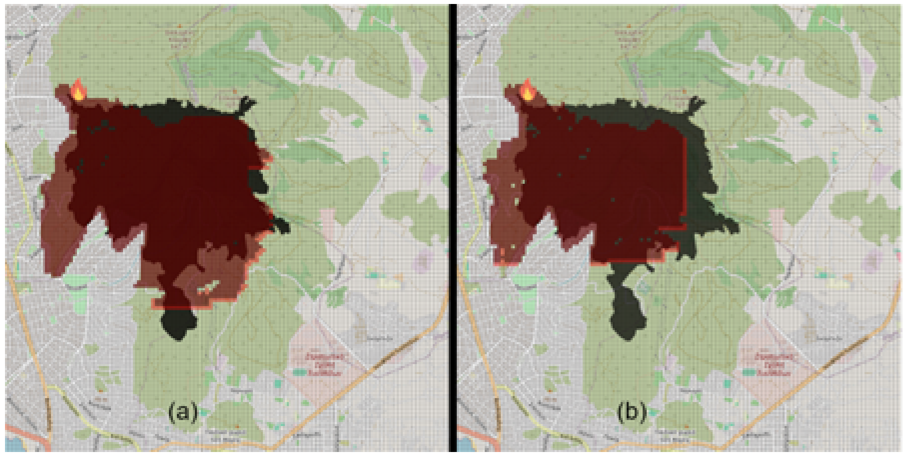

Fig. 3. Simulated area (a) without shape correction and (b) with shape correction. Same parameters used in both runs. The simulated area is marked in red, while the affected area according to the Copernicus report is marked with Gray.

one, a similar correction approach can also be applied.

VII. Conclusions

We proposed a new method for estimating the spread of a wildfire, incorporating CA-based techniques with macroscopic fire dynamics in a hybrid method able to capture fire behavior in a more accurate way. Although the base model that we adopted does not incorporate some of the more sophisticated physical processes that influence fire spread dynamics, our analysis demonstrates that it can still function as a reasonably effective estimator of the overall burned area, when our shape correction method is applied. Like any estimation technique, results are subject to post processing and interpretation from experts, while choosing the values of the tuning variables requires a degree of expertise, empirical knowledge and fine tuning. We believe that the proposed method may serve as a basis for a mobile wildfire simulation engine able to operate on portable devices, especially mobile phones under limited data connectivity, processing and power constraints. The simplicity of the method, combined with its modular web-based architecture, enhances its portability and adaptability. Because each component is designed to operate independently and communicate by exchanging (Geo)JSON objects, the entire solution can be easily deployed across a wide range of platforms and devices. This flexibility allows new developers to integrate or replace modules as needed, like weather forecast models and spread estimation models, ensuring smooth implementation whether the target environment is a desktop application or a mobile device.

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