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Simulating wildland surface fire behaviour to support emergency management

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Abstract

The recent upsurge in the incidence of extreme wildfire events, the expected impact of climate change on the frequency and severity of fires, and the progressive expansion of wildland-urban interface areas highlight the tangible need for improvement in our ability to predict, mitigate and manage the growing risk to which communities are exposed. The aim of this research is to contribute to deepen the knowledge on the spatial simulation of the complex dynamics of wildland surface fire behaviour through the development and application of a spatially distributed predictive model for the simulation of wildland surface fire spread intended for operational purposes. Given the position of one or more ignition points, the developed model allows to (i) obtain near real time dynamic estimates of the geo-environmental parameters that control the fire spread, (ii) compute the direction and intensity of the maximum rate of fire spread in heterogeneous environments, and (iii) simulate the surface fire spread using agent-based models. The final aim is to provide competent authorities with timely information on the expected evolution of the flame front to optimise decision-making processes. The model, developed under synthetic conditions, is then applied to case studies recorded in the territory of the Autonomous Region of Sardinia, that offers institutional information on the ignition location, the evolution of the flame front, and the completed fire suppression activities, which are implemented in the model as well. Overall, the model showed a promising predictive capacity evaluated in quantitative terms of morphological matching between the observed and predicted fire spread patterns, returning more accurate results in areas with less complex morphologies and dominated by herbaceous rather than shrubby fuels. The model also made it possible to obtain simulations with processing times compatible with its operational application as a tool for optimising and planning fire risk prevention and mitigation strategies and policies as well as fire management activities. Future research will be aimed at estimating the propagation of the parametric uncertainty through the model and applying the model to fire events occurred across different Mediterranean-type climate regions to consistently evaluate its predictive capacity.

1. Introduction

Wildland fires are a global and pervasive phenomenon whose incidence and intensity are expected to further increase in the next decades in response to the complex interactions between climatic and anthropogenic factors (Jolly et al. 2015; Flannigan et al. 2016; Williams and Abatzoglou 2016; Turco et al. 2018; Forkel et al. 2019; Dupuy et al. 2020; Jones et al. 2020). Mediterranean-type climate regions appear to be particularly prone to suffer for such an exacerbated fire activity (Turco et al. 2016; Bowman et al. 2017; Kelley et al. 2019; Salis et al. 2019; Mantero et al. 2020). Contextually, recent studies have highlighted that wildfire management policies in Mediterranean-type climate regions are predominantly focused on reactive fire suppression strategies, while struggling with proactive preparation and mitigation actions (Moreira et al. 2020; Ganteaume et al. 2021). Hence, the latest report by the European Commission's Directorate-General for Research and Innovation, which was aimed at providing evidence-based scientific support to the European policymaking process, warned about the emerging risk of a disproportionate increase in uncontrolled extreme wildfire events and the consequent urgent need for a reassessment of wildland fire management policies and strategies at the European level (Rego et al. 2018). An integrated wildfire risk management requires contribution from multiple disciplines, ranging from susceptibility mapping to early active fire detection and fire spread simulation modelling. Accurate predictions of the spatiotemporal evolution of both predicted and ongoing events are of crucial importance for planning and optimising emergency response strategies, which are essential to control the fire spread before it could overwhelm suppression capabilities (Tedim et al. 2018).

The development of a comprehensive model for simulating the spread of surface fires includes (i) a method for converting a multi-dimensional set of geo-environmental data into a set of parameters describing the spread of wildland surface fires and (ii) a method for extending these one-dimensional measurements in space and time and simulate the evolution of the flame front. Sullivan (2009a, 2009b, 2009c) and then Papadopoulos and Pavlidou (2011) conducted exhaustive comparative reviews of the strategies adopted and developed to model the fire spread, (i.e., physical and quasi-physical or empirical and quasi-empirical models), and to simulate the fire growth, (i.e., raster and vector implementations). Modelling fire spread and growth is a complex task due to multiple factors including the spatiotemporal heterogeneity and variability of geo-environmental conditions as well as the uncertain effect of fire suppression interventions (Alexander and Cruz 2013). Especially in the last decades, the increasing computational resources and the growing availability of remotely sensed datasets have fuelled the development of a considerable number of wildland surface fire behaviour models (Szpakowski and Jensen 2019; Jain et al. 2020). However, the optimisation of near real-time simulation of fire spread and growth in operational environments remains an open issue.

The objective of this study is to support the optimisation of the decision-making processes of wildland surface fire risk management in the island of Sardinia, Italy, which is preliminary assumed as representative of Mediterranean-type climate regions. This project intends to pursue the main objective of developing and validating a spatially distributed predictive model for the simulation of wildland surface fire spread intended to be implemented as a geospatial decision support system aimed at providing strategies and tools for an integrated wildfire risk management.

2. Methods

2.1. Model development

When considering models that can be used as decision support tools for operational fire management, some constraints become evident: (i) short decision time frame; (ii) fine-scale spatiotemporal resolution; (iii) input data retrievability in operational environment; (iv) low complexity of laboratory and field experiments; (v) minimum computational requirements at the desired spatiotemporal resolution. The simulation model design and implementation are aimed at providing competent authorities with near real-time multi-temporal maps of the expected evolution of the surface fire spread and growth capable of accurately and dynamically capturing the spatiotemporal variability of the geo-environmental drivers of fire spread.

The quasi-empirical mathematical model defined by Rothermel (1972), one of the most extensively employed method for simulating fire behaviour in operational environments, has been adopted for the prediction of the maximum rate of fire spread. In fact, despite their site-specificity and their tight dependence on local geo-environmental conditions, the empirical and quasi-empirical models boast calculation promptness and usability compared to physical and quasi-physical models. To obtain more flexibility in handling the model equations (Rothermel 1972; Albini 1976; Andrews 2012, 2018), an independent algorithm capable of estimating the same parameters defined by the model has been implemented. The algorithm takes as input combinations of the drivers of fire spread, including geo-morphometrical parameters, horizontal wind speed and direction, fuel types, and their characterisation in terms of live and dead fuel moisture contents, and performs pixel-based evaluations of the magnitude and direction of the maximum rate of spread relative to upslope, the flame length, the intensity of the flame front, and the eccentricity of the ellipse which represents the analytical approximation of the spatial pattern produced by a wildland fire spreading under ideal homogeneous conditions. The algorithm has been then integrated into a spatial simulation model which adopts a hybrid raster-vector approach to simulate the spatiotemporal growth of the flame front. Indeed, while vector implementations for simulating fire growth generally offer greater accuracy, the advantages of raster implementations include simplicity, better portability to parallel computing environments, and higher computational efficiency. Therefore, an agent-based model has been implemented to simulate fire growth with discrete time intervals of 1-minute length and discrete spatial units with a modular area. Spatial units are represented by hexagonal cells, each of which can host at most one and only one agent. An agent instantiated in a cell might represent both the actual ignition point of an active fire or a simulated ignition originating from the elliptical vector simulation propagated from one of the adjacent cells (Figure 1).

2.2. Model application to case studies

The model has been developed under synthetic conditions to verify its conceptual validity and then, applied to case studies referring to historical wildland fire events recorded in the fire database of the Autonomous Region of Sardinia to evaluate its accuracy and predictive capacity.

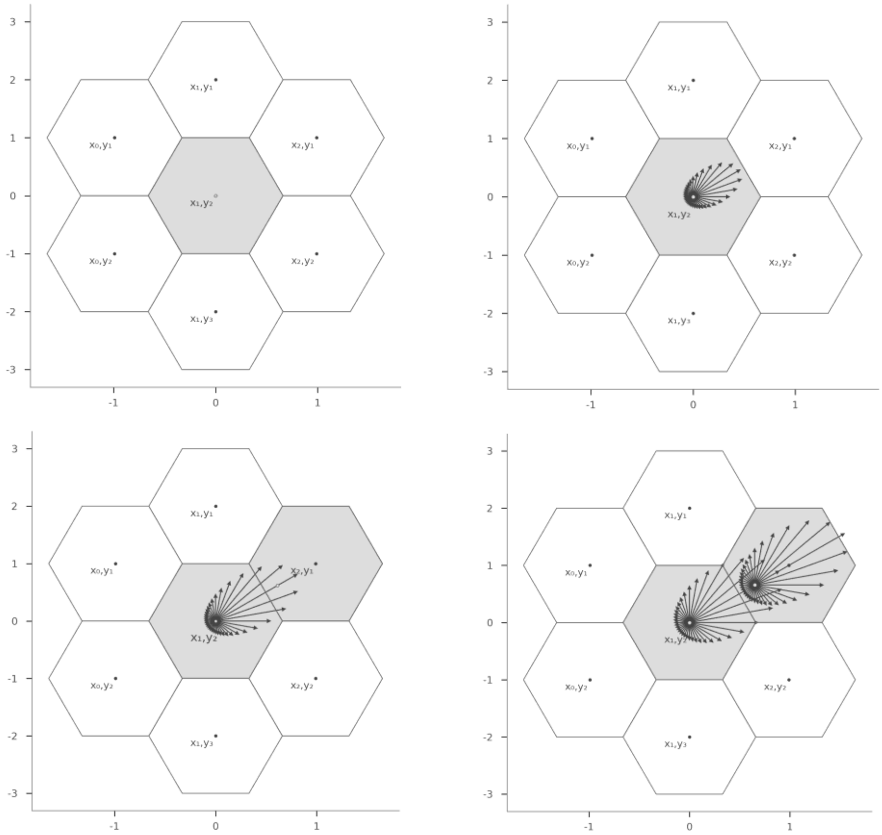


Figure 1- Agent-based model behaviour. A single ignition agent is instantiated in the centroid of the grey hexagonal cell at time t0 (a). After a time t1, an elliptic vector simulation has started from that agent spreading according to the rate and direction of fire spread calculated for that cell by the Rothermel's model (b). After a time t2, the elliptical vector simulation has generated a new agent in one of the white adjacent hexagonal cells (c). After a time t3 a new elliptical vector simulation has started from the new agent (d).

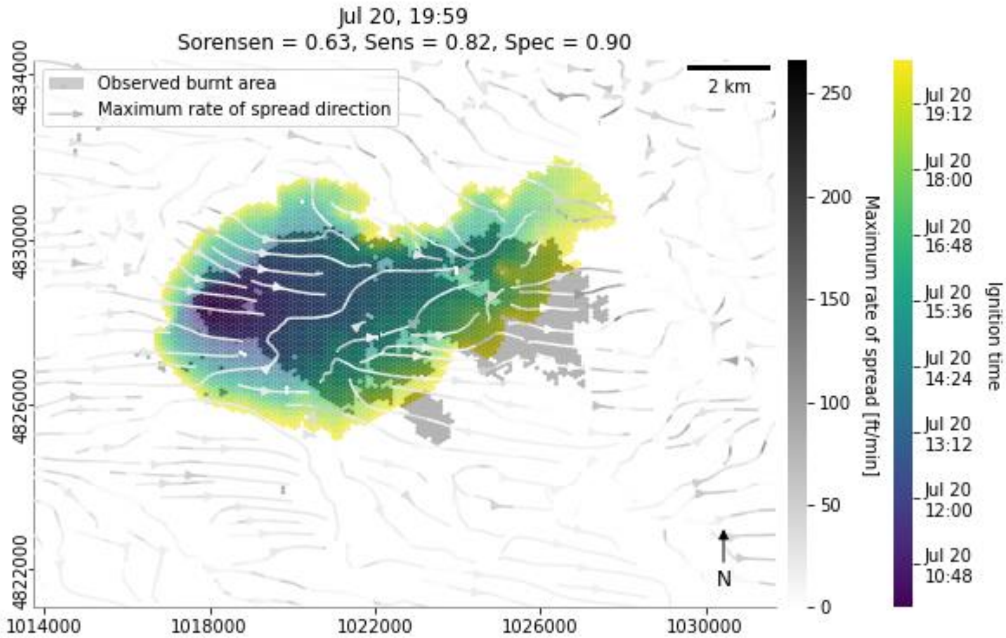
Obtaining dynamic estimates of the geo-environmental parameters that control the fire spread and growth, is essential for the model to compute the direction and intensity of the maximum rate of spread and to simulate the spatiotemporal patterns of fire growth. The near real-time simulation of the evolution of expected and ongoing fire events requires a continuous monitoring of the spatiotemporal variability of the geo-environmental drivers, including wind speed and direction and fuel moisture content. Remote sensing methodologies, making use of either airborne or spaceborne active and passive sensors, provide exceptional advantages over traditional methods for the estimation of geo-environmental parameters, especially in an operational context. Dynamic estimates of the drivers of fire spread have been derived from remotely sensed datasets and global reanalysis with suitable spatial and temporal resolutions. Information on the spatiotemporal variability of live and dead fuel moisture fractions have been derived by adopting empirical relationships already defined in literature for plant communities in Mediterranean-type climate regions (Chuvieco et al. 2004; García et al. 2008; Frey et al. 2012; Nolan et al. 2016), which relate vegetation indices (MODIS Terra NDVI; Vermote and Wolfe 2015) with land surface temperature estimates (MODIS Terra LST; Wan et al. 2015). Horizontal wind speed and direction have been obtained from the ERA5-Land climatic reanalysis, produced by ECMWF, which provides measurements at 10 m above the ground with a spatial resolution of 9 km and a temporal resolution of 3 hours (Muñoz Sabater 2019). Both standard and custom fuel models for Sardinia (Duce et al. 2012) have been assigned to land cover units (Autonomous Region of Sardinia, 2008) according to the literature (Salis et al. 2013).

The availability of accurate institutional information regarding the evolution of the fire spread and growth as well as of successful fire suppression activities, such as control lines, have been also simulated. Finally, standard quantitative indices such as the Sørensen similarity coefficient or sensitivity and specificity measures, have been computed to estimate the model performance in terms of spatiotemporal agreement between the observed and simulated fire spread and growth patterns.

The procedure for estimating the drivers of fire spread has been automated by means of the Google Earth Engine platform (Gorelick et al. 2017) and the spatial model simulating fire spread and growth is entirely developed in Python (Kluyver et al. 2016).

3. Results and Discussion

The predictive patterns resulting from fire growth simulations exhibited a satisfying level of agreement with theoretical knowledge on fire behaviour modelling. It has been observed that wind speed and direction play a decisive role in determining the speed and direction of maximum spread of the flame front. Similarly, fuel continuity and its vertical structure have shown a significative impact on the predicted patterns of fire growth.



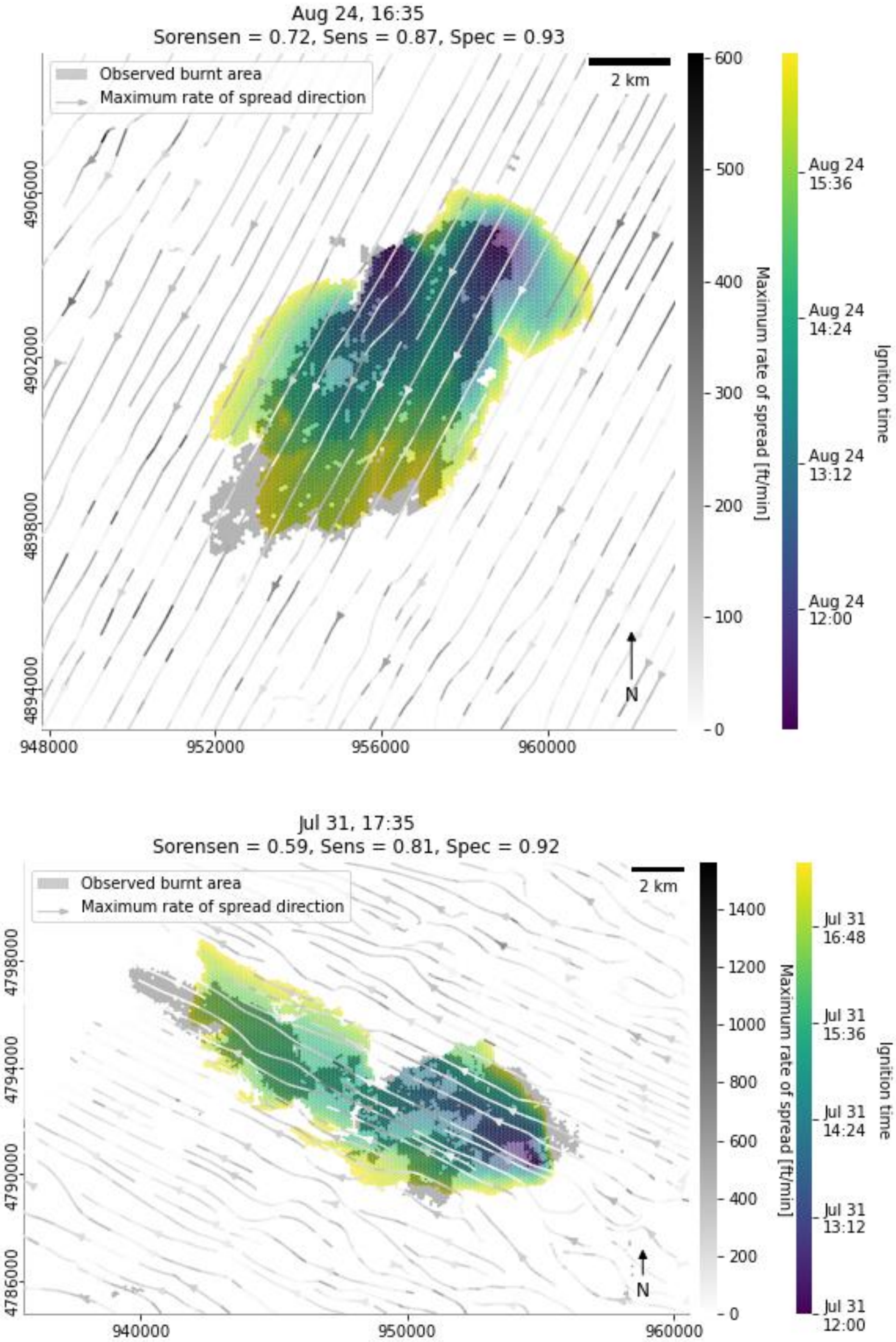


Figure 2- Predicted patterns of fire growth for the case studies of Isili (CA), July 20th, 2016 (a), Sagama (OR), August 24th, 2016 (b), and Gonnosfanadiga (VS), July 31st, 2017 (c). Grey shadows indicate the observed burnt area while the predicted patterns of fire growth are represented with a colormap referring to the hexagonal cell ignition time. Sensitivity and specificity measures and the Sørensen similarity coefficient are reported. Grey arrows indicate the magnitude and direction of the maximum rate of spread according to the Rothermel's model.

Although not fully representative of the complexity and diversity of the geo-environmental conditions in the study area, the selection of case studies for the model application strived to capture heterogeneous geo-environmental conditions. Predicted patterns of fire growth exhibited probability of omission or commission errors lower than 20% (Figure 2), even without the simulation of active fire suppression interventions, which played a significant role in reducing commission errors. A greater model predictive capacity has been observed in the absence of complex morphologies (Figure 2b), reflecting intrinsic limitations of the Rothermel's model and the complexity of properly simulating wind fields, found to be critical for the estimation of both the magnitude and direction of maximum surface fire spread. A higher predictive capacity also emerged in the presence of herbaceous fuels (Figure 2a-b) compared to fuels characterized by sclerophyllous shrubs typical of the Mediterranean maquis and garrigue (Figure 2c), hence, highlighting the need to obtain more accurate estimates of the horizontal and vertical fuel continuity. Omission errors might be attributable to (i) uncertainties connected with the estimation of geo-environmental parameters and their propagation within the model, but also to (ii) ground fire spread phenomena or secondary outbreaks triggered by embers carried by the wind.

Comprehensively, the model developed for the simulation of the propagation of surface forest fires showed a satisfactory predictive capacity in terms of morphological correspondence between the observed and simulated perimeter. Results of the model application to case studies recorded by the Autonomous Region of Sardinia suggest the model suitability for operational use as a tool for the near real-time forecast of the magnitude and direction of the maximum rate of surface fire spread.

Future studies will aim to: (i) calibrate and validate the methodology for the estimation of the geo-environmental parameters; (ii) propagate the parametric uncertainty through the model; (iii) simulate the occurrence of secondary outbreaks due to reignitions or spotting events; (iv) implement a wider range of fire suppression activities and techniques; (v) apply the model to fire event occurred across different locations in Mediterranean-type climate regions to consistently evaluate its predictive capacity.

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