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Implementing a probabilistic fire modeling system at the pan-European level

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Abstract

This research shows the potential use of cross-boundary fire modeling systems at the pan-European level. Despite the growing interest in building fire-resilient cultural landscapes, European Union (EU) level efforts have been reactive and focused on early detection, fire propagation monitoring, and perimeter mapping rather than predicting where the disaster can potentially occur to develop a comprehensive wildfire management strategy. We propose a modeling system that integrates wildfire occurrence models and observed fire-weather scenarios with a fire spread model to generate the probabilistic risk components, i.e., wildfire likelihood and hazard estimates. We selected four NUTS-2 level administrative division pilot sites from different fire-prone countries to implement the modeling system. The European-level pyromes were first delineated based on ecoregions and historical wildfire activity. We then generated human and lightning wildfire occurrence models to display the ignition points. Remote sensing products were used to derive fire spread modeling spatial input data such as surface fuels and canopy metrics. Global atmospheric products were used to calculate the fuel moisture content with physical models and determine the most frequent wind scenarios for each pyrome. We then used the Minimum Travel Time algorithm to model the fire footprints that correspond to 10,000 years or synthetic iterations. This modeling approach accounted for the spatial variation of ignition locations and the changing weather conditions across the different pyromes within each pilot site. The modeling results include the annual burn probability and fire intensity rasters, and fire perimeter vector outputs. Modeled burn patterns showed a close agreement with observed fire size distributions. We compared this modeling system with previous works to explain why stochastic fire modeling is essential to assess wildfire exposure of natural values at risk and human communities. Our results may help predict future catastrophic fires and provide quantitative estimates to identify high-priority management areas within vast regions. The probabilistic predictions generated in this work represent the foundation for developing long-term adaptation strategies to better coexist with fire. This work is also a demonstration of how this modeling system is replicable in any European country.

1. Introduction

In the European Union (EU), some 72,500 fires burned about 450,000 ha annually from 1990 to 2019, and Mediterranean countries alone (i.e., Portugal, Spain, France, Italy, and Greece) accounted for 86% of the total burned area (San-Miguel-Ayanz et al., 2021). Despite the high effectiveness in suppressing most ignitions, the few extreme fires escaping initial attack overwhelm firefighting efforts and burn vast areas (Rodrigues et al., 2019a). These wildfire events show very high spread rates, exhibit extreme behavior and produce massive amounts of embers showered at long distances (Tedim et al., 2018). The 2007 fire season in Portugal and the Greek fires of 2021 (e.g., a single mega-fire burned 45,000 ha) are the most recent extreme wildfire manifestations (Ribeiro et al., 2020). Increasing fuel loads in cultural landscapes and more frequent severe droughts are the main factors explaining the increase of severe wildfire episodes in Mediterranean areas. As a result, the European Commission promoted the development of early detection and fire risk monitoring systems that facilitate a coordinated emergency response among the EU members. However, as the fire exclusion policy fails to protect socioeconomic and natural values at risk, wildfire managers request a paradigm shift towards a management-oriented, more preemptive strategy (Wunder et al., 2021).

The wildfire risk assessment integrates burn probability estimates with fire effects at different fire intensity levels (Finney, 2005). On the other hand, the wildfire exposure analysis describes burn probability and fire intensity but ignores potential effects. Fire intensity and burn probability show complex patterns across landscapes due to the interaction between fire spread direction, weather scenarios, topography, and heterogeneous fuels. Moreover, a given location will show a variable fire intensity depending on the changing interactions between the previously mentioned factors. Therefore, understanding wildfire exposure and spatial risk patterns is paramount for strategic management in extensive areas (Palaiologou et al., 2022).

Fire simulation modeling is essential to generate a large sample of fires, reduce uncertainty, and capture the stochastic variation in fire ignition location and changing weather conditions (Finney et al., 2011). Observed extreme fires are rare episodes, rearrange fuels over large areas, and represent a far too limited sample of the potential burn patterns. Modeling the fire footprints for thousands of years or iterations from a sufficiently large set of plausible scenarios allows for describing the magnitude of the next “black swan” event. In this line, recent fire modeling studies showed strong capabilities for predicting catastrophic wildfires (Ager et al., 2021).

In this study, we generated the spatial dataset of probabilistic wildfire risk components for three NUTS-2 level fire-prone administrative units from different EU countries. Our previous works implemented fire modeling systems in Mediterranean areas at regional and national levels (Alcasena et al., 2021; Palaiologou et al., 2021; Salis et al., 2021). We demonstrate in this work how probabilistic modeling systems can be replicated at the pan-European level using a harmonized set of input data. The outcomes showed a high potential to allocate management efforts efficiently at the continental level from science-based consistent fire exposure and risk metrics.

2. Material and methods

2.1. General framework

This modeling system parallels previous works conducted in the US (Finney et al., 2011; Short, 2017). The system includes a wildfire occurrence module to predict lightning and human ignitions across the landscape, and weather conditions are sampled from the most frequent observed scenarios during the wildfire season (Fig. 1). The landscape file contains spatial data for fuels and terrain. The outputs include the annual burn probability, flame length probabilities, and modeled fire perimeters for the NUTS-2 fire-prone selected sites.

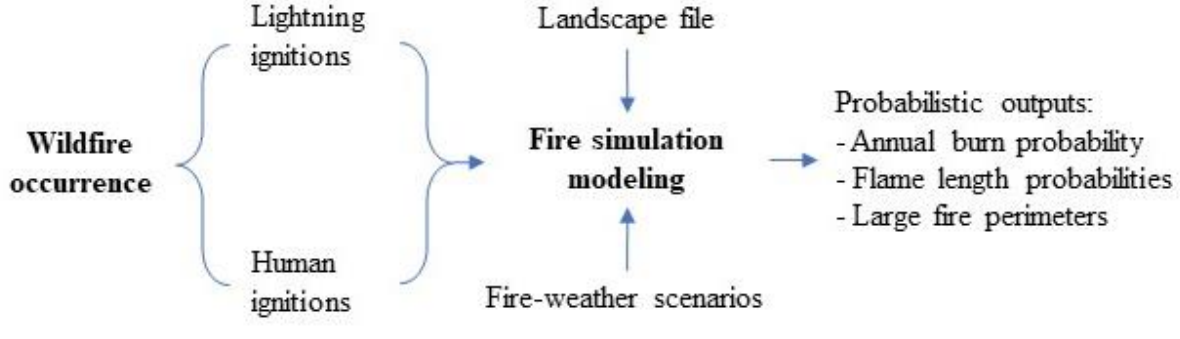

Figure 1: General flowchart of the modeling system.

2.2. Pyrome delineation

We used clustering techniques to delineate the pyromes within the EU ecoregions based on historic wildfire activity (i.e., annual burned area) and large fire weather typologies (Rodrigues et al., 2020). The ecoregions describe the areas with similar ecosystems resulting from edaphoclimatic conditions and dominant vegetation types. The burned area was calculated for a 100-km^2 grid using remote sensing global products. The pyromes were 2,500 to 5,000 km^2 cross-boundary blocks nested within the ecoregion map.

2.3. Pilot site selection

The pilot sites were selected from the NUTS-2 level EU administrative division considering the annually burned area. The burned areas were calculated using remote sensing data and available wildfire records from the last 25 years. We selected four administrative units from different fire-prone Mediterranean countries (Portugal, Spain, Italy, and Greece).

2.4. Input data

2.4.1. Wildfire occurrence

We generated different wildfire occurrence models to predict human and lightning ignition locations. The models were built with machine learning techniques using European-level geospatial data extracted from ignition point locations (Rodrigues and De la Riva, 2014). The number of available years varied between countries but were sufficient to enable us to extract a large data sample to build the models. The fire modeling input data were presented as 100 m resolution ignition probability grids for lightning and human ignitions.

2.4.2. Landscape file

The landscape (LCP) spatial data grids include terrain (aspect, elevation, slope), surface fuels, and canopy metrics. First, we associated a standard fuel model to each land cover class from the 2018 Corine land cover grid to generate the fuel model map (EEA, 2018; Scott and Burgan, 2005). Next, the canopy metrics were **Fire-weather scenarios**

We characterized the most frequent fire-weather scenarios for each pyrome. The winds (speed, direction, and probability) were derived from atmospheric circulation patterns (Rodrigues et al., 2019b), and the fuel moisture content was calculated at 500 m resolution for different percentile values (e.g., 50, 85, 90 and 97th percentiles) with physical models from global products (Resco de Dios et al., 2021).

2.5. Fire simulation modeling

We used the minimum travel time algorithm (MTT) to model fire spread (Finney, 2002). The MTT has been widely used in fire-prone areas to model fire footprints for thousands of synthetic years (Alcasena et al., 2021; Salis et al., 2021). First, the fire spread model was calibrated to replicate the observed fire size distributions. Then, we modeled 10,000 years or iterations at 100 m resolution. Lightning and human fires were separately modeled considering different fire-weather percentile thresholds and frequencies calculated from observed burned areas.

3. Expected results

The expected dataset of probabilistic fire risk components for the three fire-prone NUTS-2 pilot sites will contain the annual burn probability (number of times a pixel burns divided by the modeled years), flame length probability grids (burn probabilities for 20-bin 0.5 m flame length levels), and fire perimeters polygons.

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