ForeFire: A Modular, Scriptable C++ Simulation Engine and Library for Wildland-Fire Spread

Jean-Baptiste Filippi [1¶], **Roberta Baggio** [1], **Ronan Paugam** [2], **Frédéric Bosseur** [1], **Antonio Leblanc** [4], and **Alberto Alonso-Pinar** [1,3]

1 SPE, UMR 6134, CNRS, University of Corsica Pascal Paoli, Corte, France **2** Centre for Technological Risk Studies, Department of Chemical Engineering, Universitat Politécnica de Catalunya **3** Faculty of Science, The University of Melbourne, 4 Water St., Creswick, Australia **4** umgrauemeio 1.5°C, Brazil ¶ Corresponding author

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Reviewers:

- @xiazeyu
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Summary

Wildfire forecasting is both an active research area and an important need for decision support systems. **ForeFire** is a modular, high-performance, scriptable, discrete-event-driven simulation engine (Filippi et al., 2009) focusing computational effort on the active region of a fire front defined as a dynamic mesh (or multipolygons) of fire markers. It is designed to model the spread of wildfire perimeters over large landscapes at a meter scale resolution in seconds, serving both as a research platform and a tool for operational forecasting. The core C++ library has Fortran and Python bindings and is accompanied by a lightweight, scriptable interpreter (a custom FF language) that can load, save, and export data in NetCDF, GeoJSON, KML, PNG, and JPG, and includes a local HTTP service with a customizable graphical user interface. ForeFire can also account for fire-atmosphere interaction by two-way coupling with the MesoNH (Lac et al., 2018) atmospheric model (Filippi et al., 2013).

Statement of need

Wildfire modeling tools have historically been split between **complex combustion research models** and **streamlined operational tools**, each with distinct limitations. Computational combustion and fluid dynamics (CFD)- based models (e.g., FIRETEC (Linn & Cunningham, 2005) or WFDS (Mell et al., 2007)) are highly computationally intensive yet unable to provide large-scale wildfire forecasts faster than real time. Atmospheric-coupled codes, such as WRF/SFire (Mandel et al., 2011), must be run within an atmospheric model and require substantial processing power and data. Operational wildfire simulators, such as widely used Farsite (Mark A. Finney, 1998) (now Flammap (Mark A. Finney et al., 2023)), or Canadian Prometheus (Garcia et al., 2008), can simulate fire fronts spanning tens of kilometers in a matter of seconds, but have definite built-in modeling assumptions and are distributed as compiled software with graphical interfaces with limited scriptability. Other open-source libraries include ElmFire (Lautenberger, 2013) and Cell2Fire (Pais et al., 2021), which are tied to a single spread model and do not include a scripting language. Deep-learning approaches also exist, such as PyTorchFire (Xia & Cheng, 2025).

ForeFire was developed as a community tool to fill the gap between highly complex customizable models and more rigid operational tools: a **unified** wildfire simulator that is both **adaptable** (highly scriptable with multiple bindings) and **high-performing** (discrete-event-driven simulation with dynamic mesh allows to concentrate computation at meter scale resolution only on the active part of the front to perform speed over 100 Ha per second on a single CPU). It is intended to serve both as a research platform and a tool for operational forecasting.

Typical Use Cases

Rapid prototyping of new models

ForeFire implements several standard fire flux and spread rate models, such as Rothermel (Andrews, 2018) and Balbi (Balbi et al., 2009), and makes it trivial to switch, extend, or add to this base with a single `.cpp` file using any existing model file as a template. Internally, data is handled as *layers* that can come from a NumPy array, be read from NetCDF, or be generated on the fly by ForeFire (e.g., slope derived from the elevation layer, fuel loaded as an index map with tabulated fuel — with standard fuel tables (Scott & Burgan, 2005) already available). Developing a Rate Of Spread wildfire model was the original purpose of this simulation code and helped to iterate versions of the Balbi Rate Of Spread formulation on case studies (Balbi et al., 2009; Santoni et al., 2011). It also served to implement various heat and chemical species flux models used for volcanic eruption (Filippi et al., 2021), plume chemistry (Strada et al., 2012), or industrial fires (Baggio et al., 2022). In addition, the code includes a generic `ANNPropagationModel` that implements a feedforward artificial neural network (ANN) and expects a pre-trained graph file.

Batch simulations with the ForeFire scripting

Custom FF language allows users to easily generate multiple scenarios, including fire-fighting strategies, model evaluation (Filippi et al., 2014), ensemble forecasts (Allaire et al., 2020), or generate a deep learning database (Allaire et al., 2021). A FF script is a set of scheduled instructions that are interpreted in real-time, advancing the simulation clock with a `step[dt=]` or a `goTo[t=]` command. Each of these commands (such as `goTo[t=42]`, `include[state.ff]`, `startFire[lonlat=(-8.1, 39.9,0)]@t=42`, `setParameter[propagationModel=Rothermel]` or `plot[parameter=speed;filename=ROS.png]`) can also be called from HTTP, C++, Fortran or Python, and constitutes the core logic of the library. Help and autocompletion are directly available in the interactive shell interpreter that also includes a batch mode. The graphical user interface is web-based through an embedded HTTP service (command `listenHTTP[host:port]`) with user-defined or default pages as shown in Figure 1.

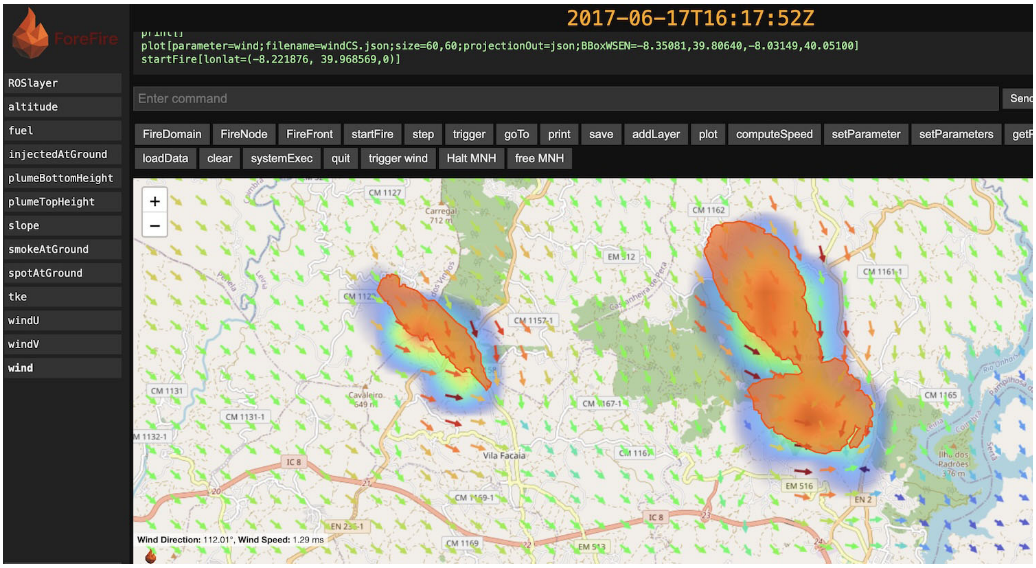

Figure 1: Default web interface with data layers on the left pane, commands displayed as buttons and displaying an atmospheric coupled simulation of a wildfire in Portugal.

By utilizing pre-compiled datasets over extensive regions, this approach supports continentwide operational forecasting services. It has been deployed to identify optimal escape routes (Kamilaris et al., 2023), integrated into the French National WildFire Decision Support System OPEN DFCI, showcased on the FireCaster demonstration platform, and also currently used in commercial simulation services AriaFire Firecaster, umgrauemeio Pantera, and Ororatech FireSpread.

Two-way coupling with the MesoNH atmospheric model

The same scripts can be executed in coupled mode with the Open-Source atmospheric model MesoNH (Lac et al., 2018) with fire propagating using surface fields (wind) from MesoNH and forcing heat and other flux fields into the atmosphere. An idealized coupled simulation can be run on a laptop at field scale (Filippi et al., 2013), but also on a supercomputer to forecast fire-induced winds of large wildfires (Filippi et al., 2018), fire-induced convection (Campos et al., 2023; Couto et al., 2024), or even to estimate wildfire spotting (Alonso-Pinar et al., 2025).

Coupled simulations generate gigabytes of 3D data that can be converted to VTK/VTU files using Python helper scripts to visualize in the open-source tool ParaView, as shown in Figure 2.

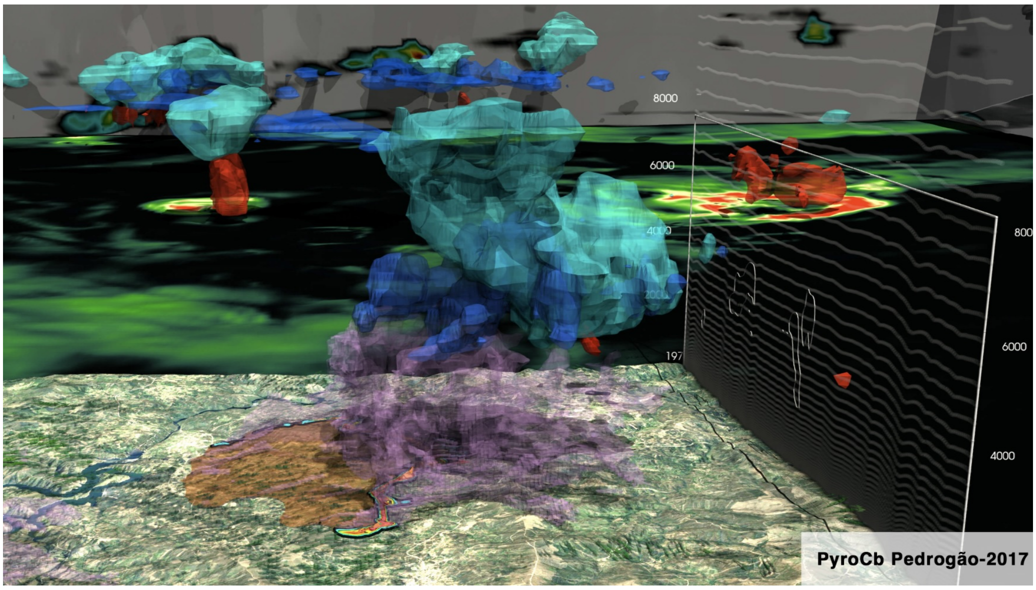

Figure 2: Coupled simulation of the Pedrogao Grande wildfire (Couto et al., 2024) (ParaView rendering). On the ground, the burned area is in orange, while among atmospheric variables, downbursts are highlighted in red and pyro-cumulonimbus clouds in blue.

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