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

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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 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), can load, save and export data in NetCDF, GeoJson, KML, PNG and JPG, and includes a local HTTP service with 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 and yet unable to provide large 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 a large amount of 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), are able to 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 are ElmFire (Lautenberger, 2013) or Cell2Fire (Pais et al., 2021) that are tied to a single spread models and do not include scripting language, or deep learning based (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 100Ha per second on a single CPU). It is inteded 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) or Balbi (Balbi et al., 2009), but also makes it trivial to switch, extend or add to this base with a single `.cpp` using any existing model file as a template. Internally data is handled as *layers* that can come from a NumPy array, read from NetCDF or generated on the fly by ForeFire (e.g. slope derived from the elevation layer, fuel loaded as index map with tabulated fuel (with part of (Scott & Burgan, 2005) fuel table 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 in (Balbi et al., 2009) and (Santoni et al., 2011). It also served to implement various heat and chemical species flux models used for volcanic eruption in (Filippi et al., 2021), plume chemistry (Strada et al., 2012) or industrial fires in (Baggio et al., 2022). In addition, the code includes a generic `ANNPropagationModel`, which implements a feedforward artificial neural network (ANN) that 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 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.

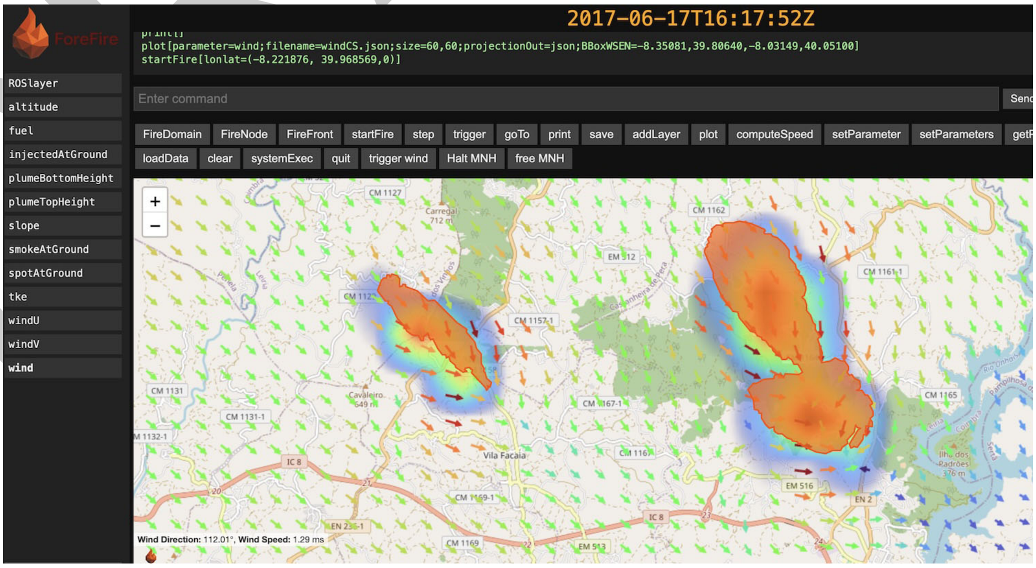

Figure 1: Default web interface with data layers on the left pane, commands displayed as buttons and displaying an atmospheric coupled simulation of a wildfire in Portugal.

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 (Couto et al., 2024),(Campos et al., 2023) 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.

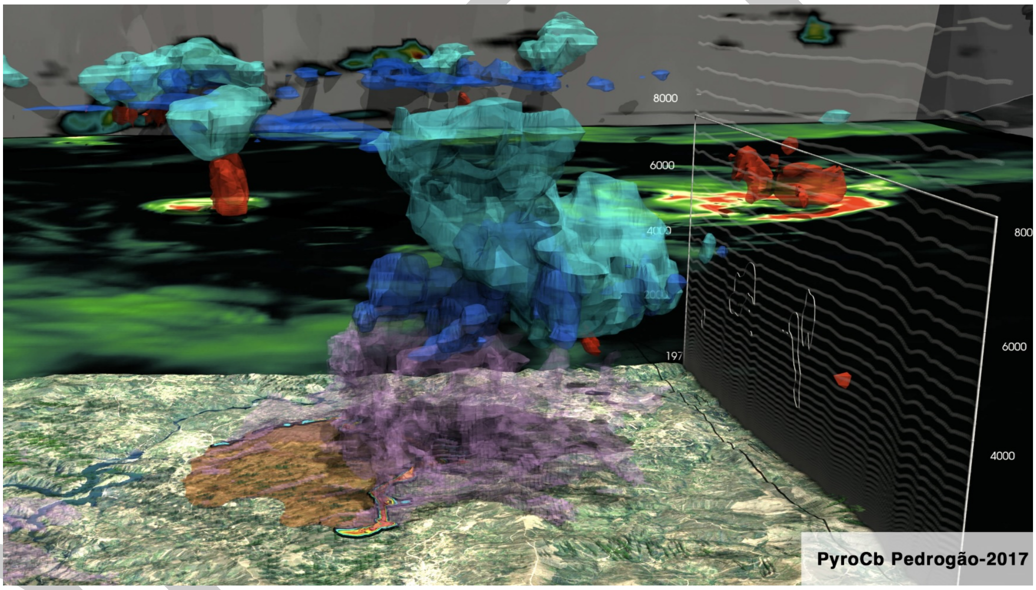

Figure 2: Coupled simulation of the Pedrogao Grande wildfire (Couto et al., 2024) (Paraview). On the ground, the burned area is in orange, while among atmospheric variables, downbursts are highlighted in red and pyro-cumulonimbus clouds in blue.

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