From Research to Operational Tool:

PROPAGATOR as an Open-Source Cellular Automata Wildfire Simulator

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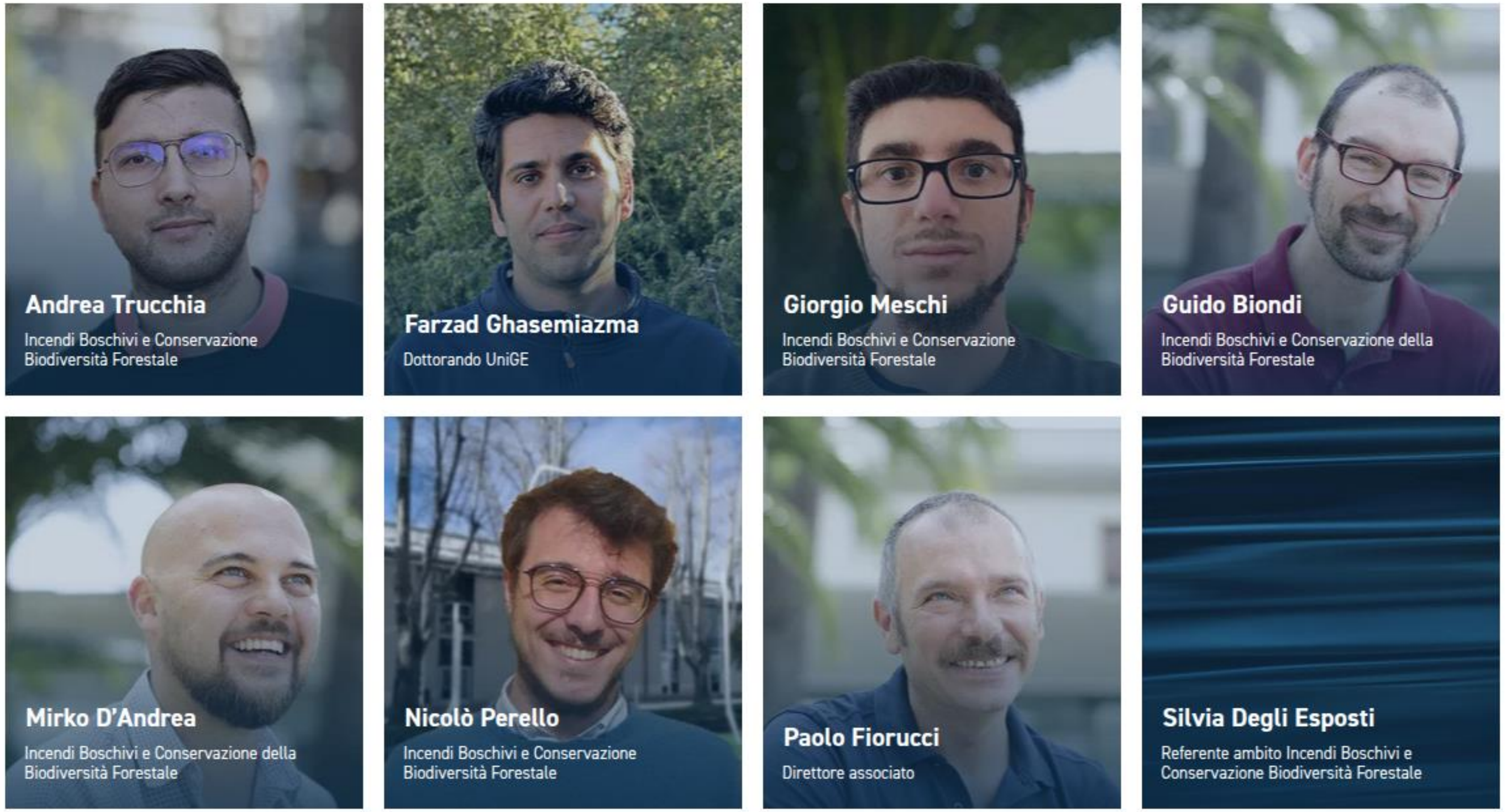
The Fire Team
@cimafoundation



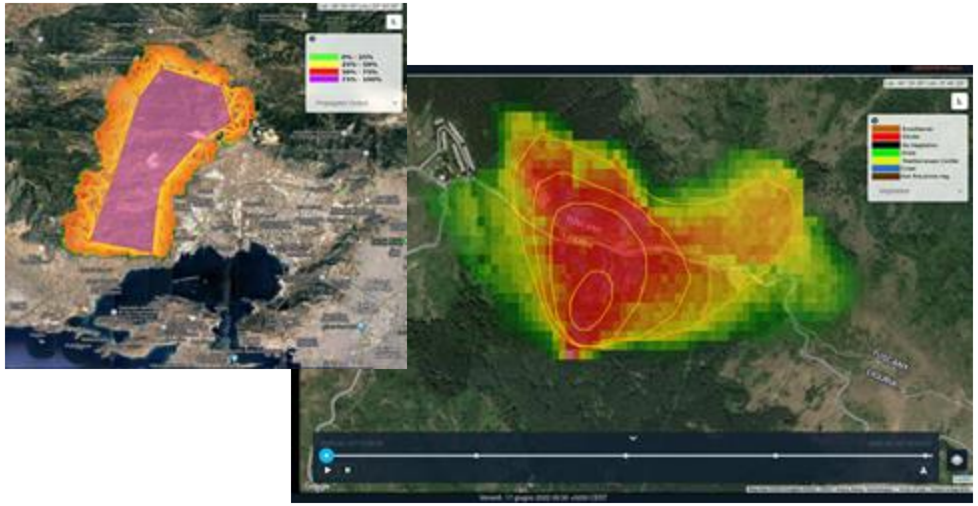
PROPAGATOR is a fast wildfire propagation model. It has been developed in 2008 under request of the Italian Civil Protection Department.

Main objective: to rapidly develop scenarios for the Disaster Risk Management (emergency response) in Civil Protection context

A Burning Tale

2008 **1st release**
no temporal dynamics

2011 **2nd release**
time-dependent maps



2014 **3rd release**
Python port

2019 **4th release**
Dynamic wind conditions and fuel moisture

2020

Open Access | Article

PROPAGATOR: An Operational Cellular-Automata Based Wildfire Simulator

by Andrea Trucchia [1,*], Mirko D'Andrea [1], Francesco Baghino [1], Paolo Fiorucci [1], Luca Ferraris [1,2], Dario Negro [3], Andrea Gollini [3] and Massimiliano Severino [4]

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Fire **2020**, *3*(3), 26; **https://doi.org/10.3390/fire3030026**

Submission received: 24 April 2020 / Revised: 19 June 2020 / Accepted: 23 June 2020 / Published: 6 July 2020

2021 **5th release**
firefighting actions, RoS and fire-line intensity maps, spotting

2024

Chapter 3

Experiences and Lessons Learnt in Wildfire Management with PROPAGATOR, an Operational Cellular-Automata-Based Wildfire Simulator

Andrea Trucchia, Mirko D'Andrea, Francesco Baghino, Nicolò Perell

Book Editor(s):Daniel Sempere-Torres, Anastasios Karakostas, Claud

First published: 02 February 2024 | https://doi.org/10.1002/97811

Agricultural and Forest Meteorology
Volume 350, 1 May 2024, 109989

Fire-spotting modelling in operational wildfire simulators based on Cellular Automata: A comparison study

Marcos López-De-Castro [a,1], Andrea Trucchia [b], Umberto Morra di Cella [b], Paolo Fiorucci [b], Antonio Cardillo [c], Gianni Pagnini [a,d]

Original research | Open access | Published: 22 January 2024

Cellular automata-based simulators for the design of prescribed fire plans: the case study of Liguria, Italy

Nicolò Perello, Andrea Trucchia, Francesco Baghino, Bushra Sanira Asif, Lola Palmieri, Nicol Paolo Fiorucci

Fire Ecology **20**, Article number: 7 (2024) | Cite this article

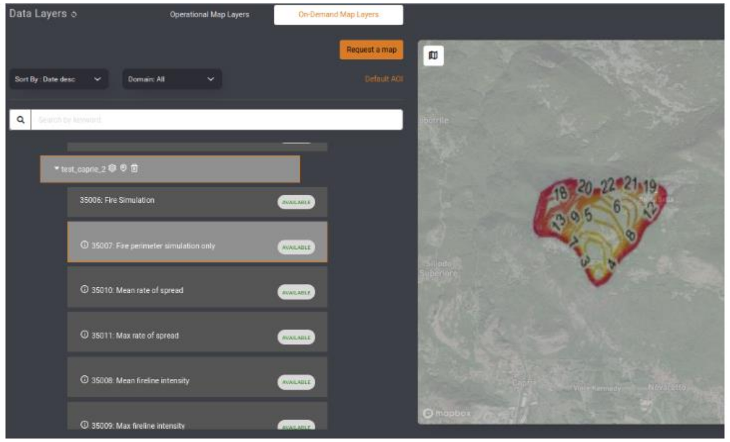
2025

6th release
Open-source on GitHub

...and beyond!

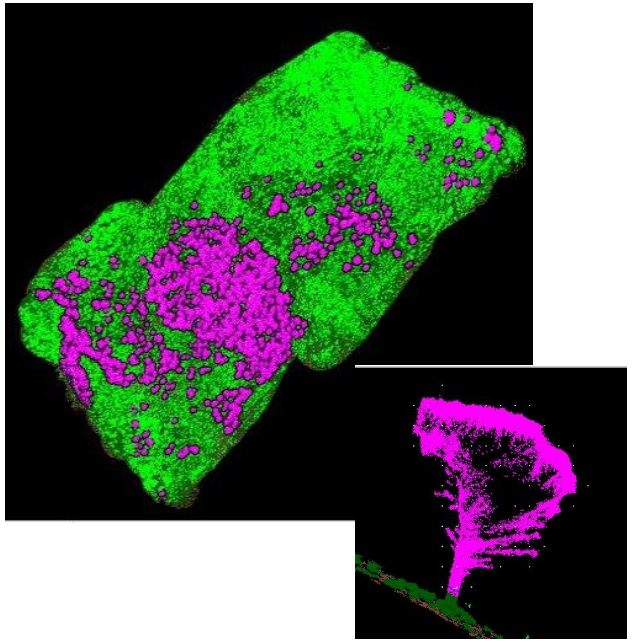
PROPAGATOR Inside the Projects

SAFERS



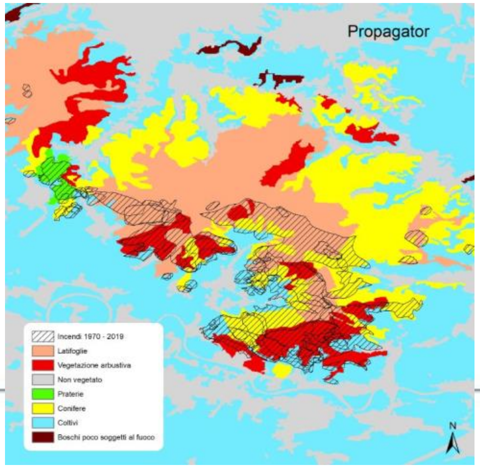
Interreg
MARITTIMO-IT FR-MARITIME
MED-Star

Return

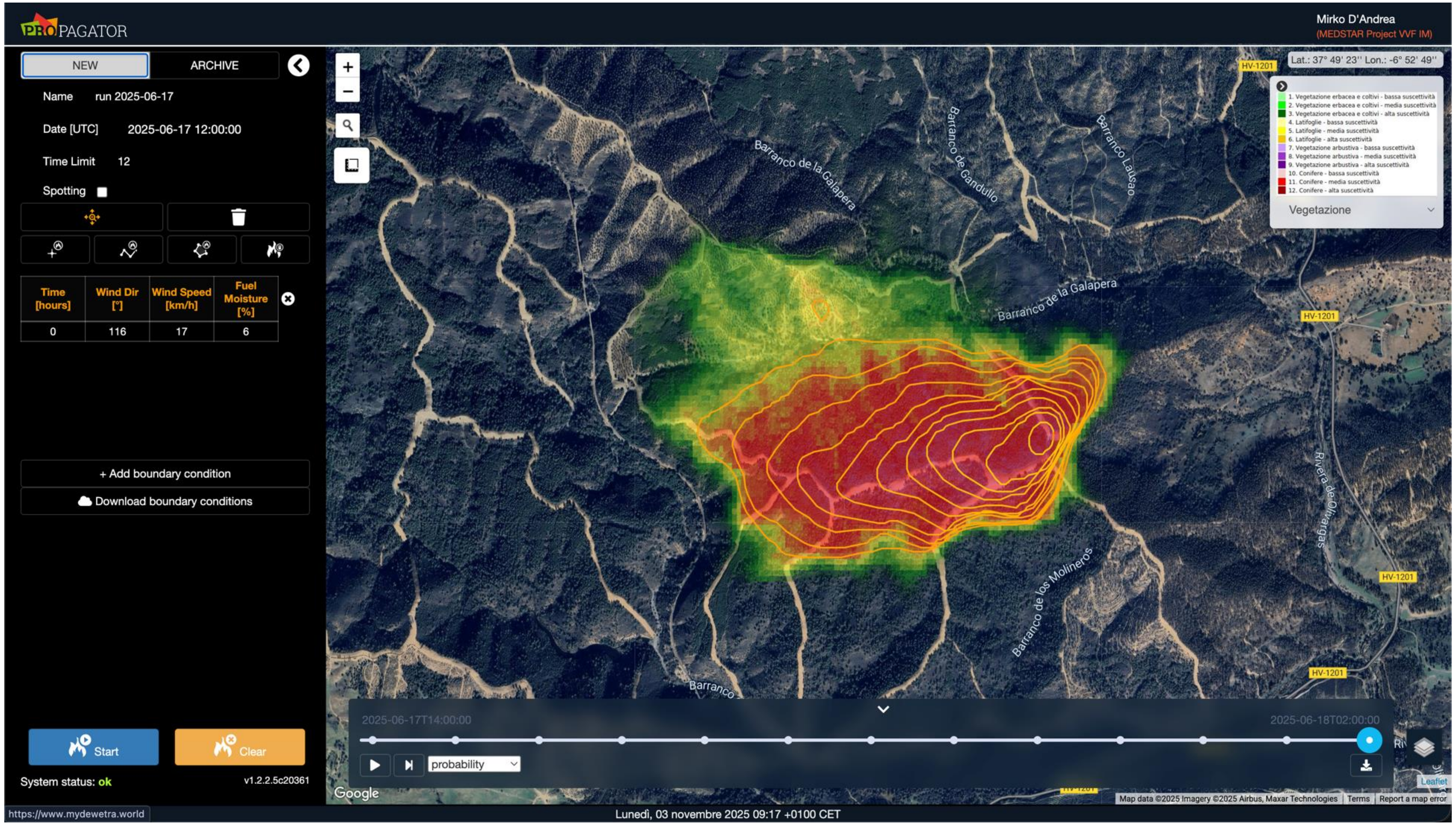


ANYWHERE

NATIONAL BIODIVERSITY FUTURE CENTER



MyDewetra



Try Me!

https://www.mydewetra.world/apps/propagator/

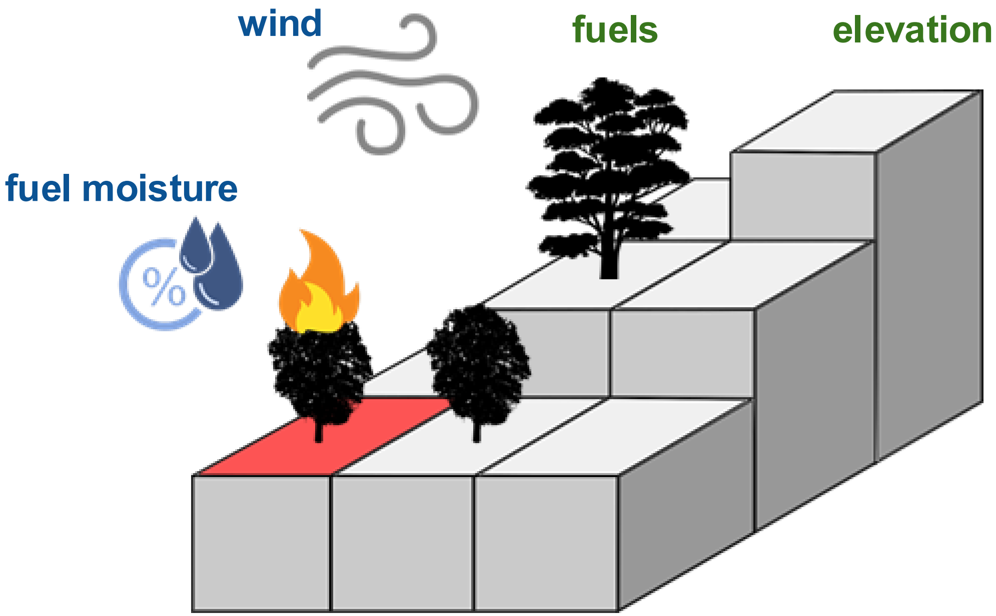
user: **cargese2025**

password: **dew4cargese**

Diving into the model

Input

Output

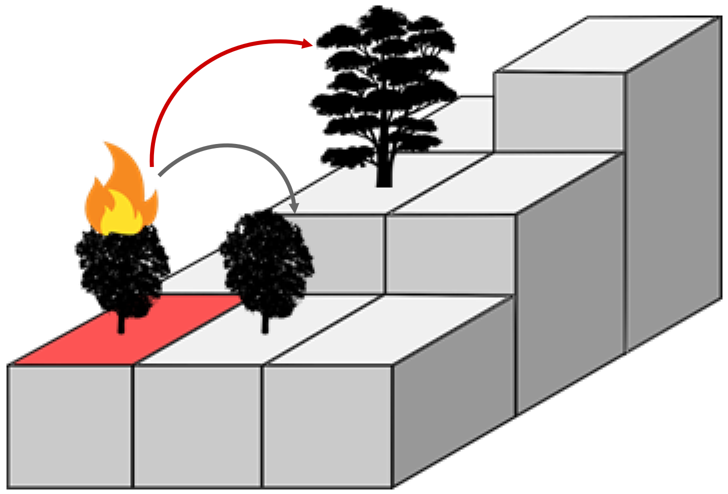


Stochastic Cellular Automata

STATIC INPUT*

DYNAMIC INPUT

*spatial resolution: 20m



Propagation probability

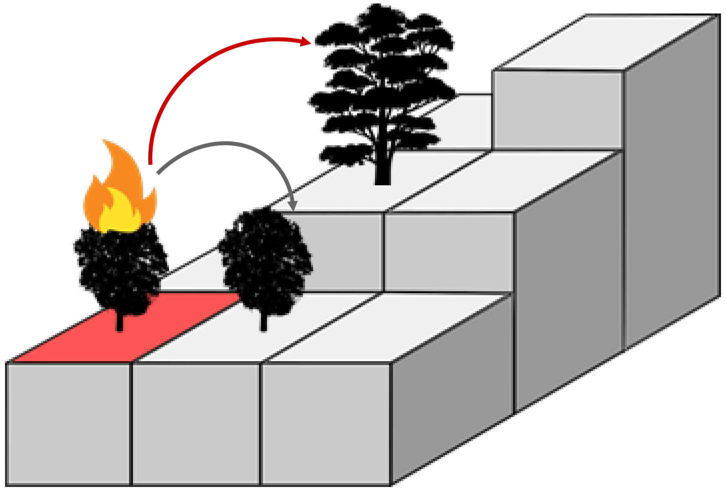
$$p_{ij} = (1 - (1 - \boxed{p_n})^{\alpha_{wh}})\, e_m$$

- Fuel
- Wind-topography
- Fuel moisture

Transition Matrix		**Burning cell *j***					
		Broadleaves	Shrubs	Grassland	Conifers	Agro-forestry	Not-fire prone forest
To be burnt *i*	B.	0.3	0.375	0.25	0.275	0.25	0.25
	S.	0.375	0.375	0.35	0.4	0.3	0.375
	G.	0.45	0.475	0.475	0.475	0.375	0.475
	C.	0.225	0.325	0.25	0.35	0.2	0.35
	A.	0.25	0.25	0.3	0.475	0.35	0.25
	N.	0.075	0.1	0.075	0.275	0.075	0.075

Input

Output



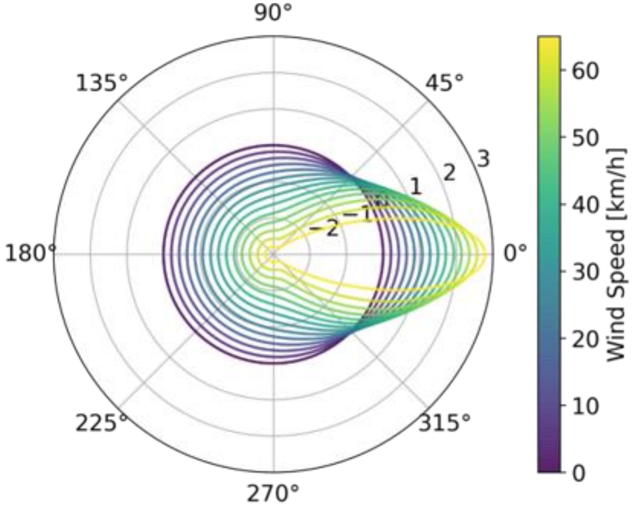
Propagation probability

$$p_{ij} = (1-(1-p_n)^{\boxed{\alpha_{wh}}})\, e_m$$

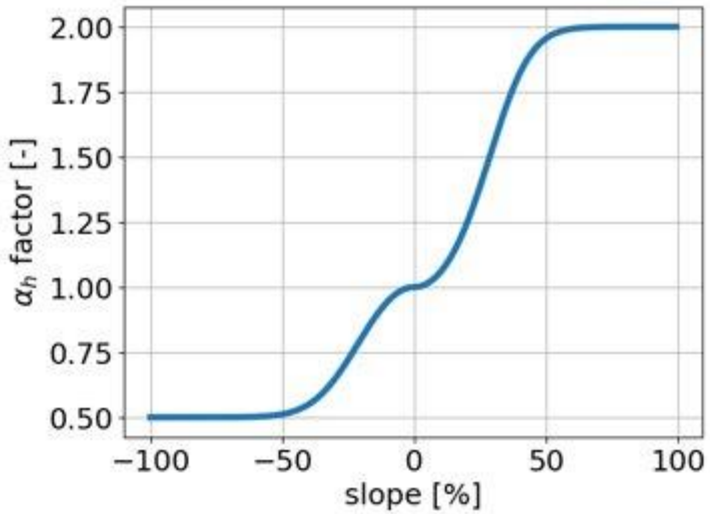
- Fuel
- Wind-topography
- Fuel moisture

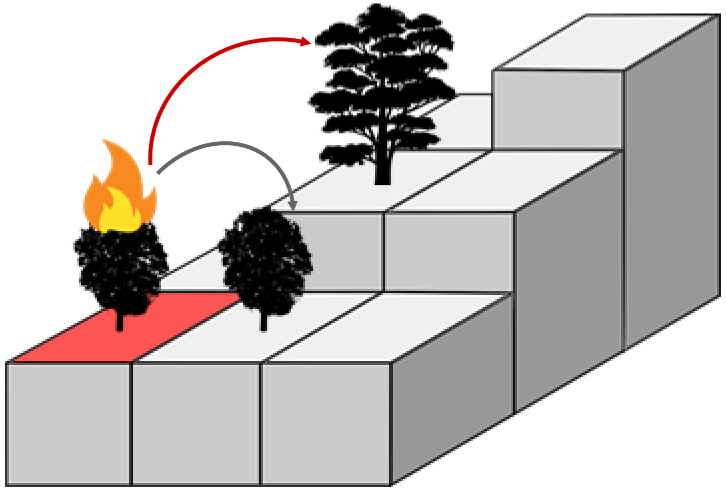
$$\alpha_{wh} = \alpha_w \alpha_h$$

Wind effect



Slope effect

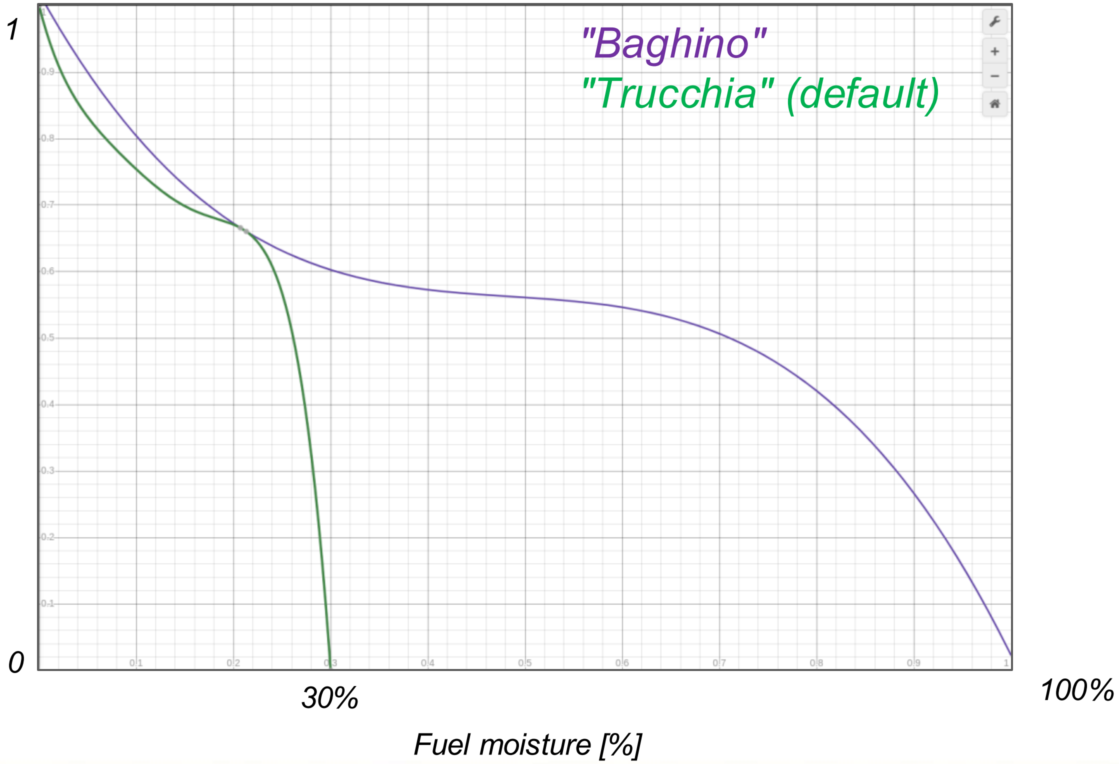


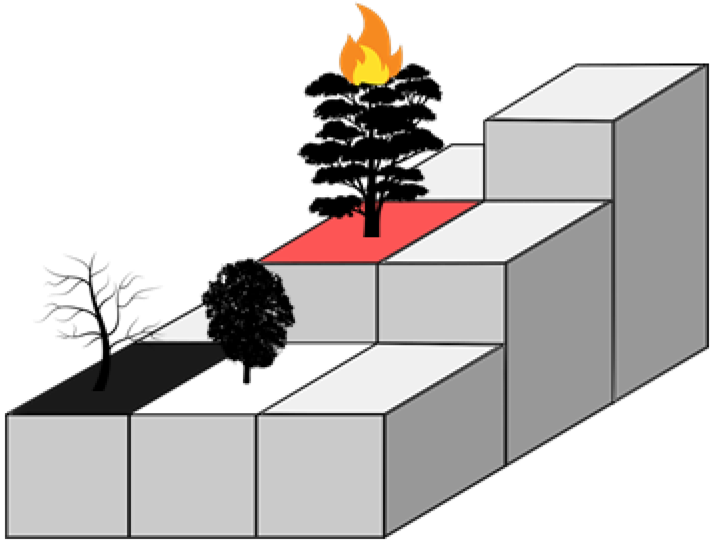


Propagation probability

$$p_{ij} = (1 - (1 - p_n)^{\alpha_{wh}})\boxed{e_m}$$

- Fuel
- Wind-topography
- Fuel moisture





Rate of Spread

$$v_{prop} = v_n \boxed{K_w K_s f_m}$$

Nominal rate of spread depending on fuel type

"Rothermel"

...you know it...

"Wang" (default)

Wind effect	$K_w = \exp(0.1783 w_s)$
Slope effect	$K_s = \exp\left(3.533 (\tan s)^{1.2}\right)$
Fuel moisture effect	$f_m = \exp(-0.014 FFMC)$

Sun et al. 2013

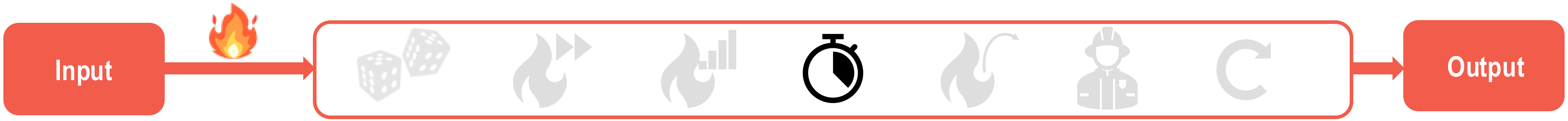
Fireline Intensity

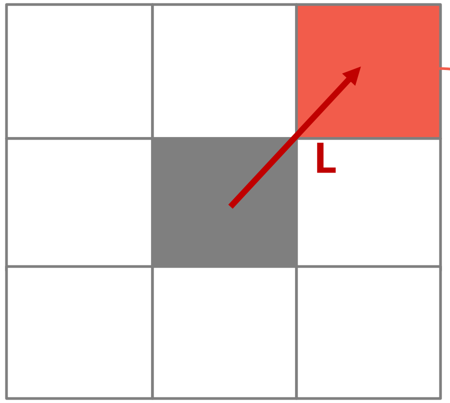
$$FI = v_{prop} \left(\underbrace{\boxed{d_0\, lhv_0}}_{\text{Dead fuel}} + \underbrace{\boxed{d_1\, lhv_1}}_{\text{Live fuel}} \right)$$

$$lhv_i = hhv \left(1 - \frac{m_i}{100}\right) - Q \left(\frac{m_i}{100}\right)$$

Lower heating value

M_i: moisture content

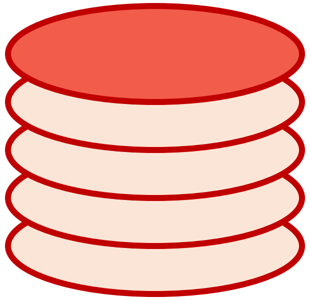




Scheduling time

$$\Delta t = \frac{L}{v_{prop}}$$

Scheduler



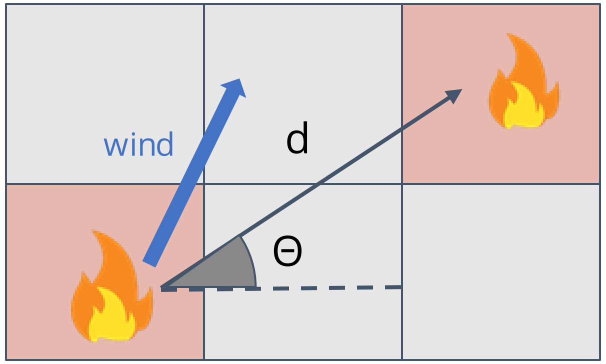
Event-based approach

- Burning cells
- Ignitions
- Wind changes
- Fuel moisture changes
- External actions

Spread dynamics

Status changes

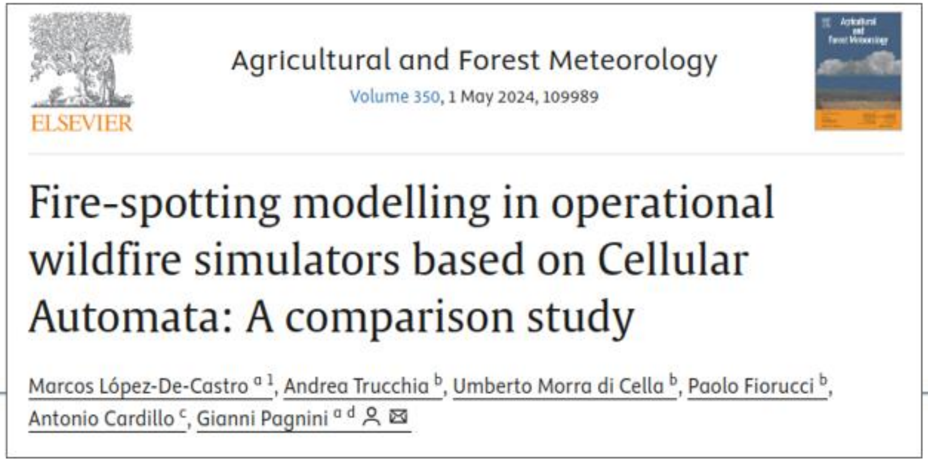
Spotting module



"Alexandridis" (default)

Triggered by burning conifers

Number of firebrands	$N \sim Poisson(2)$
Angle and distance of landing	$\theta \sim Uniform(0, 2\pi)$ $d = r \exp\left(0.191 w_s \left(\cos\left(w_d - \theta\right) - 1\right)\right)$
Ignition probability	$P_i = 0.6(1 + 0.4)$ *Conifers correction*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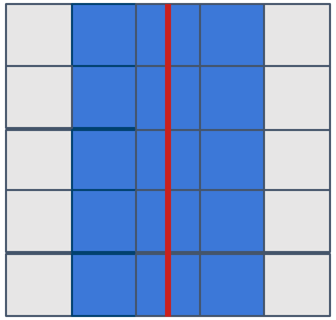
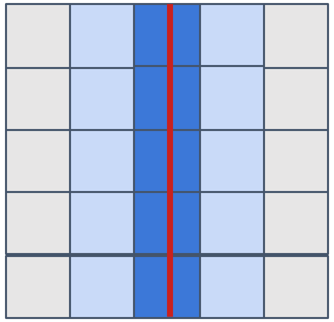
Inside the PROPAGATOR core, two different categories of actions can be implemented:

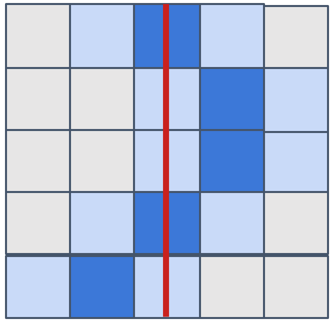
Moisture actions



waterline actions

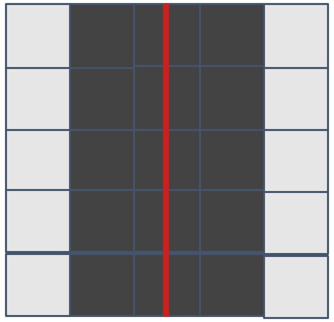


Canadair



Helicopters

Fuel actions



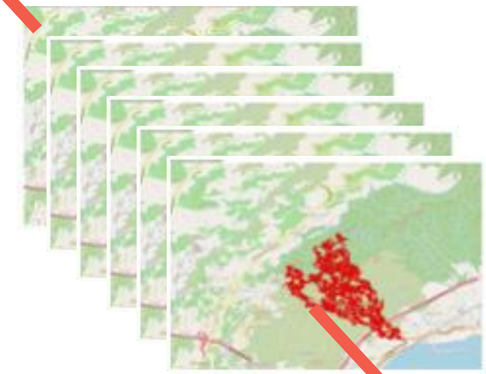
Heavy actions

We implemented these *firefighting actions* thanks to the interaction with firefighters (*MEDSTAR project*)

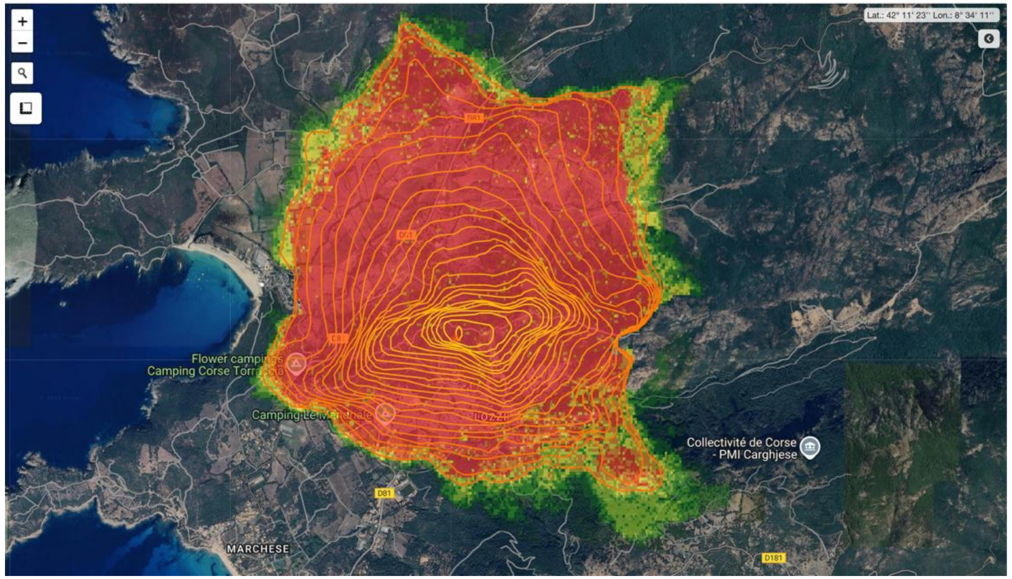
Input

Output

Simulation enemble



Statistical analysis

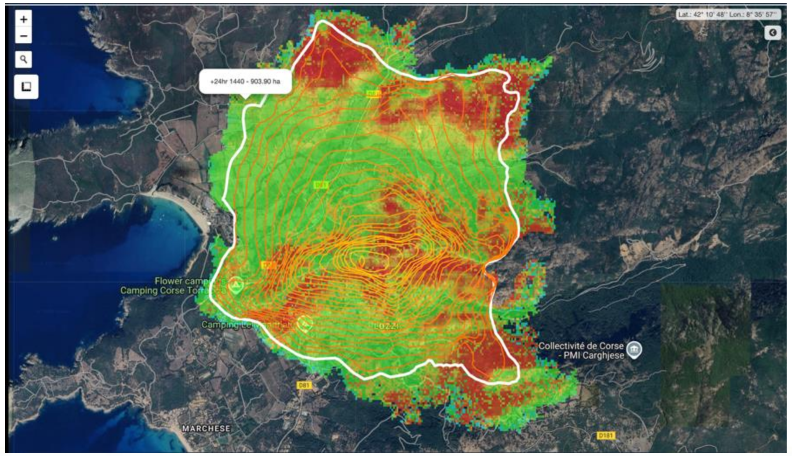


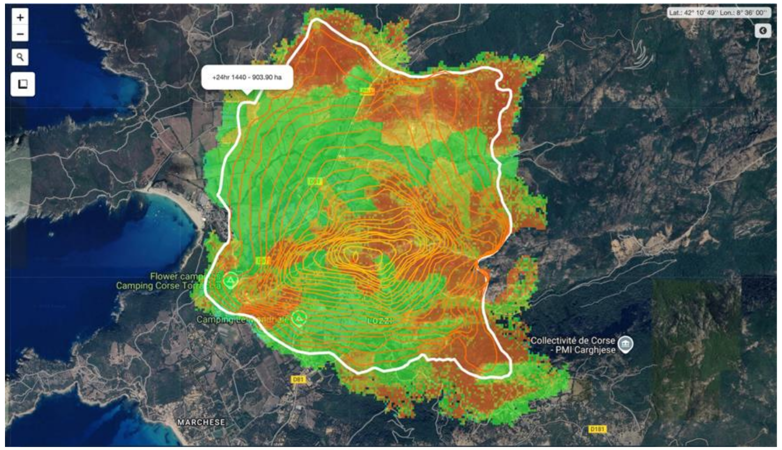
Fire probability

+

Isochrones at different probability thresholds

Mean/Max Rate of Spread and Fireline Intensity





Refactoring

Why?

2008

2014

Numpy-based

2024

Spaghetti-code

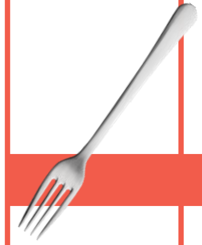
2025

Untie the knots

Many projects, 1 PhD and 2 master thesis later...

Refactoring

- Only CLI
- Monolithic code mess
- Numpy index-based vectorization



- Reusable Pip installable module
- Modular architecture (core / IO / CLI)
- Simpler numba *for* loops
- Formalized fuel systems
- Typing, Documentation, Testing

Code Architecture

Command Line Interface

Simple & configurable model execution

I/O

Input and output handling for geographical data

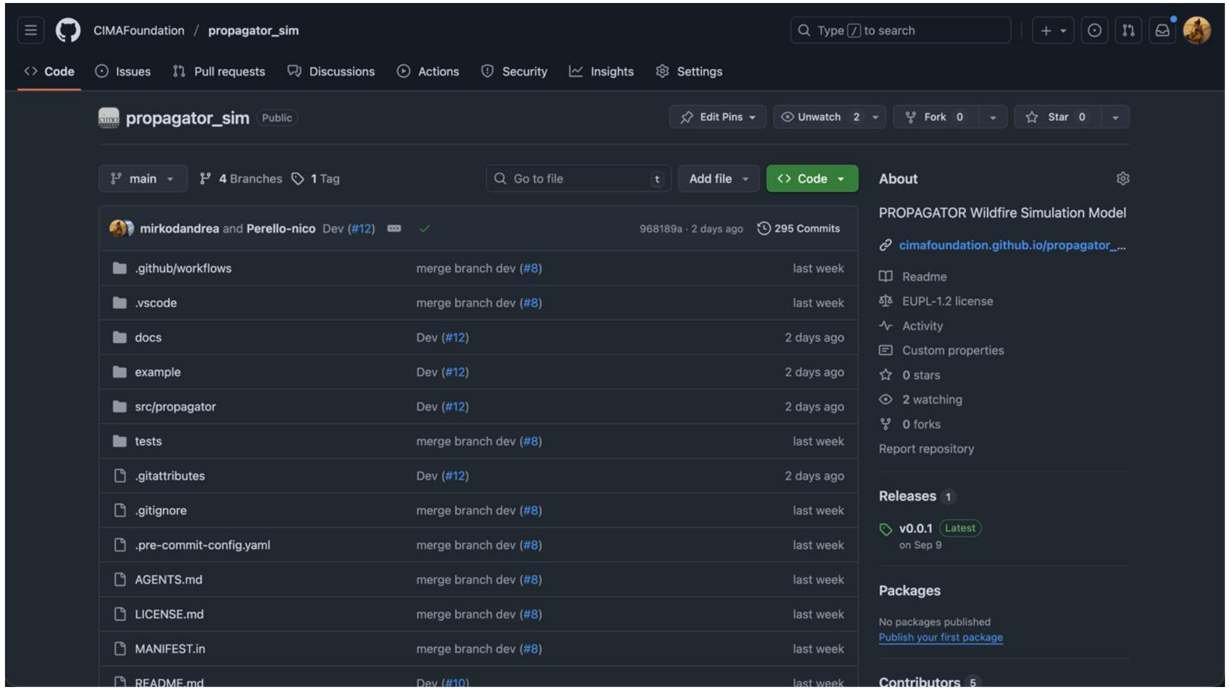
Shapely rasterio GeoPandas

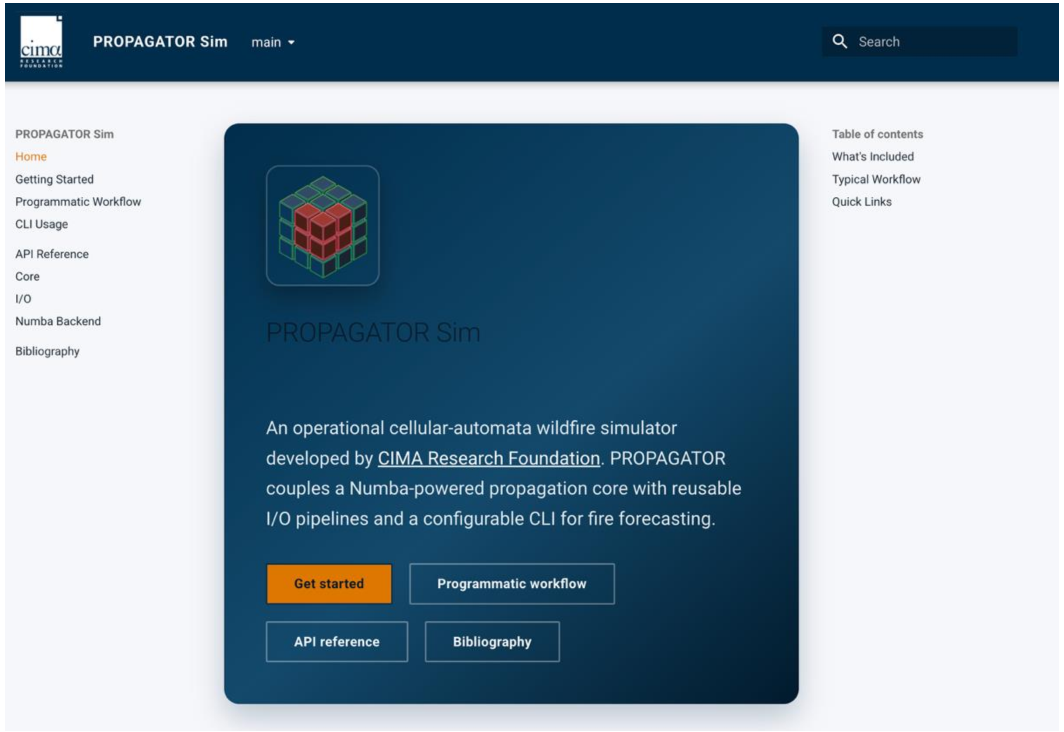
CORE

Standalone Numerical computation engine

Numba NumPy

Open Source & Documentation





Repo:
https://github.com/CIMAFoundation/propagator_sim

Docs:
https://cimafoundation.github.io/propagator_sim/main/

CLI: Minimal usage example

```
uv run propagator \
  --config example/config.json \
  --dem example/dem.tif \
  --fuel example/fuel.tif \
  --output results/run-2025-02-19
```

Static data (.tiff) > NEED TO BE ALIGNED!

Configuration file (.json)

```json
{
    "ignitions": [
        "POINT: [52.51751;-6.82354]"
    ],
    "realizations": 10,
    "time_limit": 144000,
    "do_spotting": true,
    "time_resolution": 1800,
    "boundary_conditions": [
        {
            "time": 0,
            "w_dir": 0,
            "w_speed": 30,
            "moisture": 0,
            "heavy_action": [
                "LINE:[52.556601726325894 52.546600601885977];[-6.89301682922232 -6.851764124705658]"
            ]
        },
        {
            "time": 6000,
            "waterline_action": [
                "LINE:[52.554699791027026 52.543359795262248];[-6.934363502444168 -6.947919359450347]"
            ]
        }
    ]
}
```

NOTE: time in seconds

CLI: Minimal usage example

```
uv run propagator --help
```

Flag	Type / Default	Description
`--config PATH`	required	JSON configuration file parsed into `PropagatorConfigurationLegacy`.
`--fuel-config PATH`	optional	YAML file defining a custom fuel system (`fuels` mapping).
`--mode {tiles,geotiff}`	`tiles`	Select how static rasters are loaded (see above).
`--dem PATH`	required in geotiff mode	DEM GeoTIFF when running in geotiff mode.
`--fuel PATH`	required in geotiff mode	Fuel/vegetation GeoTIFF when running in geotiff mode.
`--tilespath PATH`	required in tiles mode	Base directory containing tiled rasters.
`--tileset NAME`	optional	Tileset to use within `tilespath` (defaults to `default`).
`--output PATH`	required	Destination directory; created if missing. Stores GeoTIFF, GeoJSON, and JSON outputs.
`--isochrones FLOAT …`	`0.5 0.75 0.9`	Probability thresholds for GeoJSON isochrone export. Repeat the flag to set multiple values.
`--record`	flag, default off	When enabled, saves a Rich console log in the output directory.
`--ignore-out-of-bounds`	flag, default off	Continue the simulation when the fire reaches the DEM boundary.
`--verbose`	flag, default off	Print status tables, boundary conditions, and timing information.

Core: Minimal API usage example

```
simulator = Propagator(
    dem=dem,
    veg=veg,
    realizations=10
)

boundary_condition = BoundaryConditions(
    time=0,
    ignition_mask=ignition_array,
    wind_speed=np.ones(dem.shape) * 40,  # km/h
    wind_dir=np.ones(dem.shape) * 90,  # degrees from north
    moisture=np.ones(dem.shape) * 0,  # percentage
)
simulator.set_boundary_conditions(boundary_condition)


while simulator.next_time():
    simulator.step()


output = simulator.get_output()
fire_prob = output.fire_probability
ros_mean = output.ros_mean
```

Create the
simulator object

Core: Minimal API usage example

```
simulator = Propagator(
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    veg=veg,
    realizations=10
)

boundary_condition = BoundaryConditions(
    time=0,
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    moisture=np.ones(dem.shape) * 0,  # percentage
)
simulator.set_boundary_conditions(boundary_condition)

while simulator.next_time():
    simulator.step()


output = simulator.get_output()
fire_prob = output.fire_probability
ros_mean = output.ros_mean
```

Add
Boundary Conditions
and ignition mask

Core: Minimal API usage example

```
simulator = Propagator(
    dem=dem,
    veg=veg,
    realizations=10
)

boundary_condition = BoundaryConditions(
    time=0,
    ignition_mask=ignition_array,
    wind_speed=np.ones(dem.shape) * 40,  # km/h
    wind_dir=np.ones(dem.shape) * 90,  # degrees from north
    moisture=np.ones(dem.shape) * 0,  # percentage
)
simulator.set_boundary_conditions(boundary_condition)


while simulator.next_time():
    simulator.step()


output = simulator.get_output()
fire_prob = output.fire_probability
ros_mean = output.ros_mean
```

Run the simulation

Core: Minimal API usage example

```
simulator = Propagator(
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    veg=veg,
    realizations=10
)

boundary_condition = BoundaryConditions(
    time=0,
    ignition_mask=ignition_array,
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    moisture=np.ones(dem.shape) * 0,  # percentage
)
simulator.set_boundary_conditions(boundary_condition)


while simulator.next_time():
    simulator.step()


output = simulator.get_output()
fire_prob = output.fire_probability
ros_mean = output.ros_mean
```

Extract relevant output

Coding Examples

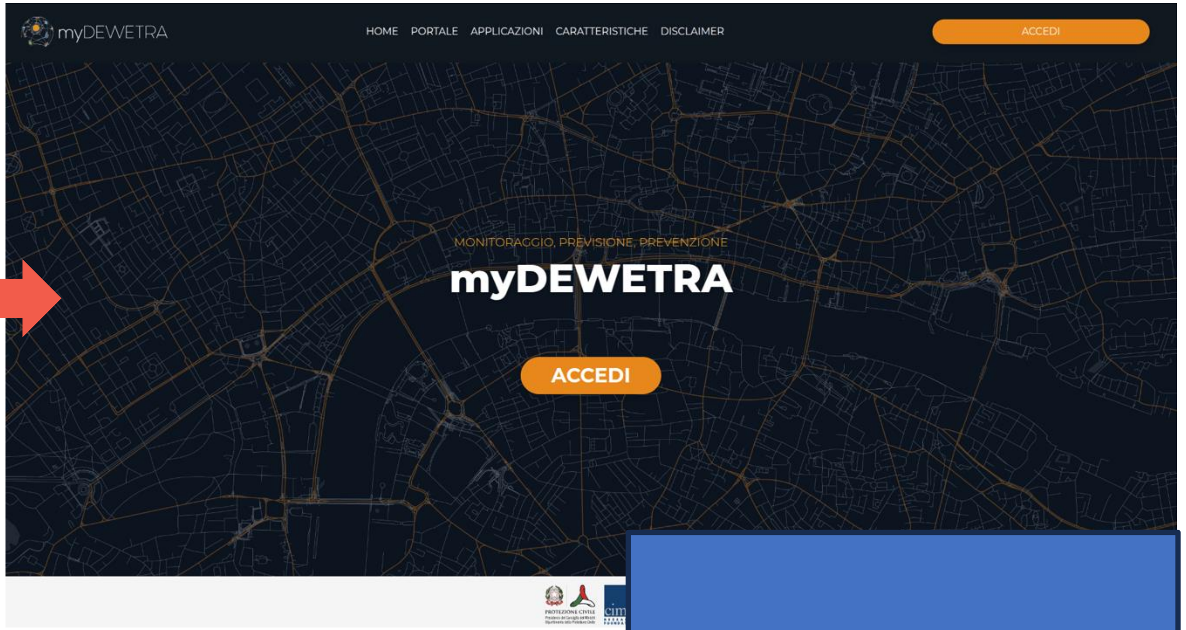
https://github.com/CIMAFoundation/cargese2025

What's Next?

New web GUI & running infrastructure

MyDEWETRA 2

MyDEWETRA 3

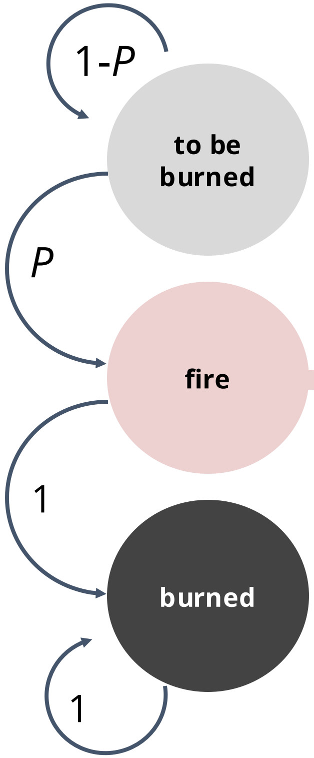


?

On-premise compute
Monolithic backend infrastructure

Cloud-native
Micro-services infrastructure

PROPAGATOR 2.5D



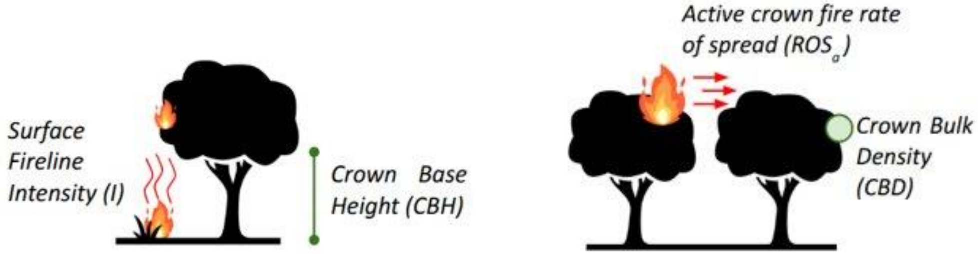
Crown Fire Module

Crown Fire Initiation? → yes → $RoS_a > RoS_c$?

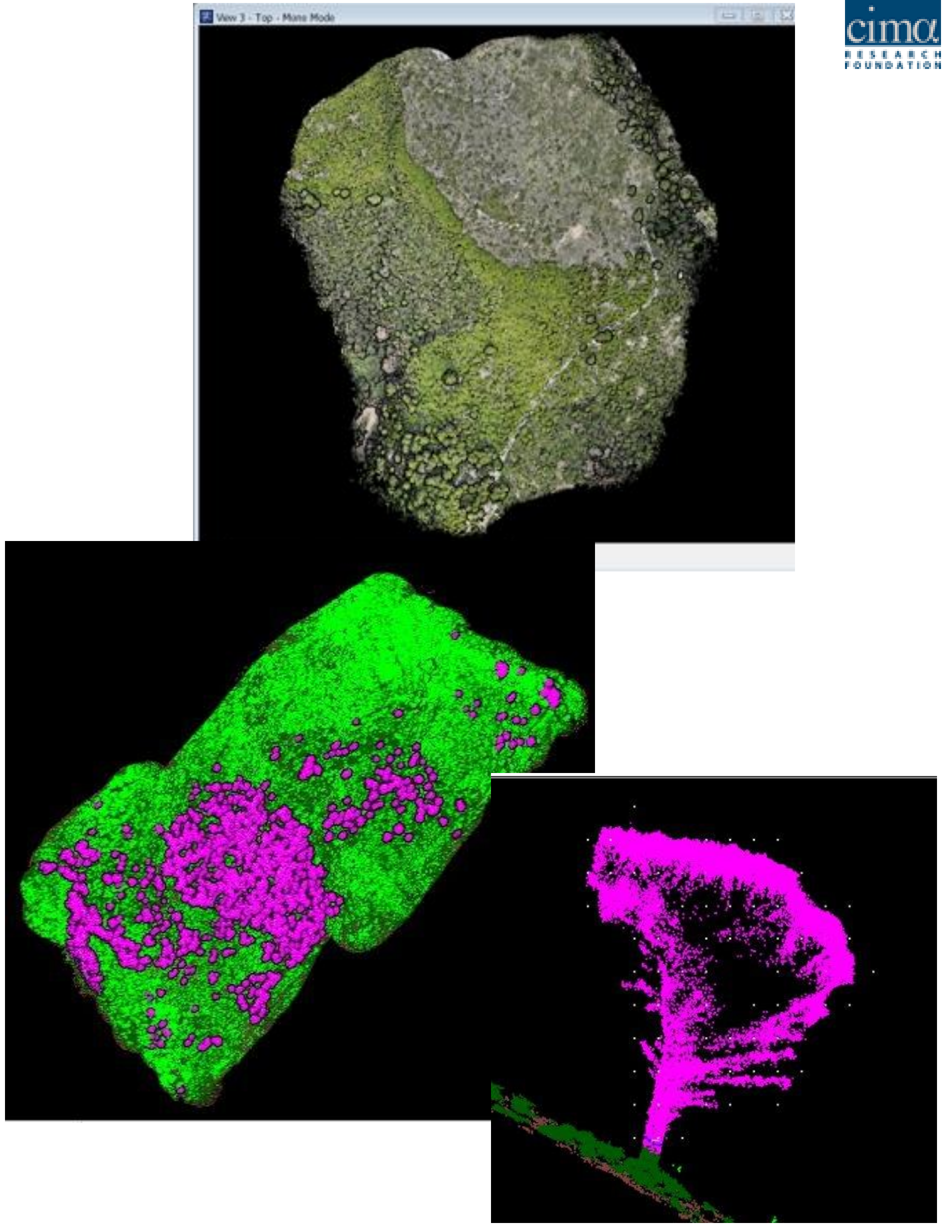
yes → **Active crown fire**

- Increased propagation probability
- Increased rate of spread

no → Passive crown fire

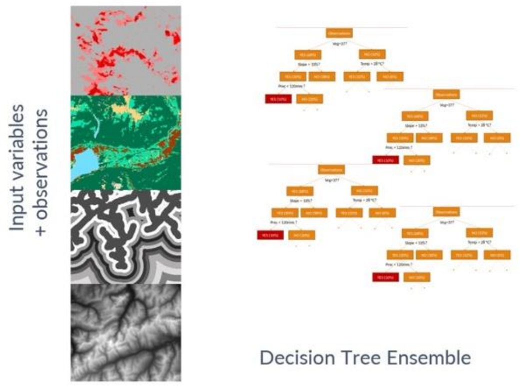


Integration of LiDAR data



ML-Informed Fuel Map

Machine Learning (*Random Forest*)



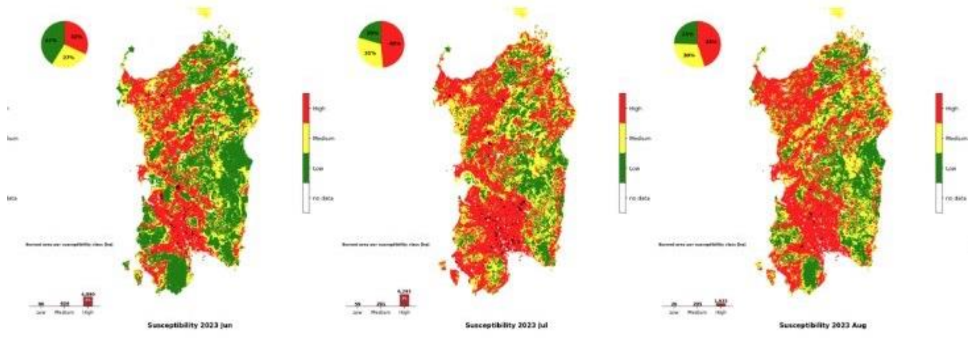
Static Susceptibility Maps

Predisposing Factors
Elevation (m), Slope (°), Aspect (°)
Vegetation types, neighbouring vegetation
SPI 1-m / SPI 3-m / SPI 6-m
SPEI 1-m / SPEI 3-m / SPEI 6-m

Observation
Historical Fires

Dynamic Susceptibility Maps

Monthly Susceptibility Maps



Combination with vegetation types:

- Grasslands
- Broadleaves
- Shrubs
- Conifers

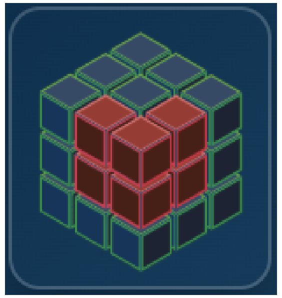
Fuel Maps

Suscettività / Tipo di combustibile	1 Prati e colture	2 Foresta poco infiammabile	3 Arbusteti	4 Foresta altamente infiammabile
1 Bassa	1 Incendi superficiali di bassa intensità con bassa probabilità	4 Incendi boschivi di media intensità con bassa probabilità (foreste di latifoglie)	7 Incendi di arbusti ad alta intensità con bassa probabilità	10 Incendi boschivi di alta intensità con bassa probabilità (foreste di conifere)
2 Media	2 Incendi superficiali di bassa intensità con probabilità media	5 Incendi boschivi di media intensità con probabilità media (foreste di latifoglie)	8 Incendi di arbusti ad alta intensità con probabilità media	11 Incendi boschivi di alta intensità con probabilità media (foreste di conifere)
3 Alta	3 Incendi superficiali di bassa intensità con alta probabilità	6 Incendi boschivi di media intensità con alta probabilità (foreste di latifoglie)	9 Incendi di arbusti ad alta intensità con alta probabilità	12 Incendi boschivi di alta intensità con alta probabilità (foreste di conifere)

Take-home Message

From this....

Operational needs



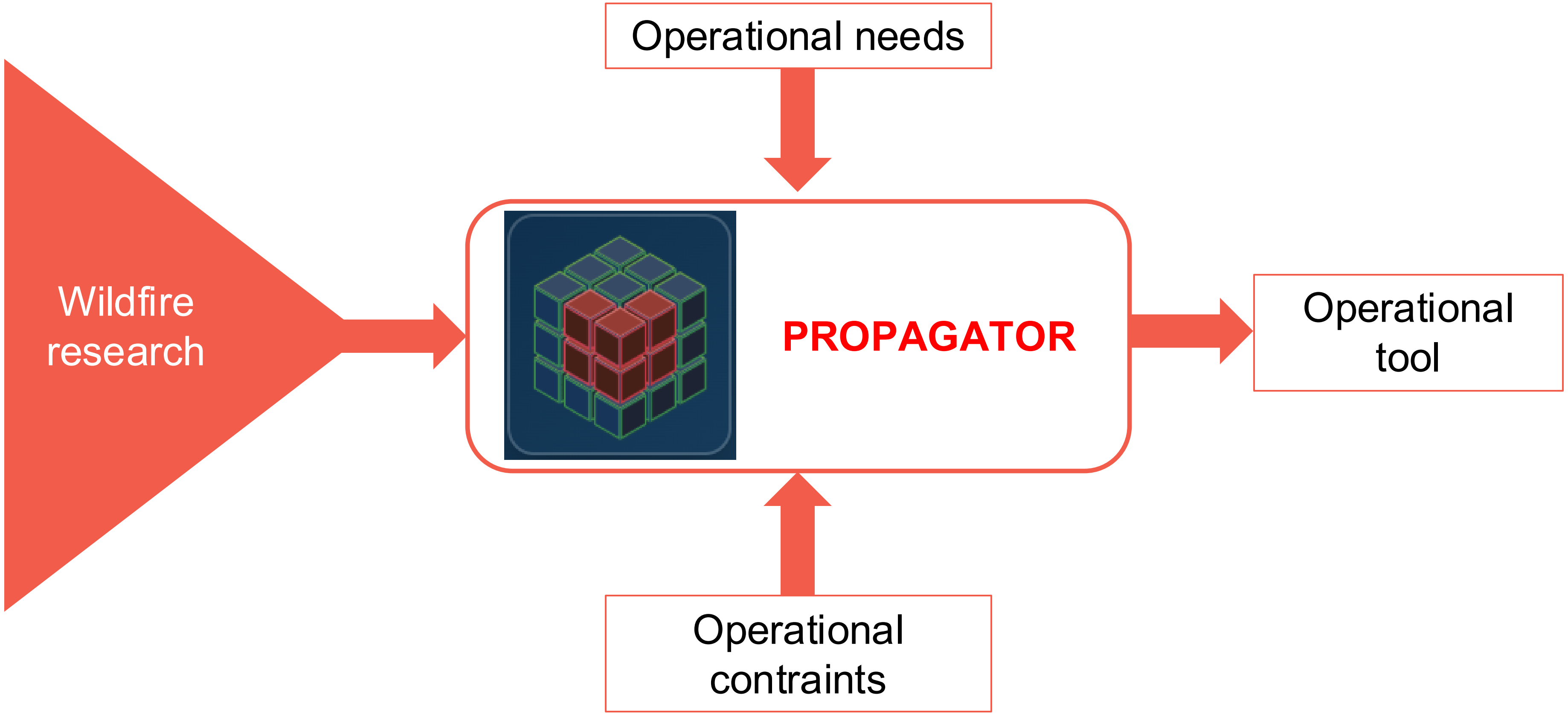
PROPAGATOR

Operational tool

Operational contraints

Take-home Message

...to this



New spotting models

Smoke dynamics

Fire-wind interactions

Convection processes

Change in spatial resolution

Merging fires effect

GPUs

I WANT YOU
for PROPAGATOR

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Thank you!

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