Supplementary Materials: PROPAGATOR: an operational cellular-automata based wildfire simulator

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1. Response analysis of PROPAGATOR

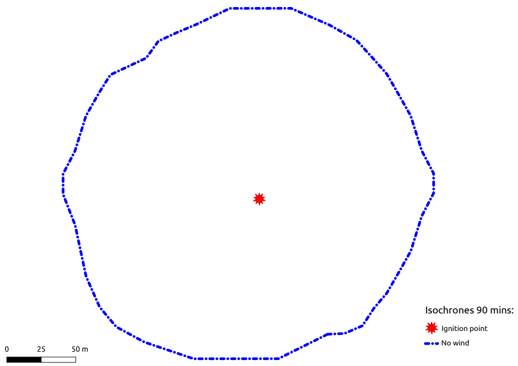
These Supplementary Materials concern the response analysis of the PROPAGATOR model to the main factors affecting the fire propagation: fuel type and distribution, mean wind direction and magnitude, orography and necromass moisture content.

While a thorough Global Sensitivity Analysis (see, e.g., [1]) is out of the scope of the present work, the qualitative response of the Cellular Automata model is investigated through a series of numerical experiments.

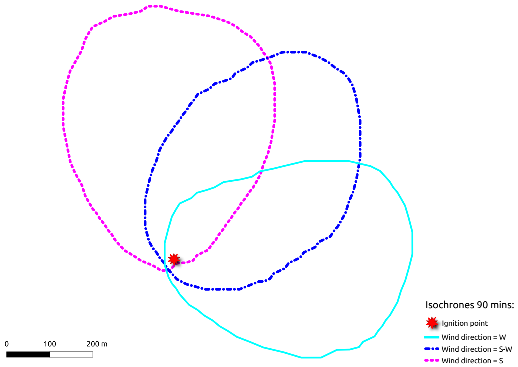
2. Response to slope, wind speed and direction

For the case of an homogeneous Mediterranean conifer fuel distribution, the 0.5 iso-contour of the probability u, output of a PROPAGATOR run is portrayed in Fig. S1, with

- the wind magnitude, $|\boldsymbol{v}| \in \{0, 30, 60\}[km/h]$
- the wind direction, $\boldsymbol{n}_w \in \{(1,0), (\sqrt{2}/2, \sqrt{2}/2), (0,1)\}$ (that is, wind from West, South-West, South)
- an uniform slope s, with its aspect oriented rightwards, from West to East ($\boldsymbol{n}_s = (1,0)$. $s \in \{0\%, 50\%\}$

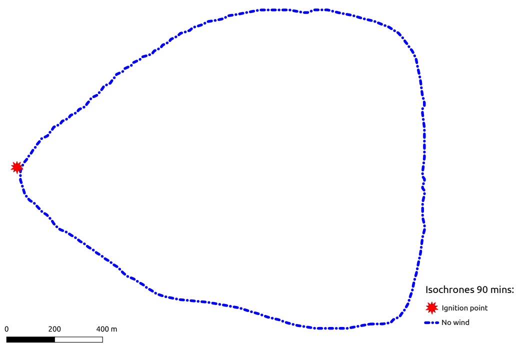


(a) Shrubs - no wind - no slope

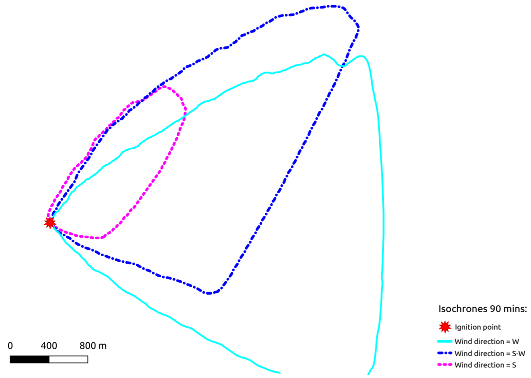


(b) Shrubs - $|v| = 30$ km/h - no slope

(c) Shrubs - $|v| = 60$ km/h - no slope



(d) Shrubs - no wind - 50% slope



(e) Shrubs - $|v| = 30$ km/h - 50% slope

Figure S1. In the first line the no-slope case is presented. Three different wind magnitudes are tested, with increasing wind magnitude from left to right. When $|v| > 0$, three different wind directions are portrayed in each figure: solid cyan lines represent wind blowing from West, dash-dotted dark blue lines represent wind blowing from South-West, and magenta ones wind blowing from South. In the second line, the simulated domain has a constant slope of 50%. Fig. d corresponds to the no-wind case, while in e $|v|$ is set to 30 km/h. Again, in Fig. e, three different wind directions are portrayed in each figure: solid cyan lines represent wind blowing from West, dash-dotted dark blue lines represent wind blowing from South-West, and magenta ones wind blowing from South. The red star represents the ignition point and the portrayed iso-contours correspond to T=90 minutes of the simulation. There are different scale bars for the different images: image (a) has a scale bar that ranges from 0 to 50 meters; the scale bars of images (a) and (c) range from 0 to 200 meters; scale bar of image (d) ranges from 0 to 400 meters, while the one of image (e) ranges from 0 to 800 meters.

3. Response to different vegetation covers

In the following numerical experiments, different vegetation covers are tested, in a homogeneous (Fig. S2) and heterogeneous (Fig. S3) domain.

Again, the 0.5 iso-contour of output probability u, output of a `PROPAGATOR` run is portrayed.

In Figure S2, the same plot of Figure S1, panel b is plotted for several spatially homogeneous vegetation classes: broadleaves, conifers, grass and shrubs, with a constant wind magnitude $|v| = 30$ km/h and no slope.

In Figure S3, for an increasing uniform wind field $\boldsymbol{v} \in \{(0,0),(30,0),(60,0)\}$ km/h, is plotted for a domain characterized by two different vegetation covers neatly separated by an horizontal line. The upper half of the domain is covered by broadleaves, while the lower half by Mediterranean conifers. The whole time duration of the process is represented, by plotting iso-chrones of 0.5 probability iso-contours from $t = 20$ min to $T_{\text{end}} = 240$ min.

4. Response to fuel moisture content

In the following numerical experiments, different fuel moisture contents $\mu \in \{0\%, 5\%, 10\%, 20\%\}$ are tested for several vegetation cover configurations, for uniform wind speed field of aligned to $\boldsymbol{v} = (60,0)$ km/h in the no-slope case.

In Figure S4, the surface plot of the whole `PROPAGATOR` output probability 90 minutes after the ignition is represented. The upper half of the domain is covered by broadleaves, and the lower half by Mediterranean conifers. From panel (a) to panel (d), the necromass moisture content is respectively equal to $0, 5, 10$ and 20%.

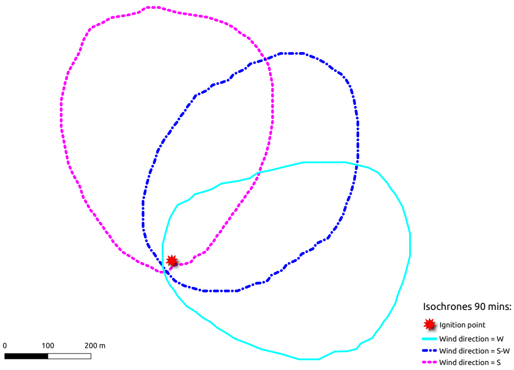
In Figure S5, the response to variation in fuel moisture content for different land covers is investigated. Again, the iso-contour corresponding to the 0.5 probability of fire arrival is plotted, 90 minutes after the ignition. Each panel corresponds to a different homogeneous vegetation cover. From panel a to panel c respectively, the vegetation class is grassland, Mediterranean conifers, and shrubs.

5. Ittiri test case: response to different wind conditions

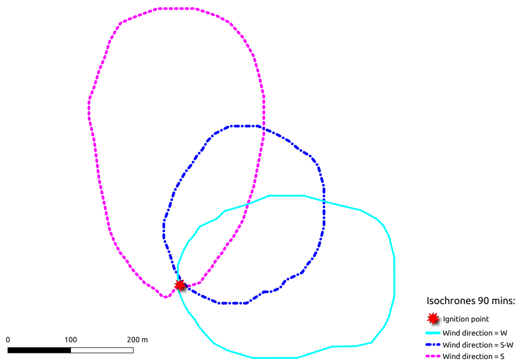
In the following numerical experiments, different wind conditions are tested for the Ittiri test case (described in the main text) to explore the sensitivity of the numerical model to variation on synoptic wind input data. In Figure S6, a constant wind field is considered. The wind magnitude is fixed to $35km/h$, while the wind direction is different for each panel. The wind direction in panels (a), (b), (c), (d) has been respectively set to 180°, 200°, 220°, 240°. In Figure S7, the time-varying wind vector provided by the official meteorological model used by the Italian Civil Protection Department for weather related events forecasting, namely COSMO I7 (now COSMO I5), is adopted. The meteorological model has been evaluated on the closest grid point to the ignition point. In panel (a), COSMO I7 data has been used for both wind speed and direction. In panel (b) the wind magnitude has been fixed to $35km/h$ while the direction is taken from the COSMO I7 data. Performance indicators (introduced in the main text of the paper) corresponding to the aforementioned Ittiri simulations are reported in Table S1.

Table S1. Performance of the simulation of the Ittiri test cases.

Wildfire	I_1 $[-]$	I_2 $[-]$	I_3 $[-]$	S_c	*Sens.*	*Spec.*
$\lvert\mathbf{v}\rvert = 35km/h, 180°$	$2.74 \cdot 10^{-3}$	$2.83 \cdot 10^{-3}$	$6.73 \cdot 10^{-1}$	0.39	0.33	0.79
$\lvert\mathbf{v}\rvert = 35km/h, 200°$	$2.29 \cdot 10^{-3}$	$2.37 \cdot 10^{-3}$	$5.00 \cdot 10^{-1}$	0.58	0.49	0.83
$\lvert\mathbf{v}\rvert = 35km/h, 220°$	$1.68 \cdot 10^{-3}$	$1.74 \cdot 10^{-3}$	$2.99 \cdot 10^{-1}$	0.78	0.70	0.91
$\lvert\mathbf{v}\rvert = 35km/h, 240°$	$1.58 \cdot 10^{-3}$	$1.65 \cdot 10^{-3}$	$2.90 \cdot 10^{-1}$	0.80	0.71	0.92
COSMO	$2.55 \cdot 10^{-3}$	$2.56 \cdot 10^{-3}$	$7.79 \cdot 10^{-1}$	0.34	0.22	0.93
COSMO, $\lvert\mathbf{v}\rvert = 35km/h$	$1.89 \cdot 10^{-3}$	$1.98 \cdot 10^{-3}$	$3.57 \cdot 10^{-1}$	0.72	0.64	0.85

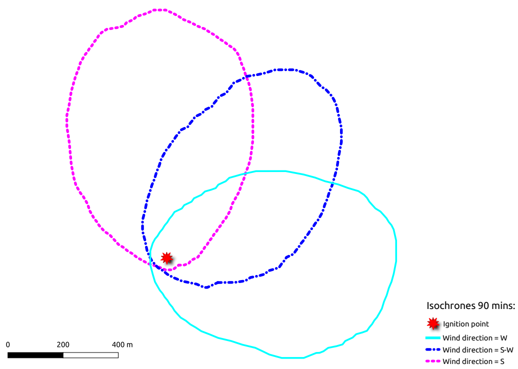


(a) Shrubs - $|v| = 30$ km/h - no slope



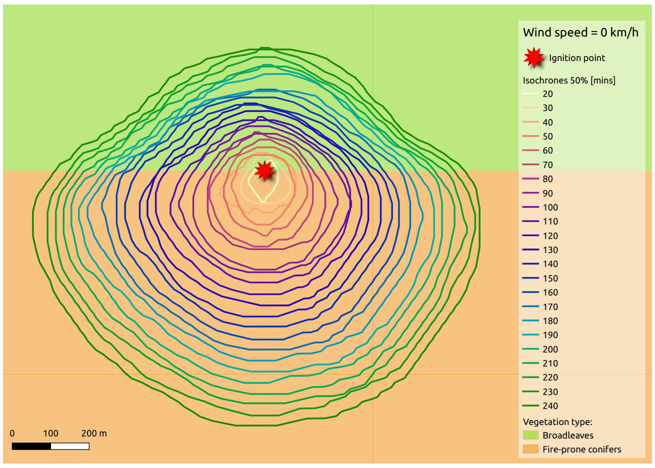
(b) Broadleaves - $|v| = 30$ km/h - no slope

(c) Grass - $|v| = 30$ km/h - no slope

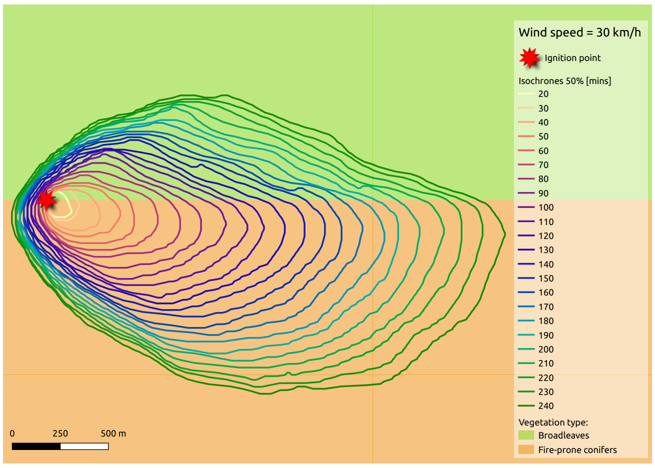


(d) Mediterranean Conifers - $|v| = 30$ km/h - no slope

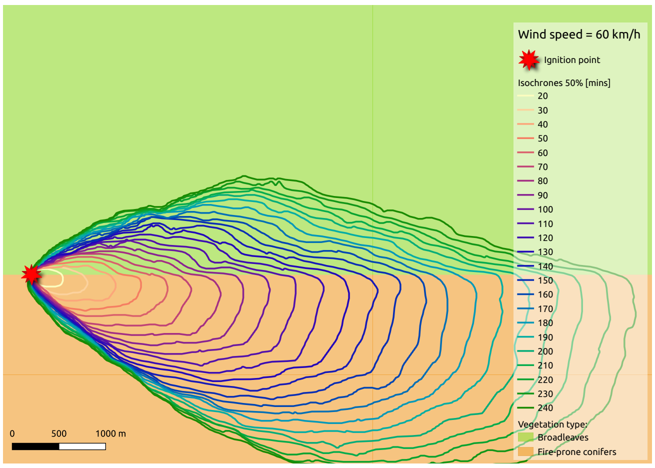
Figure S2. The 0.5 iso-contour of the output probability is plotted for several homogeneous vegetation classes: broadleaves (b), Mediterranean conifers (d), grass (c) and shrubs (a), with a constant wind magnitude $|v| = 30$ km/h and no slope. For each panel, three different wind directions are portrayed: solid cyan lines represent wind blowing from West, dash-dotted dark blue lines stands for wind blowing from South-West, and magenta ones stands for wind blowing from South. The red star represents the ignition point and the iso-contours represent the results at T=60 minutes of the simulation. The scale bars range from 0 to 200 meters for images (a) and (b), from 0 to 100 meters for image (c) and from 0 to 400 meters for image (d).



(a) $|v| = 0$ km/h

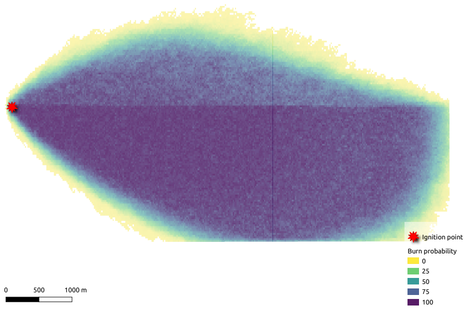


(b) $|v| = 30$ km/h

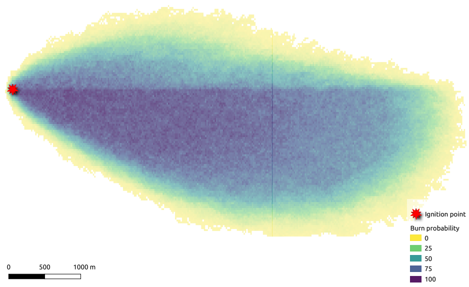


(c) $|v| = 60$ km/h

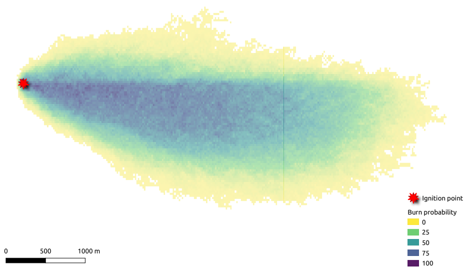
Figure S3. Time history of the simulation with heterogeneous spatial domain. The upper half of the domain is covered by broadleaves, while the lower half is covered by Mediterranean conifers. The colored lines represent the isochrones that identify the simulated burnt areas with probability higher than 50% that are produced at each time step (one hour) until the end of the simulation (240 minutes). The red star represents the ignition point; the scale bars are different for each simulation: image (a) has a scale bar that ranges from 0 to 200 meters, the scale bar of image (b) ranges from 0 to 500 meters and the scale bar of image (c) ranges from 0 to 1000 meters.



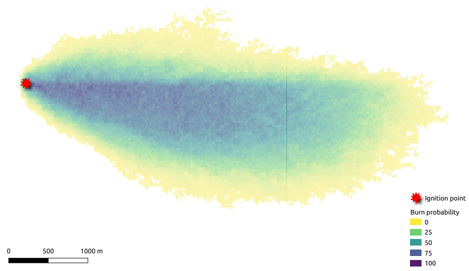
(a) $|v| = 60$km/h, $\mu = 0\%$



(b) $|v| = 60$km/h, $\mu = 5\%$

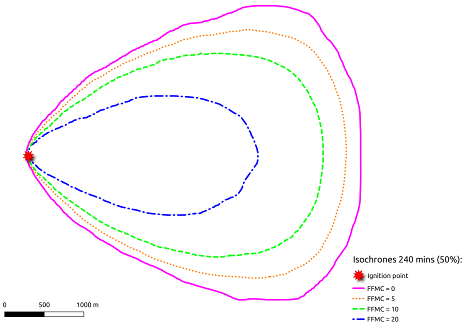


(c) $|v| = 60$km/h, $\mu = 10\%$

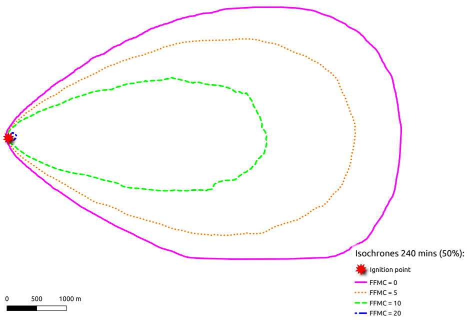


(d) $|v| = 60$km/h, $\mu = 20\%$

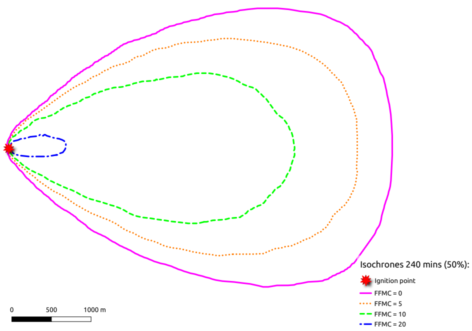
Figure S4. Surface plot of `PROPAGATOR` output probability. After 90 minutes of simulated fire. The upper half of the domain is covered by broadleaves, while the lower half by Mediterranean conifers. of the simulation (240 minutes). From panel a to panel d, the necromass moisture content is $0, 5, 10$ and 20%. The red star represents the ignition point; the scale bars range from 0 to 1000 meters in the four images.



(a) $|v| = 60$km/h, grassland

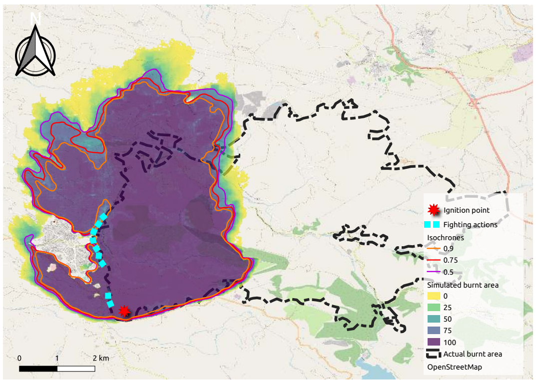


(b) $|v| = 60$km/h, Mediterranean conifers

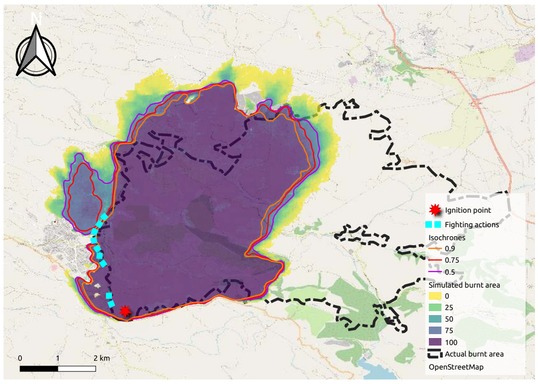


(c) $|v| = 60$km/h, shrubs

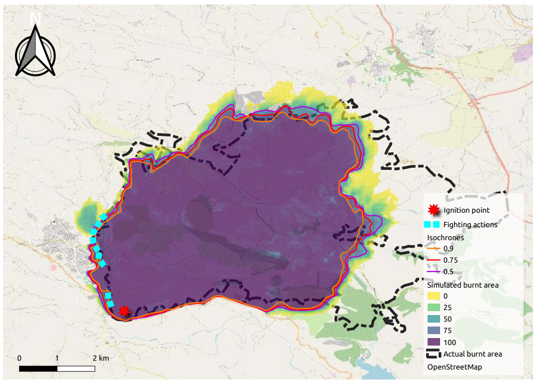
Figure S5. The 0.5 iso-contour of the output probability is plotted for several homogeneous vegetation classes: grasslands (a), Mediterranean conifers (b) and shrubs (c), with a constant wind magnitude $|v| = 60$ km/h and no slope. For each panel, four different necromass moisture contents are portrayed: solid cyan lines for $\mu = 0\%$, dotted orange lines for $\mu = 5\%$, dashed green lines for $\mu = 10\%$, and finally dark blue dash-dotted lines for $\mu = 20\%$.



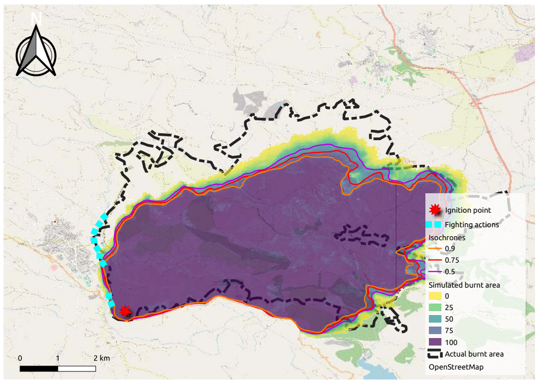
(a) 180° - $|v| = 35$ km/h



(b) 200° - $|v| = 35$ km/h

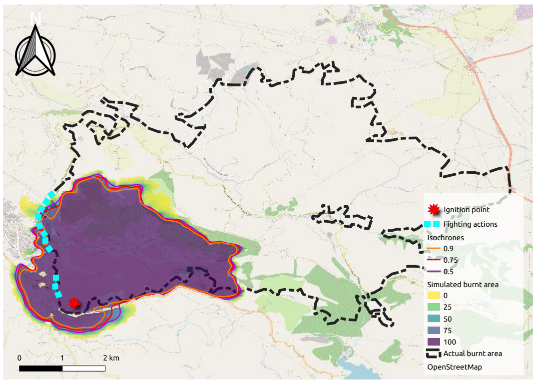


(c) 220° - $|v| = 35$ km/h

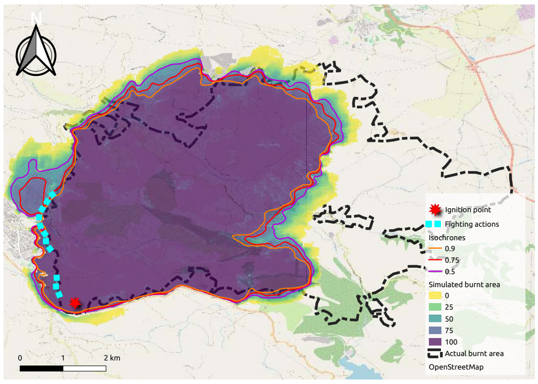


(d) 240° - $|v| = 35$ km/h

Figure S6. The images show actual burnt areas (black dash-dot lines), the ignition point (red star), the implemented fighting actions (light blue dashed lines), the simulated burnt areas with their colour scale and the isochrones (coloured lines) produced at the end of the simulations, which represent the burnt areas with probability higher than 50, 75 and 90% for Ittiri wildfire, with different wind conditions. For the four images, the wind magnitude is constant and fixed to $35 km/h$. The wind direction in panel (a), (b), (c), (d) is respectively 180°, 200°, 220°, 240°.



(a) COSMO wind



(b) COSMO wind direction - $|v| = 35$ km/h

Figure S7. The images show actual burnt areas (black dash-dot lines), the ignition point (red star), the implemented fighting actions (light blue dashed lines), the simulated burnt areas with their colour scale and the isochrones (coloured lines) produced at the end of the simulations, which represent the burnt areas with probability higher than 50, 75 and 90% for Ittiri wildfire, with different wind conditions. For the two images, the wind direction is time-dependent and provided by COSMO model. The wind magnitude in panel (a) is given by the Numerical Weather Prediction model, while in panel (b) it has been fixed to $35 km/h$.

Bibliography

1. Trucchia, A.; Egorova, V.; Pagnini, G.; Rochoux, M. On the merits of sparse surrogates for global sensitivity analysis of multi-scale nonlinear problems: application to turbulence and fire-spotting model in wildland fire simulators. *Communications in Nonlinear Science and Numerical Simulation* **2019**. doi:https://doi.org/10.1016/j.cnsns.2019.02.002.