

Supplementary Materials

This Supplementary Materials document contains Sections S1 to S3, Tables S1 to S2, and Figures S1 to S7 to add detail the main text for “*Modeling potential fire spread polygons and networks for suppression strategies*”.

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Table S1: List of abbreviations used in the main text

Acronym	Definition
BROS	Back Rate of Spread
CDF	Cumulative Distribution Function
DEM	Digital Elevation Model
FL	Flame Length
FLI	Fireline Intensity
FROS	Flank Rate of Spread
GIS	Geographic Information System
GRAF	Grup de Recolzament d'Actuacions Forestals (Forest Action Support Group)
HB	Head-Back (ratio)
HROS	Head Rate of Spread
LB	Length-to-Breadth (ratio)
MTT	Minimum Travel Time
POD	Potential Operation Delineation
ROS	Rate of Spread
ROS_p	Penetration Rate of Spread
tSDI	Terrestrial Suppression Difficulty Index
WUI	Wildland Urban Interface

S1. Fire spread logic

In this study, we use Cell2Fire adapted for the 40 fuel model classification by Scott and Burgan (2005) (Gonzalez-Olabarria et al., 2023). During the simulation, each cell parametrizes fire spread as an ellipse emanating from the cell's centroid using three quantities of rate of spread (ROS): Head rate of spread (HROS), back rate of spread (BROS), and flank rate of spread (FROS). These ROS outputs are calculated across four fuel moisture content scenarios (Scott and Burgan, 2005) by curve fitting with ROS outputs from BehavePlus (i.e., fire modeling system using semi-empirical Rothermel equations) (Andrews, 2013) to provide simplified parametric representations (Gonzalez-Olabarria et al., 2023). In more detail, HROS is computed using three parameters:

$$HROS = \frac{1}{p_1 e^{-p_2 x} + p_3} \quad (1)$$

where p_1 , p_2 , and p_3 are the three curve-fitted parameters dependent on fuel type and fuel moisture content scenario, and x is wind speed [km/h]. BROS is computed as a function of HROS and head-back (HB) ratio, which can be computed using the ellipse's length-to-breadth (LB) ratio:

$$BROS = \frac{HROS}{HB} \quad (2)$$

$$HB = \frac{(LB + \sqrt{LB^2 - 1})}{LB - \sqrt{LB^2 - 1}} \quad (3)$$

$$LB = 0.936e^x + 0.461e^{-0.1548x} - 0.397 \quad (4)$$

Lastly, FROS is computed using HROS, BROS, and LB, and is defined as:

$$FROS = \frac{HROS + BROS}{2LB} \quad (5)$$

Cell2Fire simulation outputs of fire behavior are generated as grids and converted into raster format for further processing. Simulated outputs include ROS [m/min], flame length (FL) [m], and fireline intensity (FLI) [KW/m]. FL is computed via curve fitting with FL outputs computed by BehavePlus, similar to the process for ROS above. FL is a function of fuel type, wind speed, and fuel moisture content scenario, and is defined as:

$$FL = (q_1 e^{-q_2 x} + q_3)^2 \quad (6)$$

where q_1 , q_2 , and q_3 are three parameters derived from curve fitting. FLI is computed based on Byram's intensity relationship (Alexander et al., 1982), expressed as a function of FL:

$$FLI = 259.833FL^{2.174} \quad (7)$$

S2. Fire potential polygon terminology

To clarify the terminology used in our hydrology-inspired modeling in our approach to modeling fire potential polygons, we provide a detailed explanation of various terms used in the modeling process in Table S2. There is one key detail in the modeling process. Water flows from a high to low elevation in a watershed so that the basin delineation algorithm searches upstream (i.e., higher values of elevation) for flow accumulation. When modeling fire potential polygons, however, we use “elapsed time” to model fire spread. Hence, elapsed time at the ignition point is zero and is cumulatively measured over time based on the fire’s propagation, as shown by the visualization aid in Fig. S3 in the Supplementary Materials. When computing the accumulation of fire spread paths, searching upstream would identify cells from high to lower “elapsed time” connecting as a fire pathway.

Table S2: Comparison of terms used in hydrology modeling and for our fire potential polygon modeling approach.

Hydrology Term	Descriptions based on elevation (i.e., DEM)	Fire Potential Polygon Term	Descriptions based on elapsed time
Flow	Water flowing based on gravity	Spread	Time measured from a fire spread model (Elapsed time since ignition)
Pour point	Point of precipitation or runoff initiation	Ignition point	Point of ignition or fire initiation
Flow direction	Direction of water flow determined by slope	Spread direction	Direction of fire spread determined by wind, fuel, and topography
Flow accumulation	Accumulation of water flowing from upstream into a given cell	Cumulative fire spread paths	Accumulation of fire spread paths (cells later in time and connected as a fire pathway) for a given cell
Stream Order	Hierarchical ranking of streams (i.e., Tributaries)	Fire spread order	Hierarchical ranking of fire spread pathways
Basin	Watershed or catchment area (Containing tributaries)	Fire potential polygon	Region containing local major fire pathways (i.e., Potential fire spread from an ignition or initiation point)

S3. Suppression difficulty

Suppression difficulty index (*SDI*) was developed by a former incident commander with over 25 years of experience (y Silva et al., 2014). Sub-indexes used in the *SDI* calculation are weighted by scaling thresholds (ranging between 0 and 1) which were determined through a decision-making process involving multiple incident command structure officers from Spain and the US (y Silva et al., 2014, 2020). *SDI* integrates potential fire behavior, represented as the surface fire energy behavior sub-index (I_{ce}), divided by suppression opportunity index (S_{oi}) (y Silva et al., 2014), as shown by Equation 8.

$$SDI = \left[\frac{\sum(I_{ce})}{\sum(S_{oi})} \right] = \left[\frac{\sum(I_{ce})}{\sum(I_a + I_m + I_p + I_{ar} + I_c)} \right] \quad (8)$$

where surface fire energy behavior (I_{ce}) is computed using flame length and heat per unit area while the sub-indices in S_{oi} are defined by: accessibility (I_a , road density), mobility (I_m , fuel break density), penetrability (I_p , foot travel difficulty), aerial resources (I_{ar} , cycle time), fireline construction rate (I_c). In our study, we use terrestrial *SDI* (*tSDI*), which was adapted for Western United States due to the lack of aerial resource cycle time I_{ar} data (O'Connor et al., 2016). The advantage of using *tSDI* is that it can be generated using readily available data products such as fire spread model outputs, digital elevation models, and road networks. *tSDI* omits I_{ar} and integrates a slope hazard factor (I_{slope}), as expressed by Equation 9.

$$tSDI = SDI + I_{slope} \quad (9)$$

On a conceptual level, *tSDI* can be interpreted such that more severe fire behavior (i.e., higher I_{ce}) and more slope hazards (e.g., high slopes) would be a more difficult region to suppress. On the other hand, more opportunities to suppress (i.e., higher I_a , I_m , I_p , I_c) would help reduce the level of difficulty.

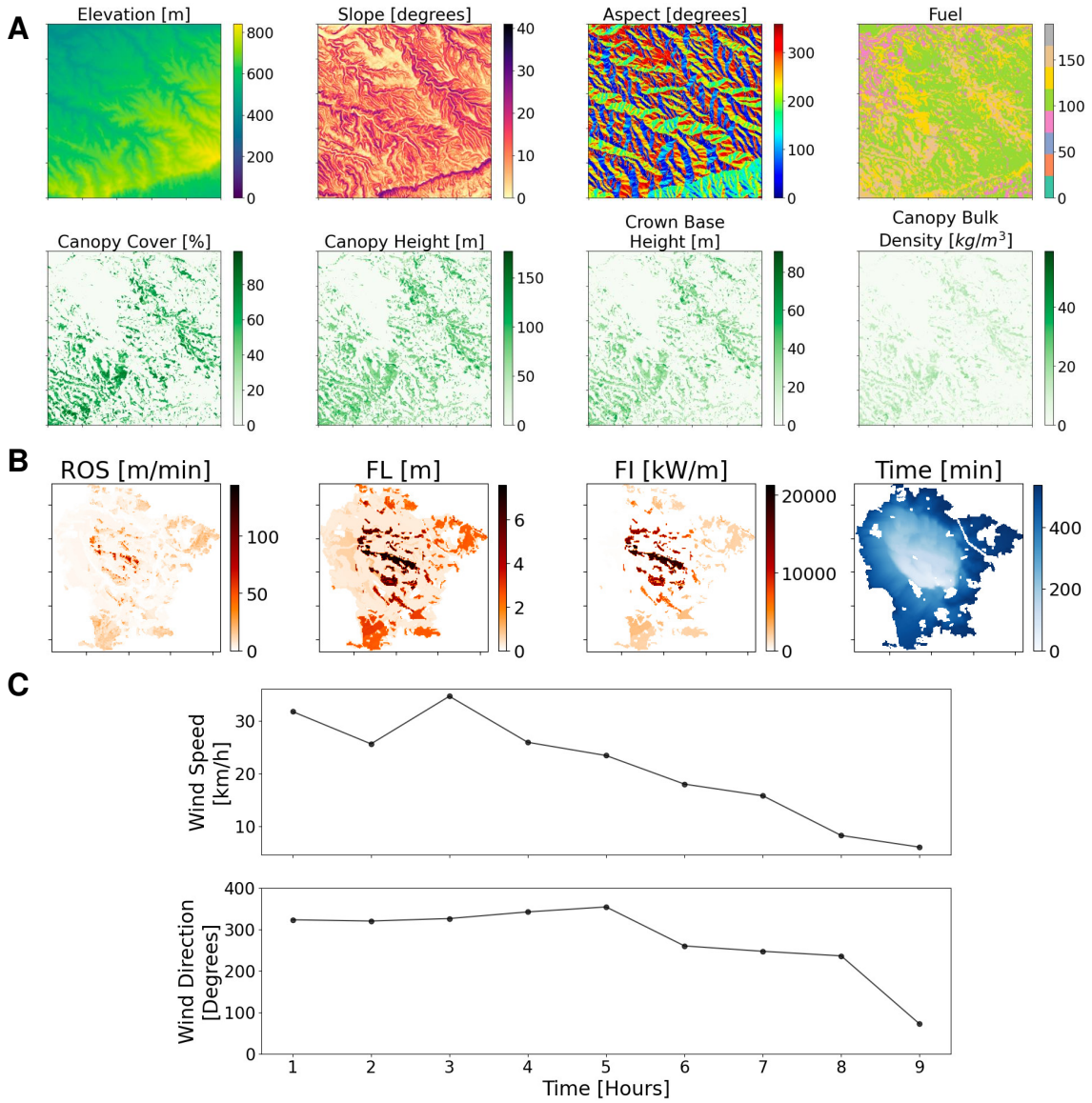


Figure S1: Input and output data used for Cell2Fire fire spread simulations in the 2024 Ciutadilla fire case study.

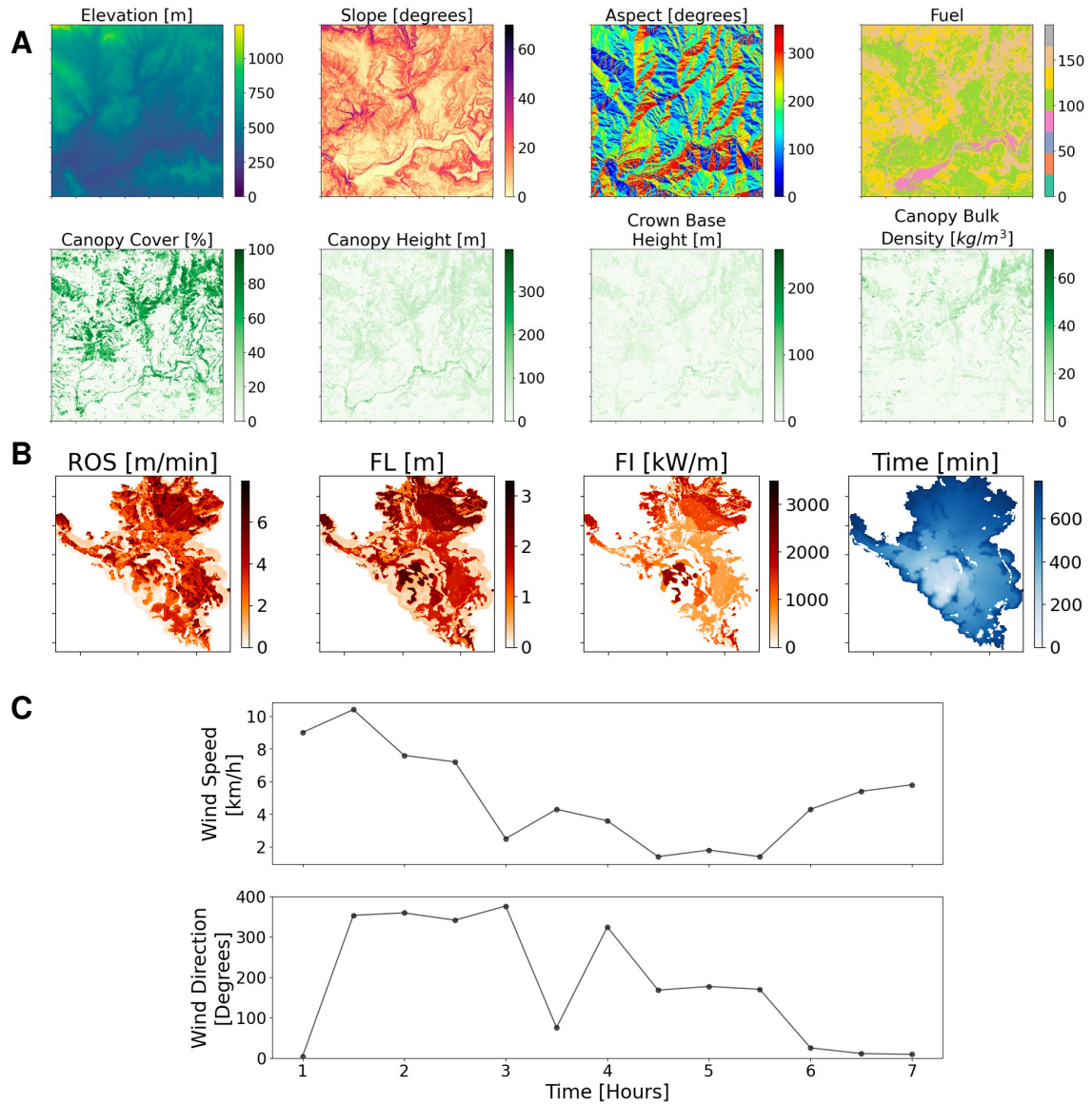


Figure S2: Input and output data used for Cell2Fire fire spread simulations in the 2024 Vilanova de Meià fire case study.

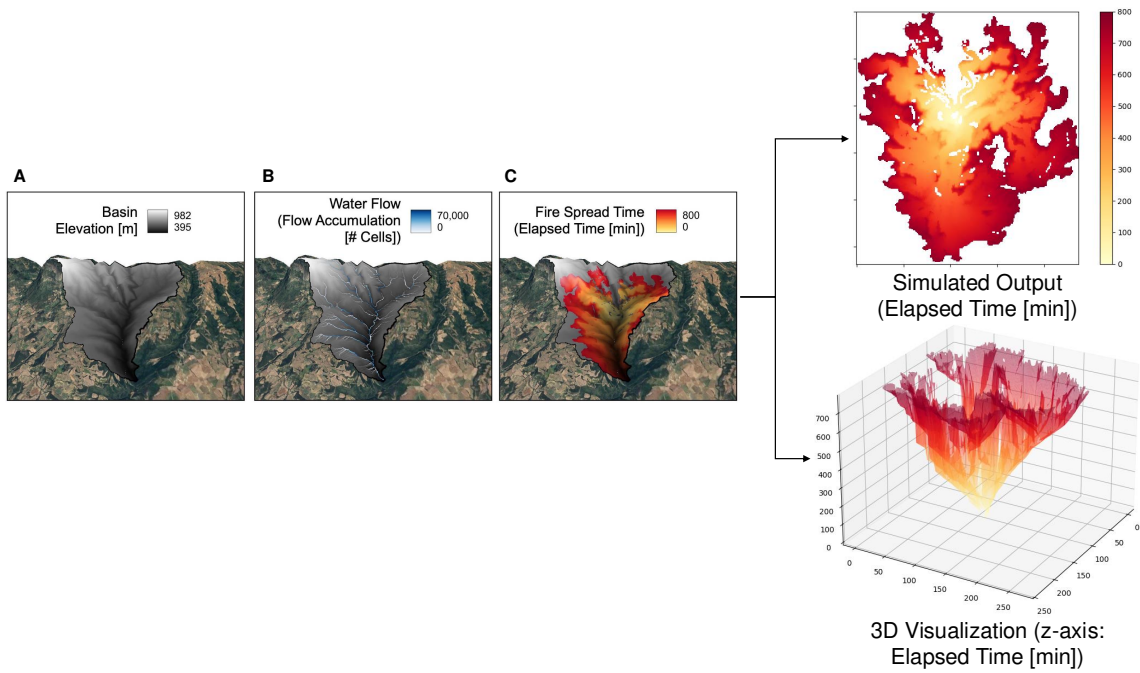


Figure S3: Visualization of elapsed time from fire spread simulations (A) Selected drainage basin shown with elevation [m]. (B) Water flow represented by flow accumulation overlain on basin elevation. (C) Elapsed time during fire spread (i.e., time elapsed since ignition in minutes) rasterized from Cell2Fire's simulated output and overlain on basin elevation.

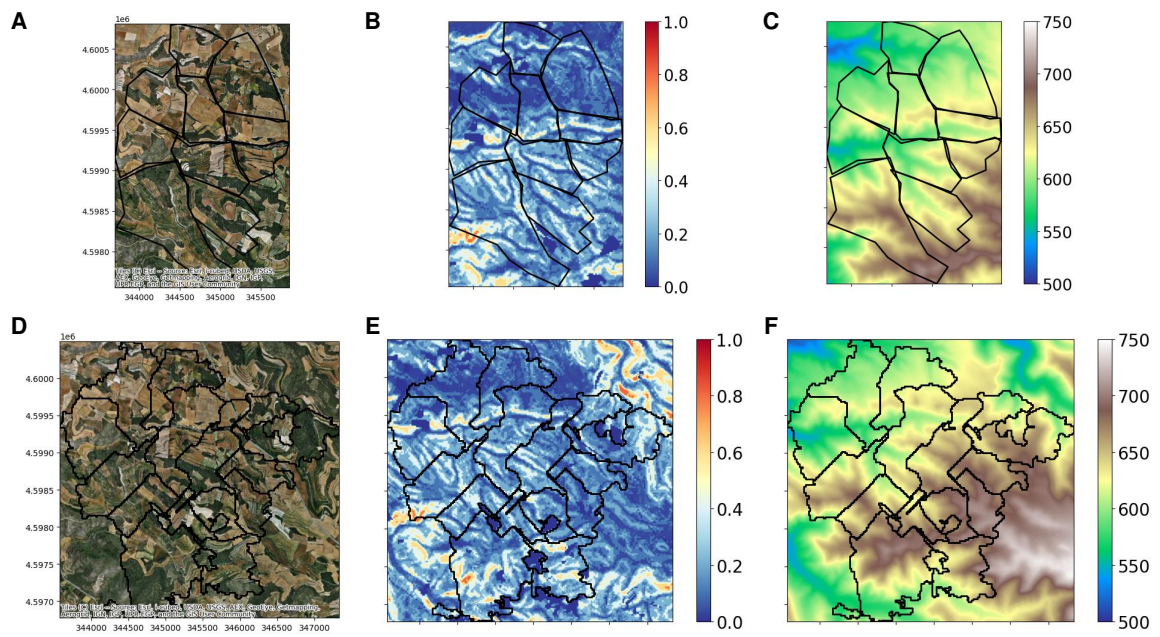


Figure S4: In-depth visualization of $tSDI$ used in the Ciutadilla Fire for the manual and automated fire potential polygons. (A-C) Basemap, $tSDI$ raster, elevation [m] for manual polygons. (D-F) Basemap, $tSDI$ raster, elevation [m] for automated polygons.

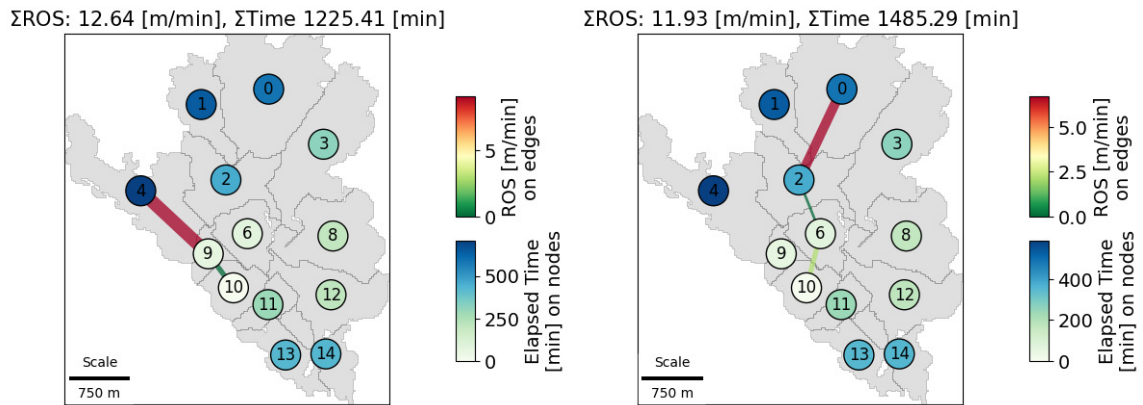


Figure S5: Fastest-spreading major fire pathways found for the Vilanova de Meià fire determined using a breadth-first search algorithm with a depth constraint. The cumulative ROS and elapsed time are shown for the identified paths.

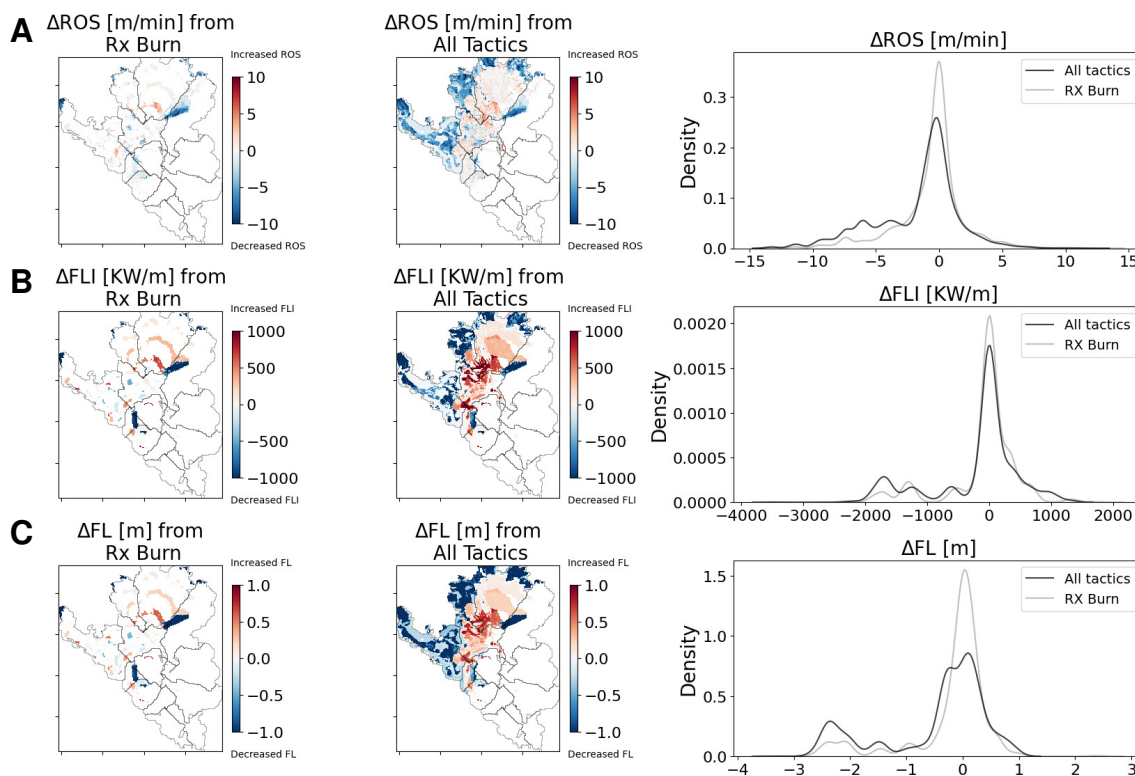


Figure S6: Comparing the impact of the prescribed burn (“Rx burn”) and proactive suppression tactics (“All tactics”) with the baseline (“No Suppression”) scenario using different fire behavior metrics. “All tactics” refers to the “Proactive” scenario (i.e., suppression tactics “S1” to “S4”). (A) Change in ROS for the “Prescribed Burn” and “Proactive” scenarios with accompanying probability distribution function in the differenced ROS values. (B) Change in FLI for the “Prescribed Burn” and “Proactive” scenarios with accompanying probability distribution function in the differenced FLI values. (C) Change in FL for the “Prescribed Burn” and “Proactive” scenarios with accompanying probability distribution function in the differenced FL values.

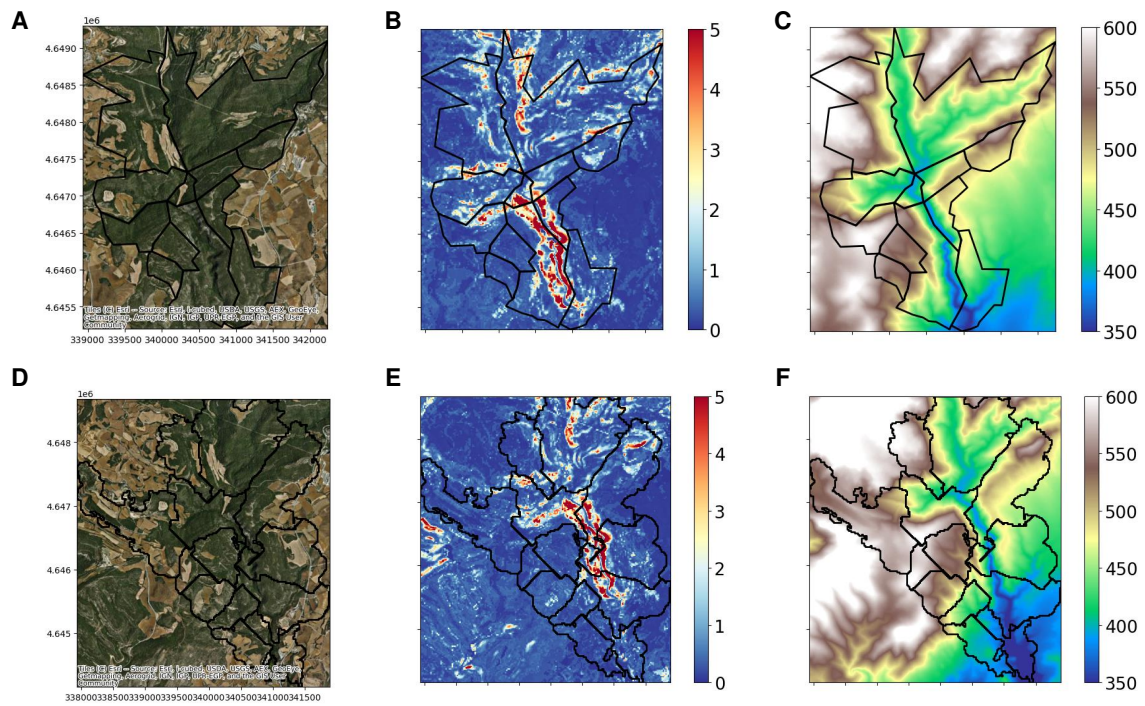


Figure S7: In-depth visualization of $tSDI$ used in the Vilanova de Meià Fire for the manual and automated fire potential polygons. (A-C) Basemap, $tSDI$ raster, elevation [m] for manual polygons. (D-F) Basemap, $tSDI$ raster, elevation [m] for automated polygons.

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