2.6.2 SET1: Efficiency, with a 10-year implementation plan.

The SET1 of scenario planning runs set the goal to treat up to 50% of the available lands for receiving fuel treatments, with a 10-year implementation plan. The available lands for each management priority were different, since although e.g., the total of available lands was 500 thousand ha, the stands that had a value for that specific priority greater than zero might sum up to only 250 thousand ha. So, differences existed both inside each Living Lab, and among them in the number of projects requested to be returned by ForSys. We asked for aggregated 100-ha projects, with a maximum project diameter of 1500 m. For Greece, Portugal, France and Catalonia we asked to prioritize for a) reduction of developed areas exposure from fire sources, b) reduction of protected areas exposure from fire sources, and c) reduction of ignition probability.

The first two objectives were selected to match the KPIs set by the European Commission and explore the possibility to reach these targets with the proposed fuel treatment strategies. In particular, the first is ”50% of Natura 2000 protected areas to be fire-resilient”. This Set identified areas that create high exposure to protected areas like Natura 2000 and proposed targeted fuel treatments there to reduce their risk by 50%, both at the fire exposure sources and sinks (areas that receive fire inside the protected areas). Measurable outcomes on what to expect to receive from fuel treatments for each LL were created and we identified where those areas that cause the 50% of exposure are. The second is “50% reduction in building losses”. We used the outputs of wildfire simulations into ForSys to identify areas that create high structure exposure to communities, and we proposed targeted fuel treatments there to reduce their risk by 50%.

For Chile, since the exposure of protected areas was found to be limited because of their low number in fire affected areas of the Bio-Bio region, we substituted this priority with the reduction of downstream protected value for communities, i.e., treat in areas where there is large “traffic” of potential fires that can reach a developed area, blocking their transmission.

For all Living Labs, using the results of the three runs, we were able to identify which stands that comprise the projects were selected more than once, meaning that the same stand was selected because it achieved more than one objective, and we produced a map to show which are those “best” stands.

2.6.3 SET2: Equity among planning areas

The second set of scenario planning runs aims primarily to distribute fuel treatment projects, and consequently funding, equitably among the different fire management districts of each Living Lab (either Forest Service Districts for Greece, or Municipalities / Counties for the other Living Labs). In contrast to the first set, where projects are allocated based solely on their performance across the landscape (i.e., a Municipality can receive disproportionate projects and area treated compared to others if the attainment goals there that can be achieved are greater compared to other Municipalities), on this set we ask to receive the best 50 projects, 100-ha each, of each district. The objectives chosen to be prioritized are the same as the first set. Similarly, we defined that the projects are spatially aggregated with a maximum project diameter of 1500 m. The main difference is

that in this set, only stands that have a flame length >1.5 m were selected so that only those that create difficulties in fire suppression will comprise a project. Also, the value for each objective of each stand should be >0. By definition, the total number of area treated is lower than SET1 since only 50 projects were requested. Finally, as in SET1, the stands that were selected for more than two objectives were identified and mapped.

2.6.4 SET3: Trade-offs and joint optimality

We quantified trade-offs generated by weighting different sets of two objectives on a scale from 0 to 10, with increments of one. After removing duplicate weight combinations (e.g., 1, 1, 1 being the same as 2, 2, 2), or combinations that were of the same weighting ratio (e.g., weight of 1 for one objective and 2 for the other produced the same results as weights 2 and 4, or 4 and 8, respectively), or combinations that included 0 (e.g., the weight of 0 for one objective and 1 for the other produced the same results as 0 and 2 or 0 and 10, respectively), this process generated 65 distinct solutions for each Municipality / County / Forest Service District), offering a diverse array of alternative treatment priorities within each administrative boundary. The main goal of this set of scenario planning runs was to produce 25 projects, 100-ha each (2500 ha), in each fuel management district (similarly to the Equity set of scenarios). We used different combinations of two objectives for the different Living Labs, selecting among the objectives of community exposure sources & sinks, biomass, protected areas exposure sources & sinks, fire intensity, ignition probability and DPV. We explored the trade-offs contained in the outputs between the different fuel management districts for each couple of objectives, along with the attainment differences of selected weighting combinations to explore whether some districts exhibit greater differences of attainment values compared to others (i.e., equal weights, 1-1; maximize the first objective and zero the other, 1-0 and 0-1; maximum weight for one objective and low weight for the other, 10-3 and 3-10).

3 Stochastic Wildfire Simulations

The main drivers for predicting and simulating wildfire behaviour are topography (elevation, slope, aspect), weather (e.g., wind direction and speed, fuel moisture content) and fuel (i.e., quantity, arrangement, and continuity at both the surface and canopy levels). In this IA, we used different stochastic fire spread modelling methods. Since our main goal was not to dictate which fire simulator each Living Lab or Country should use, we followed a bottom up approach and let the Living Labs to choose their preferred stochastic wildfire simulator as long as two conditions were met: a) outputs should include at minimum simulated ignition locations, simulated fire perimeters and wildfire hazard and b) the simulation inputs should be calibrated and up-to-date and outputs must be validated for their accuracy. Overall, four stochastic fire simulation systems/algorithms were used that include the Minimum Travel Time algorithm (MTT), as implemented through FSIM (for Greece) (Finney et al., 2011) and FConstMTT for Portugal and Catalonia (Alcasena et al., 2021a; Aparício, Alcasena, Ager, Chung, & Pereira, 2022), Cell2Fire for Chile (Cristobal Pais et al., 2019), and Burn P3 for France (Parisien et al., 2005).

3.1 FSim Simulations for the Living Lab Greece

For Greece, we used the FSim fire spread simulator (Finney et al., 2011) to ask where potential future fires will ignite and how they will propagate. Quantitative wildfire risk analysis requires complete geospatial coverage of fire impact probabilities and sizes. Wildfire simulation is the primary means of estimating these, including the frequency distribution of large fire events. These simulations can in turn be used to estimate community exposure and ecosystem risk and use the results to plan for potential preventive measures to reduce the estimated fire spread rate and intensity. All FSim simulations were performed at a cell size of 100 m after dividing Greece into 26 macro-areas (pyromes) areas that capture changing fire activity gradients based on historical fire activity and climatic stratification of the environment as described by Metzger et al. (2005) (Figure 8) that resulted in a dataset of 3,654,905 simulated fires.

FSim simulates the growth and behaviour of hundreds of thousands of fire events for risk analysis across large land areas using geospatial data on historical fire occurrence, weather, terrain, and fuel conditions. The effects of large fire suppression on fire duration and size are also simulated. The FSim simulation process involves the following: 1. Assembly of geospatial landscape and terrain data; 2. Assembly and processing of historical fire occurrence data (Fire Occurrence Database); 3. Assembly and processing of historical weather observations (WIMS, FireFamilyPlus). Using these datasets, the weather data are analysed to produce a large number of synthetic ‘years’ comprising daily weather sequences. For each day of each year the ignitions are stochastically generated, and the growth and behaviour of resulting wildfires are simulated as they burn across the landscape. The process continues for the specified number of years, which produces a probability distribution of intensities. These can be summed to obtain the annualized burn probability. Finally, the model results were calibrated by comparison with observed fire distributions.

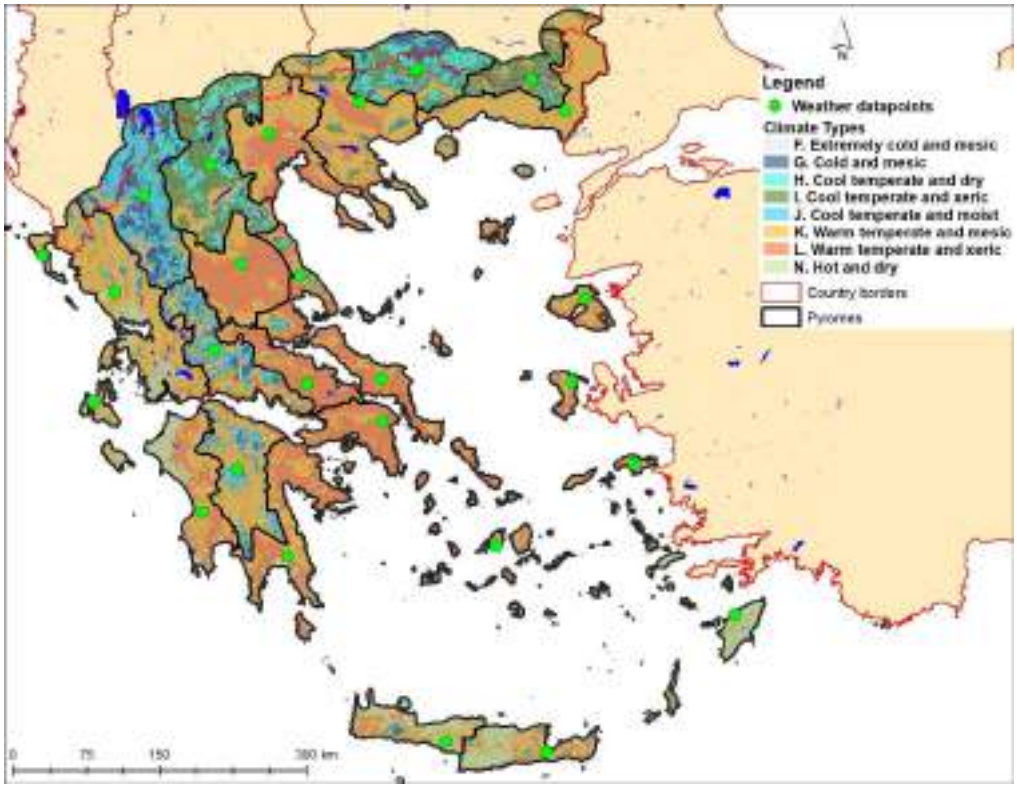

Figure 8 Climate types of study area, including a buffer zone of 20-km at the northern borders of Greece.

3.1.1 Mapping Fuel Models and Canopy Characteristics

Wildfire behaviour models, such as those of Rothermel (1972) consider numerous empirical variables. While these inputs are important for equation outputs, they are often difficult and time-consuming, if not impossible, to measure for each fuel bed. A fuel model defines these input variables for a stylized set of quantitative vegetation characteristics that can be visually identified in the field. Depending on local conditions, one of several fuel models may be appropriate.

As the base mapping layer, we used the CORINE Land Cover (CLC) (EEA, 2018) inventory (2018 version) after intersecting its main forest related classes, i.e., Broad-leaved forest, Coniferous forest, Transitional woodland-shrub and Mixed forest with a detailed vegetation species layer produced by the First National Forest Inventory of Greece that captured the species distribution and cover for reference year 1992 (Palaiologou et al., 2022). Then, based on knowledge retrieved through extensive inventories across different Greek ecoregions (Kalabokidis et al., 2016) and expert knowledge regarding the potential fire behaviour of each vegetation class, we assigned one or more fuel models at each class depending on topographic and other conditions.

For example, olive groves received three different fuel models depending on the slope of each pixel considering that smaller slopes are easier to treat and maintain in a low fuel state by their owners (≤5°; Fuel Model: GR1, Short, sparse dry climate grass), compared to those pixels with slopes between 5-15° (FM: GS1, Low load, dry climate grass-shrub)

and >15° (FM: GS2, Moderate load, dry climate grass-shrub), where fuel is usually comprised of tall grass mixed with short shrubs and other vegetation.

Similarly, grasslands burn differently across the elevation gradient, with higher altitudes be moister and with different plant properties, i.e., density, height, mixture with shrubs, dead fuel moisture of extinction and curing period. We assigned five different fuel models to grasslands and pastures based on the elevation gradient where the pixel was located, i.e., 0-600 m: GS2, >600-800 m: GS1, >800-1200 m: GR4, >1200-1700 m: GR2, and >1700 m: GR1 (see Table 1 for fuel model definitions). All pixels from the European Settlement Map Built-up areas, after resampling, were assigned with a non-burnable fuel model since those areas are mostly residential buildings or roads. To account for incoming and outgoing simulations ignitions from other countries, and to avoid edge effects during the simulations i.e., having all simulations technically stopping and the country borders, we extended the mapping landscape by 20 km at the northern borders of the country, entering Albania, North Macedonia and Bulgaria since we have evidence of past actual fires that crossed the borders with these countries. For the case of Turkey, this was not necessary since the land border is separated by the river Evros and the borderline on the banks of the river is covered by cultivations, so, no fire spread is possible between the two countries. The final fuel model map is presented in Figure 9.

The most widespread fuel model for forested areas is the TL6, assigned mostly to mixed broad-leaved forests (5.4%), *Quercus* spp. (4.24%) and *Fagus* spp. (1.5%) (Table 1). Next, TU1 was assigned to transitional woodland-shrub dominated by *Quercus* spp. (3.9%), sparse vegetation dominated by *Quercus* spp. (1.3%) and agricultural lands mixed with sparce *Quercus* spp. and other natural vegetation (1.4%) and broadleaf shrubs (0.5%). The TU5 was primarily assigned to *Pinus* spp. (2.5%), mixed broadleaf-coniferous forest (1.2%), *Pinus halepensis* (1.5%) and transitional woodland-shrub dominated by *Abies* spp. (0.7%). The TL9 was assigned mostly to high elevation conifers, such as *Abies* spp. (1.7%), and mixed broadleaf-*Abies* spp. (0.4%). Last, the TU4 fuel model was assigned mostly to sparse *Pinus halepensis* (1.10%). Regarding the non-forest fuel models, GS1 was assigned to natural grasslands with sparse wooden vegetation (8.2%), land principally occupied by agriculture, with significant areas of natural vegetation (5.4%), complex cultivation patterns (5.2%) and olive groves (5%). The SH5 was assigned to sclerophyllous vegetation (11.9%), natural grasslands with significant area covered with shrub (1.3%) and mixed forest with shrub understory (1%). The GR1 was assigned to non-irrigated arable land (8.9%), pastures (0.85%) and vineyards (0.6%). The GS2 was assigned to discontinuous urban fabric (1.6%), agricultural areas with natural vegetation and significant area covered with shrub (1.3%) and sparse vegetation with shrubs (0.55%). The GR4 was mainly assigned to natural grasslands (1.6%). Finally, the SH1 was assigned to fruit trees and berry plantations (1%) and pastures with sparse and short shrubs (0.15%).

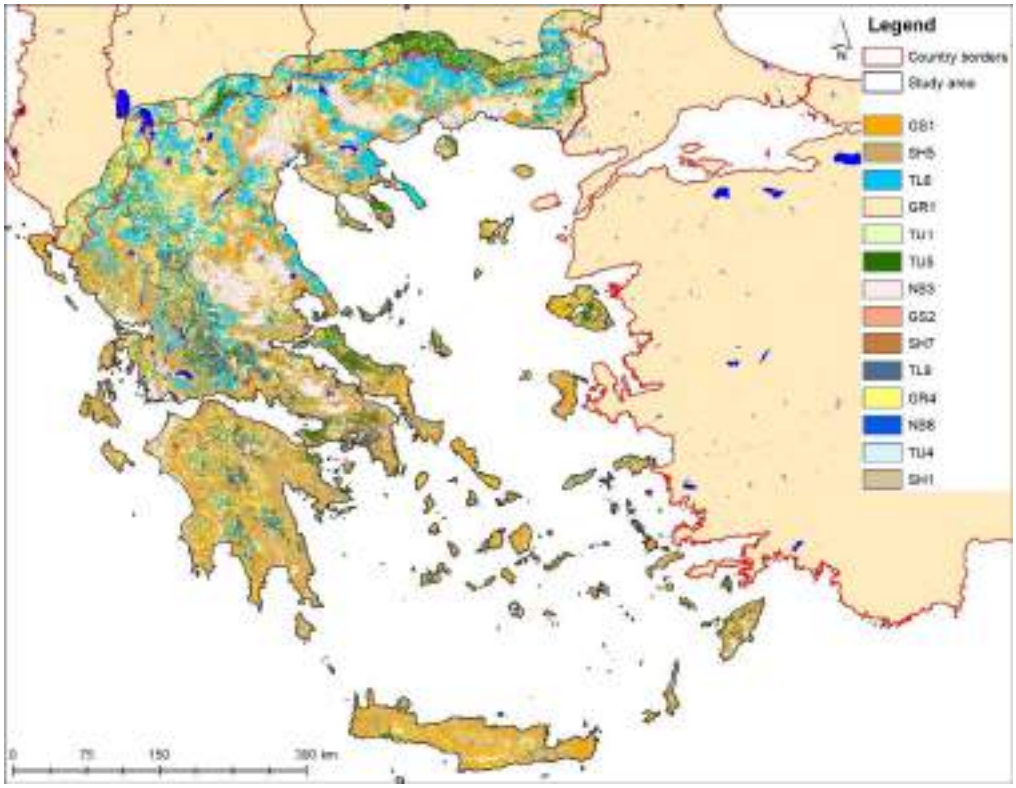

Figure 9 Fuel models of study area, including a buffer zone of 20-km at the northern borders of Greece.

For stand height, we used the ETH Global Canopy Height 2020 (Lang et al., 2022), which is a product that fused the GEDI with Sentinel-2 though probabilistic deep learning model to retrieve stand height at 10 m ground sampling distance for the year 2020. Tree canopy cover was retrieved from the Copernicus portal, showing the level of tree cover ranging from 0 (all non-tree covered areas) to 100% for the reference year 2018 in 10 m spatial resolution. For Canopy Bulk Density we used the work of (Kutchartt et al., 2024) that was conducted withing the project FIRE-RES. Kutchartt et al. (2024) used the aboveground biomass (AGB) to extract the canopy bulk density (CBD), which is the amount of thin biomass in the trees - i.e., highly flammable fuel. Bulk density refers to the amount of thin biomass per unit volume of the canopy. Thin biomass is mostly leafing biomass (mostly leaves and small twigs), thus AGB without trunk and branch biomass. To estimate the thin biomass, allometric models were used to infer the fraction of foliage biomass from the total AGB. Species specific models were used to estimate the foliage biomass according to the compendium equations provided by Forrester et al. (2017). The value of the fraction is species-specific and depends on the size and age of the tree, but also on the forest management plans in the case of forest plantations. To account for the former, they used a map of tree species probability (Bonannella et al., 2022), while tree size and age were estimated by using the canopy height map by Lang et al. (2022) and inverse allometric models to derive diameter. Therefore, a set of biomass equations at tree components provided the fraction of thin biomass (foliage) for different tree species based on diameters as an explanatory-variable (Forrester et al., 2017).

Canopy base height (CBH) was also derived from the work of Kutchartt et al. (2024). Once the biomass of the thin fuel components was determined, it was possible to determine

the density using canopy volume as the denominator. Canopy volume was determined using tree height and the estimated CBH. Subtracting CBH from total tree height provided the canopy volume. Therefore, canopy fuels are fundamental variables considering that fire usually starts from the ground and increases in intensity and spread rate if it can reach the crown easily, especially when it is near the ground (understory fuels). Therefore, the procedure included three main raster maps, such as tree species, canopy height and aboveground biomass that were combined with different species specific allometric equations including only 16 tree species for predicting the branch insertion height and foliage biomass.

Lastly, using the University of Maryland Forest Loss per Year (Hansen et al., 2013), we retrieved the locations of pixels that faced forest loss since 2019 and assigned the fuel model GS1 to describe the conditions that prevail after a disturbance, mostly wildfires in our case, that is characterized by a mixture of tall, cured grasses during the summer mixed with short shrubs. For canopy layer, for disturbances occurred after the reference years of 2020 for tree height and 2018 for canopy cover, we assigned a pixel value of zero (including all fires that burned till the end of the 2023 fire season). All raster datasets, both the inputs and the final layers, were resampled at 30 m spatial resolution.

Table 1 Fuel models distribution over the Greek landscape

Fuel Model Type	Description	Area (km²)	Percent
GS1	Shrubs are about 1-foot high, low grass load. Spread rate moderate; flame length low.	36,490	24.68
SH5	Heavy shrub load, depth 4 to 6 feet. Spread rate very high; Flame length very high.	21,104	14.28
TL6	Moderate load, less compact. Spread rate moderate; Flame length low.	16,833	11.39
GR1	Grass is short, patchy, and possibly heavily grazed. Spread rate moderate; flame length low.	15,966	10.80
TU1	Fuelbed is low load of grass and/or shrub with litter. Spread rate low; flame length low.	10,760	7.28
TU5	Fuelbed is high load conifer litter with shrub understory. Spread rate moderate; flame length moderate.	9,501	6.43
NB3	Agricultural field, maintained in non-burnable condition.	9,323	6.31
GS2	Shrubs are 1 to 3 feet high, moderate grass load. Spread rate high; flame length moderate.	5,830	3.94
SH7	Very heavy shrub load, depth of 4 to 6 feet. Spread rate lower than SH5, but flame length similar. Spread rate high; flame length very high.	4,372	2.96
TL9	Very high load broadleaf litter; heavy needle-drape in otherwise, sparse shrub layer. Spread rate moderate; flame length moderate.	3,098	2.10
GR4	Moderately coarse continuous grass, average depth about 2 feet. Spread rate very high; flame length high.	2,994	2.03

NB8	Open water	2,530	1.71
TU4	Fuelbed is short conifer trees with grass or moss understory. Spread rate moderate; flame length moderate.	1,941	1.31
SH1	Low shrub fuel load, fuelbed depth about 1 foot; some grass may be present. Spread rate very low; flame length very low.	1,800	1.22

3.1.2 Meteorological Data of the Study Area

Hourly data of 2 m air temperature, 2 m dewpoint temperature, incident solar radiation, precipitation, and 10-m northward and eastward wind components were obtained for the years 2000-2021 from the state-of-the-art global reanalysis dataset ERA5-Land (Muñoz-Sabater 2019) available in the C3S Climate Data Store (CDS). This dataset has a horizontal resolution of 0.1° x 0.1° (about 9 km), an hourly temporal resolution and covers the period from 1950 to present. Relative humidity needed as input to FireFamily plus was computed from air and dew-point temperatures, while wind speed and direction was calculated from its components.

A Principal Component Analysis (PCA) was performed on air temperature at 2m above the surface of land to identify representative sites (sites with the highest PCA loading) on each pyrome (19 in total). PCA was performed for the months from May to September and for the period 2000–2020. Moreover, to achieve a sufficient geographic distribution of the fire danger over Greece, 8 more sites, which are mainly located on islands, were considered. Figure 10 illustrates the representative sites on each pyrome as identified by PCA as well as the additional sites. Red entries indicate the final selected sites and black entries denote the corresponding elevation according to the GMTED2010 digital elevation model (USGS EROS Archive – GMTED2010), upscaled at 9 km spatial resolution.

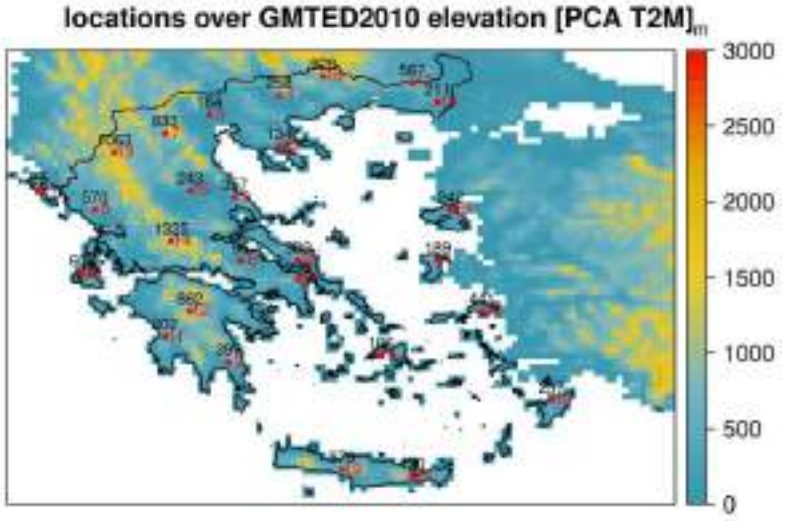

Figure 10 Representative sites on each pyrome as identified by PCA performed on 2 m air temperature (T2M) as well as the additional sites. Red entries indicate the representative site per pyrome and black entries denote the corresponding elevation (in meters above sea level) according to the GMTED2010 digital elevation model, upscaled at 9-km spatial resolution.

3.1.3 FireFamily plus and Post-Process of Meteorological Data

FireFamily plus (FFP) is a software package specifically developed to analyse fire weather data and compute a set of fire danger indices according to the United States National Fire Danger Rating System (NFDRS) (Main et al. 1982, NWCG 2002, Bradshaw and McCormick 2009). This software incorporates the certified NFDRS codes of 1978, 1988, 2016, as well as the Canadian Forest Fire Danger Rating System (CFFDRS) and the Fosberg Fire Weather Index (FFWI). Using hourly or daily fire weather observations, FFP provides all model calculations to produce fuel moistures and fire danger indices and its principal advantage, among others, is that fire danger as a measure of fire business can be analysed (NWCG 2002, Bradshaw and McCormick 2009). In this analysis, we used the most recent version of FFP (Version 5) and the 1978 version of the NDFRS model, employing hourly meteorological data.

A number of dummy stations, equal to the number of representative sites under consideration, should be constructed prior to importing the meteorological data into the FFP. Table 2 provides general information for each station, and the documentation of the assigned values is described in the subsequent paragraphs.

Table 2 General information for each station.

Pyromes	Lon. (deg.)	Lat. (deg.)	Elev. (ft)	Asp. (deg.)	Slope (%)	Slope position	Climate Class	Green-up date	Earliest freeze date	Start KBDI	Start FM1000	Avg. Prec. (in)	FM
North Aegean	26.1	38.5	620	74	9.1	L: lower	3: subhu mid-humid	3/2	31/12	100	25	23.4	G
Eastern Peloponnese	22.8	36.9	1302	167	4.5	M: mid	3: subhu mid-humid	15/2	31/12	100	25	21.9	G
Central Macedonia	22.5	40.8	538	198	2.25	L: lower	3: subhu mid-humid	3/7	31/12	100	25	26.6	G
Eastern Macedonia	23.6	41.1	846	177	15.8	L: lower	3: subhu mid-humid	12/4	31/12	100	25	30.7	G
Cyclades Islands	25.2	37	348	166	9.53	L: lower	1: arid-semiarid	15/12	31/12	100	15	15.2	G
Western Greece-Ionian Islands	20.7	39.3	1870	125	13.7	M: mid	3: subhu mid-humid	9/4	31/12	100	25	56.6	G
Western Macedonia	21.8	40.5	2733	233	4.7	U: upper	3: subhu mid-humid	22/4	31/12	100	25	29.3	G
Attica and Boeotia-Evia	23	38.5	315	61	0.14	L: lower	2: subhu mid	4/7	31/12	100	20	24.5	G

Pelion-Magnesia	22.9	39.5	1171	196	22.2	M: mid	2: subhumid	9/3	31/12	100	20	31.1	G
South eastern Aegean	27.9	36.3	778	82	2.1	L: lower	2: subhumid	28/2	31/12	100	20	23.9	G
Western Peloponnese	21.8	37.3	991	179	7.3	L: lower	3: subhumid-humid	2/3	31/12	100	25	36.7	G
Central Peloponnese	22.2	37.7	2828	289	11.5	U: upper	3: subhumid-humid	9/3	31/12	100	25	32.9	G
North Pindus	21	40.2	3488	53	13.9	U: upper	3: subhumid-humid	2/5	31/12	100	25	37.2	G
South Pindus	21.9	38.8	4347	325	16.1	U: upper	3: subhumid-humid	6/5	31/12	100	25	43.6	G
Thessalian plain	22.2	39.6	797	120	7.2	L: lower	2: subhumid	3/7	31/12	100	20	22.7	G
Rhodope-Frachto	24.3	41.4	3045	166	8.6	U: upper	3: subhumid-humid	28/4	31/12	100	25	37.6	G
Mountainous Thrace	25.7	41.3	1860	340	9.9	M: mid	3: subhumid-humid	22/4	31/12	100	25	32.1	G
Coastal Thrace	26.1	41	692	61	3.3	L: lower	3: subhumid-humid	16 /4	31/12	100	25	31.1	G
Crete	24.6	35.2	1900	11	26.3	M: mid	1: arid-semiarid	10/3	31/12	100	15	19.4	G
Extra sites													
Cephalonia island	20.49	38.28	1985	292	39.5	M: mid	3: subhumid-humid	03/3	31/12	100	25	36.1	G
Corfu island	19.83	39.61	89	42	8.9	L: lower	3: subhumid-humid	6/4	31/12	100	25	51.5	G
Chalkidiki(Polygyros)	23.59	40.32	440	5.6	35.4	L: lower	2: subhumid	28/4	31/12	100	20	26.3	G
Evia island	23.87	38.55	1247	295.6	37.5	M: mid	1: arid-semiarid	1/4	31/12	100	15	25.5	G
Agios Nikolaos (Crete)	25.73	35.08	1378	263.7	46.4	M: mid	1: arid-semiarid	31/1	31/12	100	15	11.2	G
Samos island	26.80	37.73	1447	81.8	10.0	M: mid	2: subhumid	14/4	31/12	100	20	37.7	G

Lesvos island	26.28	39.26	794	295	5.7	L: lower	3: subhu mid-humid	4/2	31/12	100	25	27.3	G
Tatoi	23.88	38.15	971	63	13.0	L: lower	1: arid-semiarid	22/2	31/12	100	15	19.8	G

3.1.3.1 General Station Information

Aspect represents the exposure of the slope on which the site is located. Aspect values are classified into nine classes with the first one indicating no slope (flat) and the rest eight classes denoting the directions the physical slopes face (NWCG, 2011). It is measured clockwise in degrees from 0 to 360. In FFP, each class is labelled with a one-digit code from 1 to 8 where slope exists and 0 for flat terrain: 0 – flat/none, 1 – northeast (45°), 2 – east (90°), 3 – southeast (135°), 4 – south (180°), 5 – southwest (225°), 6 – west (270°), 7 – northwest (315°), and 8 – north (360°) (Bradshaw & McCormick, 2001; NWCG, 2011). The aspect for the selected sites was calculated using the GIS software based on the GMTED2010 digital elevation model, and then it was sorted according to the abovementioned classes.

The slope describes the rise or fall in the terrain measured in the number of feet change per 100 feet (approximately 30.5 m) of horizontal distance, and it is expressed as percentage. According to the NFDRS, the slope is classified into five classes: 0–25, 26–40, 41–55, 56–75, and greater than 75% (NWCG, 2011; Schlobohm & Brain, 2002). Each class is labelled with a one-digit code from 1 to 5. The slope for the selected sites was calculated using GIS based on the GMTED2010 digital elevation model, and then it was sorted according to the five classes.

The slope position describes the general location of the site, and it is grouped into three classes: lower (valley bottom or flat), mid (mid-slope), and upper (ridge or peak) (NWCG, 2011). This parameter was defined using suitable elevation levels according to the study of Pluntke et al. (2016). Therefore, sites with elevation lower than 350 m were classified into the lower class, with elevation between 351 and 650 into the mid class, and with elevation greater than 650 into the upper one.

The climate class describes the general climate of the area to define the drying and wetting rates of the underlying vegetation. It is recognized that vegetation adapts to the climatic conditions of an area and that in some extend it affects the seasonal fire danger (NWCG, 2011). According to the NFDRS, climate is classified into four classes to meet danger-rating needs: 1 – arid/semiarid, 2 – sub-humid, 3 – sub-humid/humid, and 4 – wet (NWCG, 2011; Schlobohm & Brain, 2002). In order to assign a climate class to the examined sites, the classification of Nastos et al. (2013) based on the spatial distribution of the Aridity Index was used. (Nastos et al., 2013), calculated the Aridity Index (AI) for Greece for the period 1991–2000 based on observational data of temperature and precipitation and defined different climate zones throughout the Greek domain based on the United Nations Environment Programme AI classification.

The green-up date describes the beginning of a new cycle of plant growth and signals the start of the green-up processes. To assign the green-up date for each station, the High-Resolution Vegetation Phenology and Productivity (HR-VPP) product suite of the Copernicus Land Monitoring Service (CLMS) was utilized. The HR-VPP comprise of 13 parameters characterize the vegetation growth cycle and are available at a horizontal resolution of 10m resolution for the period from 2017 until today, with yearly updates. In our analysis, the day of the start of the growing season" (SOSD) parameter was used as a proxy to the green-up date. For each of the examined stations, a growing season start date was determined based on the pixel values of the SOSD parameter (reference year 2022) in a buffer zone of 5 km around each of the examined stations. The earliest freeze date describes the day of the year when the first frost may occur, and it was set constant to the default date (31 December) throughout the selected sites.

The start KBDI parameter represents the initiation value for the Keetch-Byram Drought Index (KBDI). This index is used to describe the effects of seasonal drought on fire potential. When the 1978 version of NFDRS is used, as in our case, KBDI is a stand-alone index whose values are not entered into calculations. However, its initial value is displayed in FFP, and it is a required field. Therefore, a default initiation value of 100 was adopted (NWCG, 2011; Schlobohm & Brain, 2002).

The start FM1000 parameter represents the startup values for the 1000-Hr fuel moisture content. The latter describes the moisture content in the dead fuels consisting of roundwood three to eight inches in diameter or the layer of the forest floor more than about four inches below the surface or both (NWCG, 2011; Schlobohm & Brain, 2002). According to the NFDRS, the initiation values of 1000-Hr are established based on the climate class as follows: 15 for arid/semiarid class, 20 for sub-humid class, 25 for sub-humid/humid and 30 for wet class (NWCG, 2011; Schlobohm & Brain, 2002).

The average precipitation describes the historic average annual precipitation of the site. It was calculated based on the hourly precipitation data for the period 2000—2021 for the selected sites. A fuel model intends to represent the contribution of the dead and live plant material representative of a fire danger rating area. A set of 20 fuel models has been developed for operational use in the 1978 NFDRS. These models are referred to using characters from A to U for communication purposes (NWCG, 2011; Schlobohm & Brain, 2002). FSim has been explicitly implemented using the fuel model G, since it seems to relate well to the occurrence of large fires, whatever the actual fuel conditions in an area may be (Finney et al., 2011; Scott et al., 2018). Therefore, all simulations in FFP for the selected sites were performed employing the use of NFDRS fuel model G. This model represents an area with dense conifer stands where there is a heavy accumulation of litter and down woody material and varying low vegetation. The reader can refer to Schlobohm and Brain (2002), Bradshaw et al. (1983) and Deeming et al. (1977) for more information on the technical details and description of fuel model G.

3.1.3.2 Import reanalysis data

To import the hourly ERA5-Land reanalysis data into the FFP, we had to generate files in the standard FW9 format. FW9 file is a fixed field text file that comprises a set of weather

elements. The elements used and the order in which they appear in this file format are summarized in Table 3.

Table 3 The order in which the used elements were entered to generate the FW9 file format.

Item	Description	Units	Item	Description	Units
1	Record type identifier code (W98)	—	10	Maximum dry bulb temperature	°F
2	Station number	—	11	Minimum dry bulb temperature	°F
3	Observation date	—	12	Maximum relative humidity	%
4	Observation time	—	13	Minimum relative humidity	%
5	Observation type (R, Raws)	—	14	Precipitation duration	hours
6	Dry bulb temperature	°F	15	Precipitation amount	inches
7	Relative humidity	%	16	Moisture type code	—
8	Wind direction azimuth	degrees	17	Measurement type code	—
9	Average wind speed	miles/hr	18	Solar radiation	W/m^2

In this file format, all records begin with the identifier code W98. The station number is a 6-digit number. The assigned number to each station according to Table 2 was used. The observation type element was set at R type, since we are using hourly data. Maximum and minimum dry bulb temperature and relative humidity indicate the highest and lowest values of each parameter during the preceding 24-hour period. These elements are employed for the adjustment of the standard drying function of the NFDRS algorithms to better reflect actual conditions (Schlobohm & Brain, 2002). The precipitation amount indicates the total amount of precipitation within the preceding 24-hour period. The precipitation duration describes the actual number of hours that precipitation fell in the 24-hour period immediately preceding the observation time. This element is of great importance, since it represents the total time that the fuels are exposed to liquid water (Schlobohm & Brain, 2002). The element of solar radiation is used to describe the amount of sunlight received by fuels in the area of interest, and it is expressed in watts per square meter. The moisture type code indicates the expression of atmospheric moisture used, which in this case is the relative humidity. The measurement type code signifies the system of units used, which in this case is the U.S. system where temperature is expressed in Fahrenheit, wind speed in miles per hour and precipitation in decimal inches. The generated weather files were populated with the ERA5-Land dataset, covering the period 2000—2021 at an hourly time step.

3.1.3.3 Output files

FFP incorporates a number of seasonal reports that summarize the seasonal variations of fuel moistures, NFDRS indices, and components (Bradshaw & McCormick, 2001). The FlamMap Fire Risk Export option was opted, and the corresponding output files were generated for the selected sites. This type of report provides the Energy Release Component (ERC), the fuel moisture content for dead fuels (1-hr, 10-hr, 100-hr, 1000-hr) and live fuels (herbaceous, woody, X1000-hr fuel moisture value) as well as the wind speed versus wind direction. When generating this type of report, the wind records can be further specified in relation to the years of data, the time of year and the time of day.

Therefore, the wind records were set to cover the period 2000—2021 including all months, while the time of day was set between 09:00 and 19:00. The ERC, as a calculated output of this type of report, is an indicator of how much potential energy (Btu) is available to be released per unit area (square foot) in the flaming front (Schlobohm & Brain, 2002). Since it considers both dead and live fuel moistures, it is considered a good reflection of drought conditions. Wind is not part of its calculation and thus, its daily variation is relatively small. The ERC is a cumulative type of index, and its daily calculation considers the conditions of the past 7 days. Its scale is open-ended (Schlobohm & Brain, 2002).

3.1.4 Simulation of Fire Ignitions Distribution

The simulation of realistic fire ignitions based on fire history and the corresponding microclimatic conditions constitutes one of the most significant procedures in wildfires simulation. The database with previous locations of fire hotspots in conjunction with a time series analysis of weather data may provide reliable outcomes. To this end, we divided the entire country into specific geographical regions which are related with similar climatological conditions. This fact is very important since fire weather can lead, expand and generally affect fire behavior. For each geographical region we provided hourly weather data from 2000 to 2021, including the most contributing factors, such as temperature, relative humidity, 24-hr rainfall, wind speed and direction, maximum and minimum temperature, maximum and minimum relative humidity, solar radiation and hourly precipitation for the entire calendar year. These parameters determine the fire regime for each region. Next, we proceeded to a fire probability analysis to determine the probability of large fire ignition (i.e. escaped fire) through FireFamily Plus. Similarly to Finney et al. (2011), we estimated the probability of large fire ignition based on the daily Energy Release Component (dependent variable). This process occurred by calculating the coefficients of logistic regression that are used to estimate the above probability (Scott et al., 2018). The most significant finding here is the estimation of conditional probability for the initiation of at least one large fire, which is differentiated for each region. Empirically, the threshold for a large fire in Greece is 600 ha. The ignition of more than five simultaneous large fires is very rare in Greece.

3.1.5 Calibration - Validation

The calibration-validation technique involved the comparison of the size of the simulated fires to the actual ones that happened in each location, based on the specific macroclimate zones in Greece. Even though, different measures can be used to optimize the calibration process, such as the number of large fires per year; the number of large-fire acres burned per year; the mean annual large-fire burn probability; the mean large-fire size or the agreement with the historical fire-size distribution (Scott et al., 2018), the last option was chosen, since it has successfully been tested in previous research projects, providing sufficient degree of reliability (Sakellariou et al., 2020; Sakellariou et al., 2022). A continuous calibration process was carried out before the simulation modelling final products were produced. Several factors may need to be adjusted as part of the calibration. However, some of the most significant ones are related with the burning conditions and the fire growth modules, such as calibrating the large-fire size through the adjustment of Rate of Spread (ROS) and the suppression module. The FIRE-RES deliverable 1.1 “Transfer of lesson learned on extreme wildfire events to key

stakeholders" identified that the Growth rate (S/ha) and ROS are key variables to describe the extreme fire behavior and growth patterns of EWE.

The suppression module affects the large-fire size, and it constitutes a good tool for calibration. The suppression factor can range from 1 (strong suppression capacity) to 10 (weak suppression capacity). This factor was varied, based on the geographical region and the respective firefighting capacity. Respectively, the ROS was adjusted to the existing fuels in any region. The adjustment involved the configuration of ROS to be higher than 1 which is translated to increased fire rate of spread, whereas ROS lower than 1 indicates reduced surface rate of spread. Reduced ROS and/or strong suppression will lead to lower mean large-fire size and vice versa (Scott et al., 2018). Hence, depending on the specific features of each region, differentiated combinations of the suppression module and the ROS factor were adopted. The selection of optimal values for the above factors made the simulation results present great similarity with the actual burned area distribution. The absolute matching of the two curves should be considered infeasible since the fire history data are relatively limited. The more coherent and complete the fire history database, the better the matching of the actual and simulated curves (after the appropriate adjustment).

3.2 Cell2Fire Simulations for Biobío Region (Chile)

3.2.1 Weather scenarios

The Cell2Fire simulator, implemented for the Kitral fuel model set, requires weather conditions with hourly temporal resolution throughout the simulation. The required meteorological variables are the air temperature, relative humidity, wind speed, and wind direction. To generate the weather scenarios, data from three meteorological stations located in the Biobío region were used to capture the climatic variability of the area. The selected stations are part of the network managed by the Chilean Meteorological Directorate (DMC) which ensures rigorous quality control of its data. The stations used were the Carriel Sur, the Aeródromo María Dolores and the Liceo Agrícola El Huerton. For each station, the summer months in the Southern Hemisphere (December, January, and February) from the last five years were selected. Days with daily maximum temperatures above the 80th percentile were identified, and based on this data, 100 weather scenarios, each lasting 12 hours, were randomly generated.

3.2.2 Simulations

Fire behaviour in Chile has been extensively studied, particularly in relation to the country's vegetative composition, and the findings have been incorporated into the KITRAL system. The wildland fuel types within KITRAL are categorized based on distinct vegetation and forest characteristics, such as species, size, form, arrangement, and continuity, which influence fire behaviour under specific conditions (Pedernera & Julio, 1999). The system currently recognizes 31 unique flammable fuel types, divided into categories: agricultural and forest plantations (PL codes), native woodlands (BN codes), scrublands (MT codes), coniferous logging slash (DX codes), and pastures (PC codes). These 31 fuel types are used in fire behaviour modelling with the C2F+K fire growth simulator, which is part of the QGIS toolbox (https://fire2a.github.io/docs/qgis-toolbox/).

For the landscape analysis, a 100 m resolution fuel raster of the Biobío region, spanning roughly 24,000 km², was used. This fuel map was created from the CONAF 2015 vegetation cadastre (available at: https://sit.conaf.cl/), which provides shapefile data on land use, dominant vegetation types, coverage, and structure. This data was integrated into the KITRAL fuel model system. Topographic information was sourced from NASA's Shuttle Radar Topography Mission (SRTM) digital elevation model, with a resolution of approximately 30 m. Additionally, an ignition likelihood raster was developed, showing areas with the highest probability of wildfire occurrence. This was based on a predictive machine learning model that identifies the most influential landscape features contributing to fire ignition risk.

The C2F fire simulator allows for the selection of initial ignition points by randomly choosing cells based on the ignition likelihood raster, which serves as a probability map. The simulation process involves 10,000 runs, which show a tendency for ignition points to cluster in high-probability areas, typically regions with high population density. This is consistent with the fact that approximately 99% of fires in Chile are human caused. Each simulation scenario includes a randomly selected ignition point and a set of weather conditions drawn from the 100 pre-established scenarios.

3.3 FConstMTT Simulations for Catalonia and Portugal

To model fire growth in Catalonia and northern Portugal, the minimum travel time algorithm (MTT) was used (Finney, 2002) as implemented in the FConstMTT command line version. All simulations were performed previously in Aparício, Alcasena, Ager, Chung, Pereira, et al. (2022) for Portugal and Alcasena et al. (2019) for Catalonia. The MTT algorithm calculates a two-dimensional fire growth by searching for the set of pathways with minimum fire spread times from the cell corners at an arbitrary resolution set by the user. Then, the fire spread is predicted using Rothermel's surface fire spread model (Rothermel, 1972), and fire intensity (kW m−1) is converted to flame length (FL) using Byram's equation (Byram, 1959). The FConstMTT program has been extensively described and widely used in several fire-prone areas worldwide to model wildfire spread and behaviour in large landscapes and assess wildfire exposure, transmission, and risk to valued resources and assets (Alcasena et al., 2021a; Alcasena et al., 2019; Palaiologou et al., 2022; Salis et al., 2021).

The landscape (LCP) input file for Portugal was generated at 100 m resolution using topography, surface fuel model and canopy metric raster grids. The topography data included elevation, aspect, and slope grids derived from the European Digital Elevation Model. The Portuguese surface fuel models (Fernandes, 2009) were assigned to the 2018 land-cover map to generate the fuel model grid, following the methodology proposed by Sá et al. (2023). The fuel model assignment was based on the dominant vegetation types (grass, low shrubs, high shrubs, and forest types), tree species (conifer, broadleaved, and evergreen oaks). The initial fuel model assignments were adjusted based on recent disturbances (e.g. time elapsed since the last fire), until the end of 2022. The canopy cover grid was retrieved from the 2018 Copernicus tree cover map. The fire modelling domain LCP was extended 15 km over the Spanish border to consider the transboundary fire exchange between the neighbouring areas in Spain.

Fire weather used in fire simulations was characterized for all dated fires that occurred in the period 2001-2021 (Benali et al., 2016). The meteorological data used was downloaded from the ERA5-Land reanalysis dataset (Muñoz-Sabater et al., 2021), and include temperature, relative humidity and wind speed and direction. The Meteorological conditions were then grouped to represent common weather conditions during fire propagation. The groups are created using the k-means clustering methodology (MacQueen, 1967) or model-based clustering (Stahl & Sallis, 2012), as applicable.

Historical fire ignitions were used to create an ignition probability grid (100 m x 100m). Historical ignitions were obtained from the Forest Fire Information Management System (ICNF, 2013) and augmented with data from MAPA (2016) and Mahood et al. (2022). The data were filtered to include fires ≥100 ha and covered the period 2001-2021. The data were smoothed using kernel density tool (ArcMap version 10.7.1) by setting a search radius defined by the peak distance identified by using the Incremental Spatial Autocorrelation tool (similar to Alcasena et al. (2021a)).

For model calibration, the observed large fire size distributions and fire recurrence across Portugal were replicated by adjusting the fire spread duration and combining multiple fire sets with different duration. Suppression efforts were not considered due to their limited containment capabilities during extreme fire events. Consecutive days with the same weather conditions were counted as a single event. The calibration was conducted using the semi-automatic MTTfireCAL R package (Aparício et al., 2023). The required number of fire ignitions was determined from the annually burned area in the different macro-areas. Then, the fire modelling domain was saturated with thousands of fires that burned more than 97% of the pixels at least once and more than 150 times on average. The intrinsic uncertainty of results caused by the input randomness, such as a fire ignition location, was minimized by modelling a burned area equivalent to more than 10,000 years at 100 m resolution. From the total number of simulations, we selected a subset of 714,369 ignitions that intersect the study area.

For Catalonia, topography, surface fuel, and canopy metric raster grids were assembled into the landscape file at 150-m resolution. To account for incoming fires, especially from the western side, and avoid edge effects on modelling outputs, the landscape file was extended with a 10 km buffer encompassing a total fire modelling domain area of 3.84 million ha. Topographic data grids (elevation, aspect, and slope) were generated from the 25-m resolution digital terrain model (ign.es), canopy metrics (canopy height, canopy cover, canopy base height, and canopy bulk density) were obtained from LiDAR-derived 20-m resolution woodland biophysical variable grids for Catalonia (ICGC, 2016), and surface fuels were obtained by assigning standard fuel models (Scott & Burgan, 2005) to the 1:5000-scale land use land-cover polygons (GENCAT, 2016). For the fuel model assignment to the different land cover polygons, we considered the vegetation characteristics such as species composition, cover, thickness, and shrubs and herbaceous fuels heights detailed in the 2012 map of habitats of Catalonia (GENCAT, 2012).

The fire modelling domain was divided into 10 subareas to capture the fire-weather variability across Catalonia. Some fire regime macro-areas were internally subdivided due to differences in the local wind scenarios. For every sub-area, a representative automatic

weather station with a long data series was assigned. Weather data used include the hourly temperature, rainfall, wind speed, wind direction, relative humidity, and solar radiation records to characterize the wildfire season weather conditions using Fire Family Plus (Bradshaw & McCormick, 2000). Specifically, extreme weather reference conditions (i.e., 97th percentile) were considered in terms of wind speed for most frequent wind directions and ERC-G fuel moisture content (Nelson, 2000) to obtain the fire modelling weather scenarios. Containment efforts are very effective under mild weather conditions and thus most of the area is burned by a few extreme fires overwhelming suppression capabilities.

In Catalonia, most historical fire ignitions are geospatially related to urban development and transportation corridors in highly populated sites, and concentrate in high-density hot-spots with a sharp transition to non-ignition poor access remote areas (Costafreda-Aumedes et al., 2016; Gonzalez-Olabarria et al., 2012). To capture this pattern in the fire occurrence input grid required to display the ignitions within the fire modelling domain, a fixed kernel density was used with a 2000 m bandwidth to generate a 150-m resolution ignition probability grid considering all fire ignition coordinates for the 1998-2014 period. The total number of simulations used to cover the entire Catalonia was 104,933 at 150 m resolution, which accounted for an accumulated burned area equivalent to some 10,000 seasons.

To calibrate the surface fire spread model for Catalonia, the historical large fire size (>100 ha) distribution was replicated in every macro-area separately. In each case, the fire spread duration that better replicated the historical fire size distribution under extreme weather conditions was obtained. Fire ignitions were first distributed within the modelling domain according to the ignition probability grid, and then every fire was independently modelled considering the weather scenario in the ignition location subarea. During fire modelling, weather conditions were held constant, and fire suppression efforts were not considered due to their limited containment capabilities during extreme fire events. Modelled fires saturated the study area and burned each pixel more than 30 times on average.

Outputs from fire modelling for both Catalonia and Portugal included the fire intensity and fire perimeter polygon. FConstMTT generates the fire intensity result as flame length probability (FLP) where pixel-level outputs are expressed for 20 bin 0.5 m fire-intensity levels (FIL1 to FIL20, FIL20 ≥ 9.5 m). The probability-weighted fire intensity was estimated with Equation 6.

$$CFL = \sum_{t=1}^{20} FLP_i \times FL_i \qquad (6)$$

where CFL is the conditional flame length (m), FLPi is the flame length probability of a fire at the i-th flame length category, and FLi is the flame length (m) midpoint of a 0.5 m flame length 20-bin i-th category FIL fire intensity level. The CFL computes all the fire front spreading directions and the respective probabilities at a given pixel (i.e., heading, flanking, and backing) and proxy of wildfire hazard. It describes the potential for loss given a fire burns a valued resource or asset and allows for assessment of the fire suppression

capabilities under the extreme weather conditions assumed to model wildfire behaviour in this study (Tedim et al., 2018).

3.4 Burn P3 Simulations for Nouvelle Aquitaine

3.4.1 Fire simulation tools and landscape data integration

The BURN-P3 fire simulation model was applied to simulate wildfire behaviour and assess fire management strategies in Nouvelle-Aquitaine. This probabilistic tool integrates fire spread algorithms with spatial and statistical analyses, allowing researchers to estimate wildfire likelihood and intensity across diverse landscapes.

To develop the simulation, a detailed landscape file (LCP) was created at a 30-meter resolution, incorporating topography, vegetation, and fuel characteristics. Data on elevation, slope, and aspect were sourced from the national digital terrain model (IGN, 2018), while vegetation and fuel types were adapted from regional land-cover maps to reflect local ecosystems as shown in Table 4.

Table 4 Fuel types included in the PCI method for LL Nouvelle Aquitaine

Vegetation type	Crown fire type	Fuel category (PCI estimate)	Notes
Maritime pine (plantation or natural regeneration): 1 to 3 years after reforestation	N/A	O-1-1 (grass and young pines)	Percentage of wilted grass: February 1st to May 15th: 90% May 16th to June 15th: 75% June 16th to August 15th: 65% August 16th to October 15th: 70%
Herbaceous surfaces (meadows, non-agricultural grasslands, pastures and lawns, dyked areas) and orchards	N/A	O-1-2	Percentage of wilted grass: February 1st to May 15th: 65% May 16th to June 15th: 50% June 16th to August 15th: 60% August 16th to October 15th: 75%
Uncultivated agricultural areas, moors and scrubland	N/A	O-1-3	Percentage of wilted grass: February 1st to May 15th: 75% May 16th to June 15th: 60% June 16th to August 15th: 70%

			August 16th to October 15th: 85%
Maritime pine (plantation or natural regeneration): 4 to 25 years	Sustained fire	C-4 (young jack pine or lodgepole pine)	Assumes continuous forest cover; high amount of layered fuels, so crown fire under moderate conditions
Maritime pine (plantation): 26 years and more	Sustained fire	C-3 (mature jack pine or lodgepole pine)	Assumes continuous forest cover; few layered fuels but closed forest canopy, so crown fire under high or extreme conditions
Riparian vegetation (alder and oak)	N/A	D-1/2 (aspen)	Very low potential spread, especially after May 15th February 1st to May 15th: no leaves May 15th to October 15th: with leaves
Damage area (uncleared) and landfills	N/A	S-1 (jack pine or lodgepole pine slash)	Almost all trees are on the ground; high density of windfall
Pure hardwood forest	Torching	D-1/2 (aspen)	Very low potential spread, especially after May 15th February 1st to May 15th: no leaves May 15th to October 15th: with leaves
Mixed oak (mostly maritime pine)	Torching	M-1/2 (25% coniferous) (mixt boreal forest)	Relatively low potential spread; varies according to the proportion of coniferous (pine) February 1st to May 15th: no leaves May 15th to October 15th: with leaves
Eucalyptus		C2 (temporary)	Intense and fast spread
Recently ploughed fields Irrigated fields (agriculture) Rocks, lakes, rivers, urban areas	N/A	Non-combustible	N/A

Fire weather inputs were designed to replicate the extreme conditions of the 2022 fire season and were primarily sourced from Météo France, to build a dataset based on Fire Weather Index system, as shown on Figure 11. Ignition patterns were produced by INRAE and derived from historical ignition data collected between 2011 and 2020, capturing both anthropogenic and natural fire causes using SAFRAN technology.

Calibration of BURN-P3 was achieved by comparing model outputs to historical fire size distributions, with a focus on replicating the behavior of large fires exceeding 100 hectares under extreme weather scenarios. Special attention was given to integrating daily fire behavior patterns and ensuring that the static weather assumptions in single simulations reflected realistic conditions during prolonged EWEs. Suppression efforts were excluded from modeling, as their efficacy is significantly reduced during extreme events.

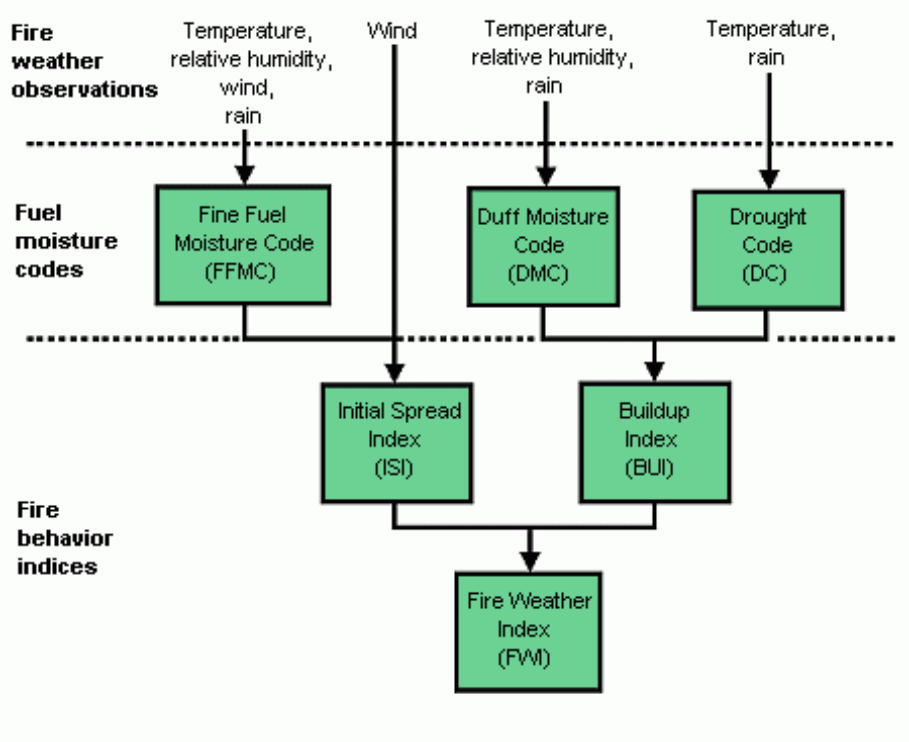

Figure 11 Fire Weather Index System

3.4.2 Complementary Fire Simulation Tools

In addition to BURN-P3, the Prometheus simulator is extensively used in Nouvelle-Aquitaine for operational fire spread modelling. Prometheus relies on detailed fuel maps developed by the Landes department, which categorize vegetation into fuel types such as mature pine, young pine, slash, and non-fuel areas. While Prometheus serves as a valuable tool for short-term firefighting operations, BURN-P3 excels in providing long-term strategic insights into fire spread and risk.

4 Results from Scenario Planning with ForSys

In this section we present the results from the four scenarios run (i.e., SET) with ForSys. Each main subsection is devoted to each Living Lab (e.g., 4.1. is for Greece, 4.2 for Portugal, etc.). Then, each additional subsection shows the results from each of the four sets with a description and analysis of the key findings in each (e.g., 4.1.1 is for SET0, 4.1.2 is for SET1, 4.1.3 is for SET2 and last, 4.1.4 is for SET3, similar for every Living Lab).

The first graph provides an estimate of cumulative attainment achieved for three management objectives (i.e., reduction of the exposure from the sources of fires that affect human communities /settlements , reduction of the exposure from the sources of fires that affect protected areas, and reduction of the probability of new ignitions) if they are allocated randomly (left graph) or in proximity to roads (right graph) over the landscape vs. if we optimize the spatial allocation of potential fuel treatment projects, for the same treated total area.

Then, we provide maps and graphs that show the efficiency of a 10-year fuel treatment implementation plan for the three main objectives of each Living Lab. We start with three maps of the projects returned by ForSys, ranked by the level of attainment they achieve and distributed evenly across each year of the 10-year implementation plan of fuel treatment with the objectives a) to reduce the exposure of developed areas from incoming wildfires (exposure sources), b) to reduce the exposure of protected areas from incoming wildfires (exposure sources), and c) to reduce new ignitions by treated in areas with high ignition probability. The only exception is the Living Lab Chile, where we prioritize the reduction of Downstream Protection Value instead of protected areas sources. In these maps we portray the available stands for receiving fuel treatments with light grey, the forest service districts / counties / municipalities boundaries, the built-up areas in black, the protected areas and the forested areas or managed forests in green. The projects appear with a red to blue colour diverging palette, with warmer colours presenting the higher ranked projects. In the lower right corner, we also provide the total area of the solution in hectares, i.e., the total area covered by all projects that appear on each map.

Each map is accompanied by a graph that shows the cumulative attainment in percent (y-axis) of all projects implemented in each year (x-axis) for each management objective (green: protected areas exposure sources; blue: protected areas exposure sinks; brown: community exposure sources; grey: community exposure sinks; red: ignition probability; orange: wildfire hazard; black: carbon; light green: biomass; and only for Chile, purple: downstream protected value; cyan: burn probability). Usually, the prioritized management objective appears to end with a higher attainment compared to the other objectives, but we noticed in several cases that the projects selected for the prioritized one are very good in achieving high attainment for other objectives as well, although not prioritized. On the x-axis, in parenthesis, we provide the total area treated for each year in thousand hectares.

We continue by providing two graphs, where the cumulative attainment for each of the management objectives is portrayed by a different colour line, that were produced by

selecting all stands from the solutions produced with ForSys for the three prioritized management objectives that met either at least two of the three objectives (left graph) or all three objectives (right). In simple words, it answers the question: what can we achieve if we treat on the stands that have the potential to achieve more than one objective? In all cases, the total treated area is larger for the pool of stands that meet two or three objectives, compared to the stands that meet all three objectives. These graphs are accompanied by a map where we highlight the locations of the stands that meet two objectives (in orange) and three objectives (in red).

Then, we continue with the second set of results that has been estimated by considering equity among the planning areas (forest service districts / counties / municipalities), with ForSys returning the same number of projects (50) for each. The objectives prioritized are the same as SET1, and they appear with the same order for this set as well. The main difference of the maps shown in this set is that the number of projects were ranked from 1 to 50 and this ranking is repeated with the same colour palette for each planning area. That way, we can understand where the best performing projects are located for each planning area, in contrast to the maps of SET1 where the best performing projects can be clustered in only few planning areas, with others having a low number of projects or even none. Note that although we requested 50 projects for each planning area, some might have a lower number since, for some of them, there was not enough available land for 50 fuel treatments projects (each 100 hectares). Each map is accompanied by a cumulative attainment graph that shows the area treated for all planning areas (x-axis) and the level of attainment (percent; y-axis) for all objectives after prioritizing for each objective considered in each case.

A graph that shows the attainment for each planning area for all objectives when prioritized for each of the examined management objectives follows. In this graph, the planning area that achieves the highest attainment for the objective prioritized, for all the projects that resulted within its area appears higher on the y-axis. On the right, we provide the total area treated (in hectares) by the solution for each planning area. On the x-axis, the percentage of attainment is displayed. The highest performance planning area for the prioritized objective appears on the top of the graph, following a gradual decline in the level of attainment as we move to the bottom of the graph. For each planning area, we can also see the performance of the other objectives that can be achieved if all 50 projects are treated. Note that although some planning areas appear lower on the graph for the prioritized objective, they can achieve high attainment for other non-prioritized objectives (e.g., reducing the exposure from the fire sources of protected areas). Finally, a similar graph and one map as of SET1 were produced for the stands that meet two or more, and three criteria.

Last, for the SET3 we created maps and graphs that show trade-offs and joint optimality after examining the performance of sets of two objectives when prioritized against each other with different weight combinations. For each Living Lab we examined four pairs of objectives. First, a map that shows the results of the trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Developed areas exposure sources objective weight maximized (10) and protected areas exposure sources set to low (3) (orange); c) Protected areas exposure sources objective weight maximized (10) and

developed areas exposure sources set to low (3) (blue). Blue- and orange-coloured projects that overlap with the equal weighing scheme are not visible, and they only appear where these projects were not selected by the other two weighting schemes. For each map the available stands for fuel treatments appear light grey, along with the planning area boundaries and the total area of the solution produced by ForSys (bottom right). Depending on each case, maps can also have the built-up areas appear in dark grey, the protected areas boundaries or the forested areas in green. After each map a graph follows with the production probability curves for each planning area for the pair of objectives examined. Axes show the level of attainment for each objective (%), while the attainment of the different solutions for the different weight combinations for each planning area are shown, normally, as a curve if sharp trade-offs exist. The final graph shows for each planning area how the attainment of each of the two objectives varies when different weights are applied. Each panel shows the attainment of each of the two objectives (e.g., black: developed areas exposure sources; red: protected areas exposure sources) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each planning area. When the coloured dots change position, i.e., in one weight combination the red is on the left while in another they flip and the black is on the left and the black on the right, that means that there are strong trade-offs between the two objectives. For the cases where the dots of each colour remain at approximately the same levels of attainment and the same position, this means that for that given set of objectives we do not expect large trade-offs when weights are changed. The purpose of this graph is to reveal which planning areas portray the highest fluctuation when weights are changed and for which pair of objectives.

4.1 Living Lab Greece

The region of application for this component in the Living Lab of Greece is the Peloponnese, a region that cover 2.13 million ha of which, 600,000 ha are available for receiving fuel treatment projects. The analysis was performed at the level of Forest Service (FS) districts (18 in total, with an area ranging from 63,000 ha to 215,500 ha). We analysed the effects of fuel treatment projects at eight management objectives: biomass retrieval, protection of carbon stocks, fire risk reduction at the community exposure sources, protection of community exposure sinks (parts of communities that receive the highest amounts of fire), reduction of fire hazard (i.e., energy release) to facilitate better fire suppression, reduction of future ignitions in high ignition probability areas, reduction of the exposure of protected areas from the sources of their exposure, and protection of the most exposed parts of protected areas (sinks).

4.1.1 SET0: Control & Evaluation

In this set of fuel treatment scenario planning, we estimated the effect that spatial optimization has in three management objectives, namely community exposure sources, protected exposure sources and ignition probability, when we select to apply fuel treatments at 50,000 ha and we compared with a random and a proximity to roads allocation schemes. We found that both random and roads allocation have very low performance when compared with the optimized allocation (Figure 12). In particular, the optimized allocation for protected areas exposure sources can achieve an attainment of up to 21% (i.e., a reduction of 21% in the total exposure that all protected areas has in

the study area) compared to the 3-4% the non-optimized allocation achieved, the community exposure sources optimized allocation achieved approximately 13% vs. the 2-3% of the non-optimized allocation, and finally, we found smaller differences between the spatially optimized allocation of the reduction of ignition probability that achieved approximately 4% attainment vs. the 2-3% of the non-optimized allocations. These results prove that the business-as-usual way of allocating fuel treatment projects (i.e., randomly or in proximity to roads) cannot provide substantial reduction to key management objectives like the protection of communities or risk reduction for protected areas and can have a similar impact only for the objective of reducing ignition probability.

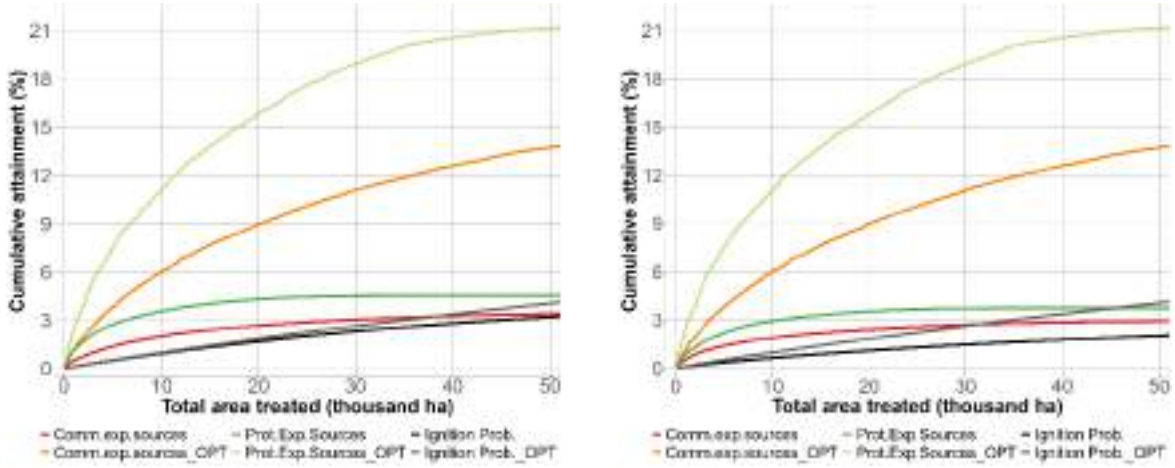

Figure 12 Left: Random project allocation; Right: Project allocation proximate to the road network. OPT: Results from the optimization runs. For comparison, similar colours with different intensity were used for the same objective.

4.1.2 SET1: Efficiency, with a 10-year implementation plan

The implementation of a 10-year plan to reduce the fire risk of the communities from the sources of their exposure by treating half (i.e., 206,000 ha) of the lands that are available for treatment and has a value greater than zero for that objective (i.e., 412,000 ha), resulted to request the spatial optimization of 2080 projects (Figure 13). The total treated area returned from the spatial optimization solution is 178,100 ha. In this optimization run we did not consider any administrative boundary. Each year, approximately 15,000 ha should be treated (Figure 14), and during the first year the main objective (i.e., community exposure sources), along with the protected areas exposure sources, can reach an attainment of up to 8%. For the first five years, the attainment of the main objective can reach 16% by treating approximately 84,000 ha, with the attainment of the other objectives be low (~4%) except for the protected areas exposure sources that is very effective and can reach up to 18% by the fifth year. After the fifth year, the attainment for the main objective is slightly increased to reach 17% by the tenth year, while the other objectives rise more sharply to reach an attainment of ~12% for carbon and biomass, and ~7% for the fire hazard, ignition probability and protected areas exposure sinks. The lower attainment when optimizing for the reduction of the main objective is achieved for the community exposure sinks, that barely reaches 5% by the tenth year. The bulk of the projects are in the FS district of Kalamata (~23k ha), followed by Tripoli (21k ha), Patra (19k ha), Sparti (17k ha) and Vytina (15k ha), with the rest FS districts receiving less than

10k ha of fuel treatments during the 10-year implementation plan (Figure 15-left). The highest attainment is achieved in the FS districts of Korinthou (3%) and Argolidas (~2%), although the total treated area is much lower (~8k ha) compared to the other FS districts (e.g., Kalamata with 23k ha achieves 1.5%). It is notable that the projects planned to be implemented during the first year and are in the FS districts of Korinthou, Argolidas and Kynourias achieve half of their total attainment (Figure 15-right). This finding suggests that they should be among the first to receive fuel treatments to faster achieving the goals of the main objective.

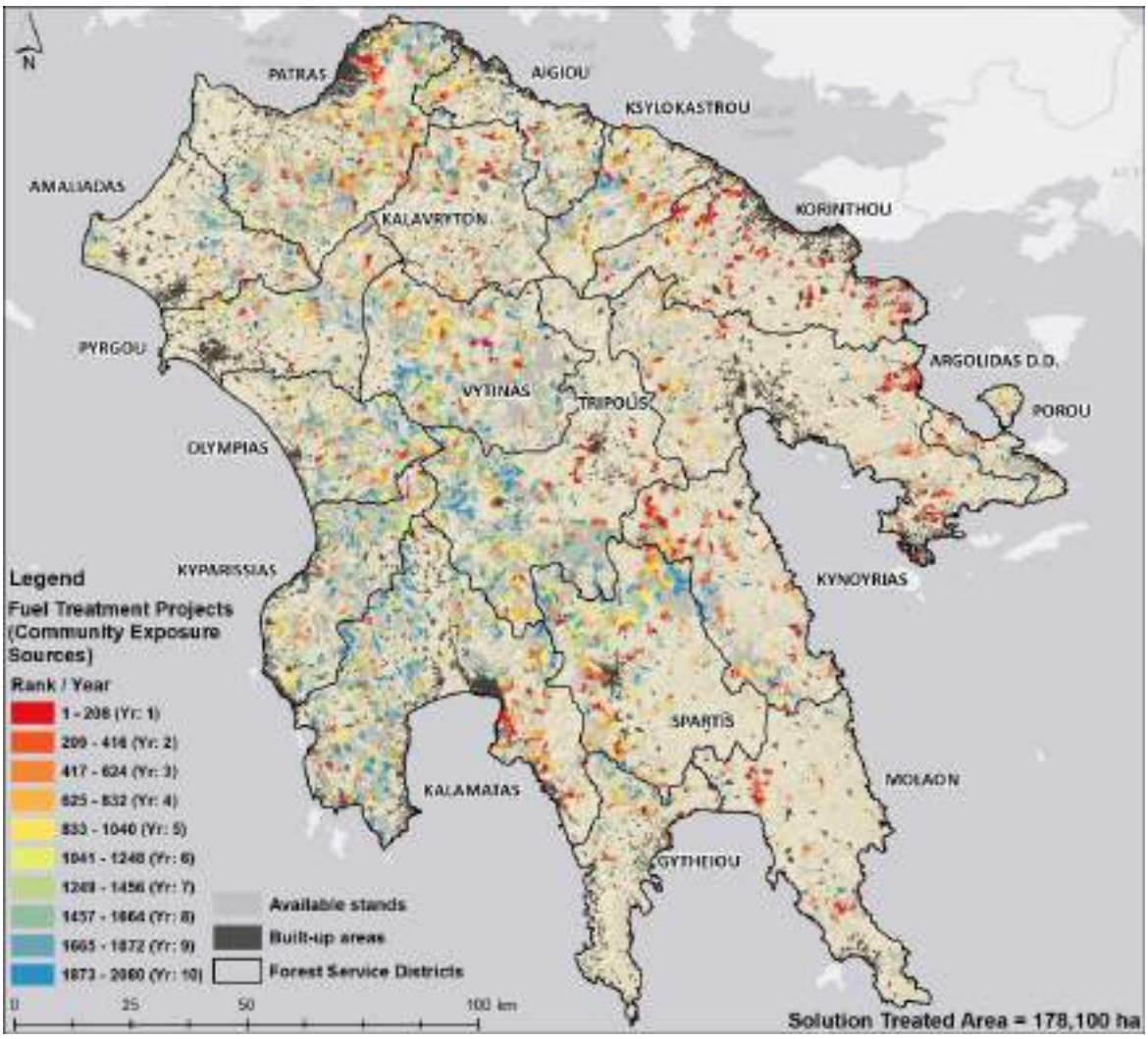

Figure 13 Map of the 2080 projects ranked by the level of attainment they achieve and distributed evenly across each year of the 10-year implementation plan of fuel treatment with the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

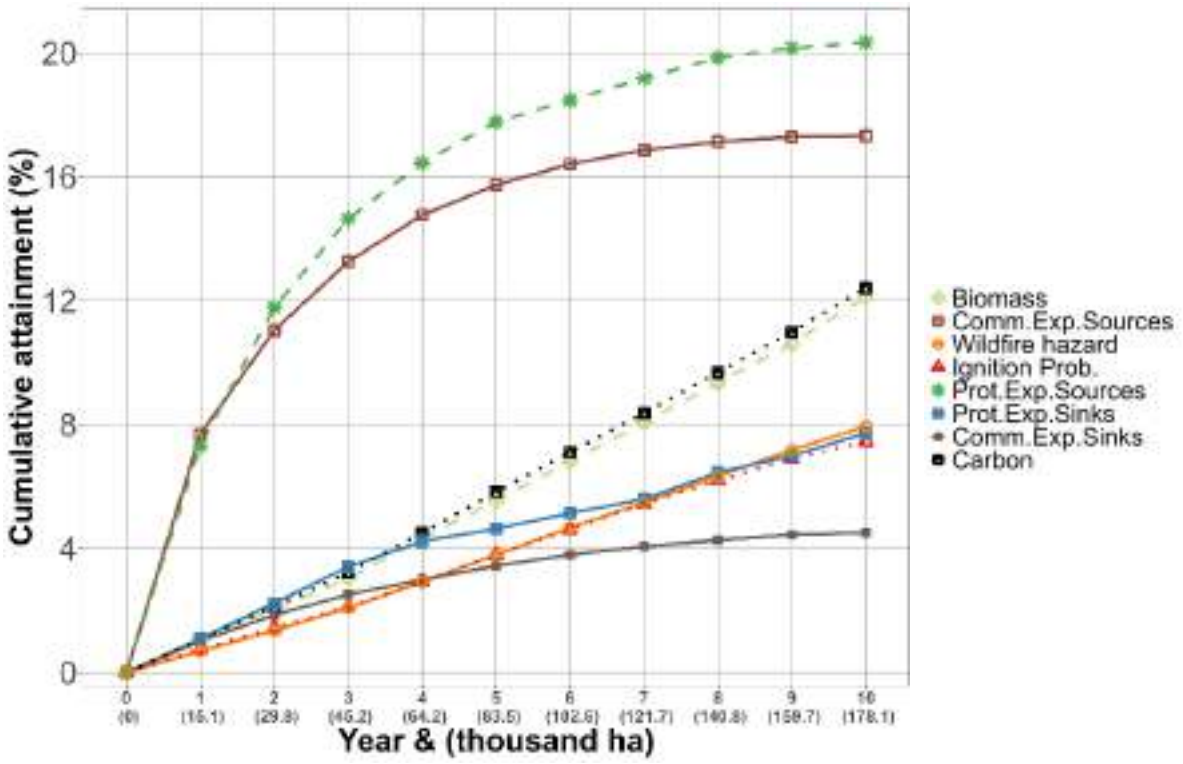

Figure 14 The 10-year implementation plan of fuel treatment with the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

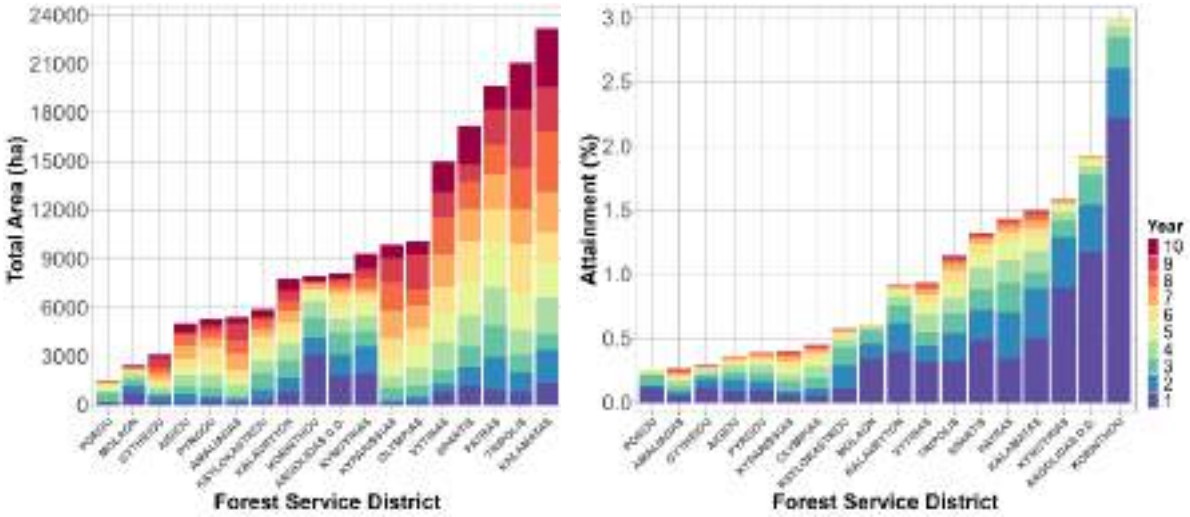

Figure 15 Left: area treated in ha for each Forest Service district by implementation year. Right: main prioritized objective attainment (%) for each Forest Service district by implementation year.

The implementation of a 10-year plan to reduce the fire risk of the protected areas from the sources of their exposure by treating half (i.e., 82,500 ha) of the lands that are available for treatment and has a value greater than zero for that objective (i.e., 165,000 ha), resulted to request the spatial optimization of 825 projects (Figure 16). The total treated area returned from the spatial optimization solution is 57,700 ha. In this optimization run we did not consider any administrative boundary. Each year, approximately 5,500 ha should be treated (Figure 17), and during the first year the main objective (i.e., protected areas exposure sources) can reach an attainment of up to 8%.

For the first five years, the attainment of the main objective can reach 18% by treating approximately 26,000 ha, with the attainment of the other objectives be low (~2%) except for the protected areas exposure sinks and community exposure sources that is effective and can reach up to 8% by the fifth year. After the fifth year, the attainment for the main objective is slightly increased to reach 21% by the tenth year, while the other objectives rise very low to reach an attainment of ~4% for carbon and biomass, and ~3% for the fire hazard and ignition probability. The lower attainment when optimizing for the reduction of the main objective is achieved for the community exposure sinks, that barely reaches 2% by the tenth year.

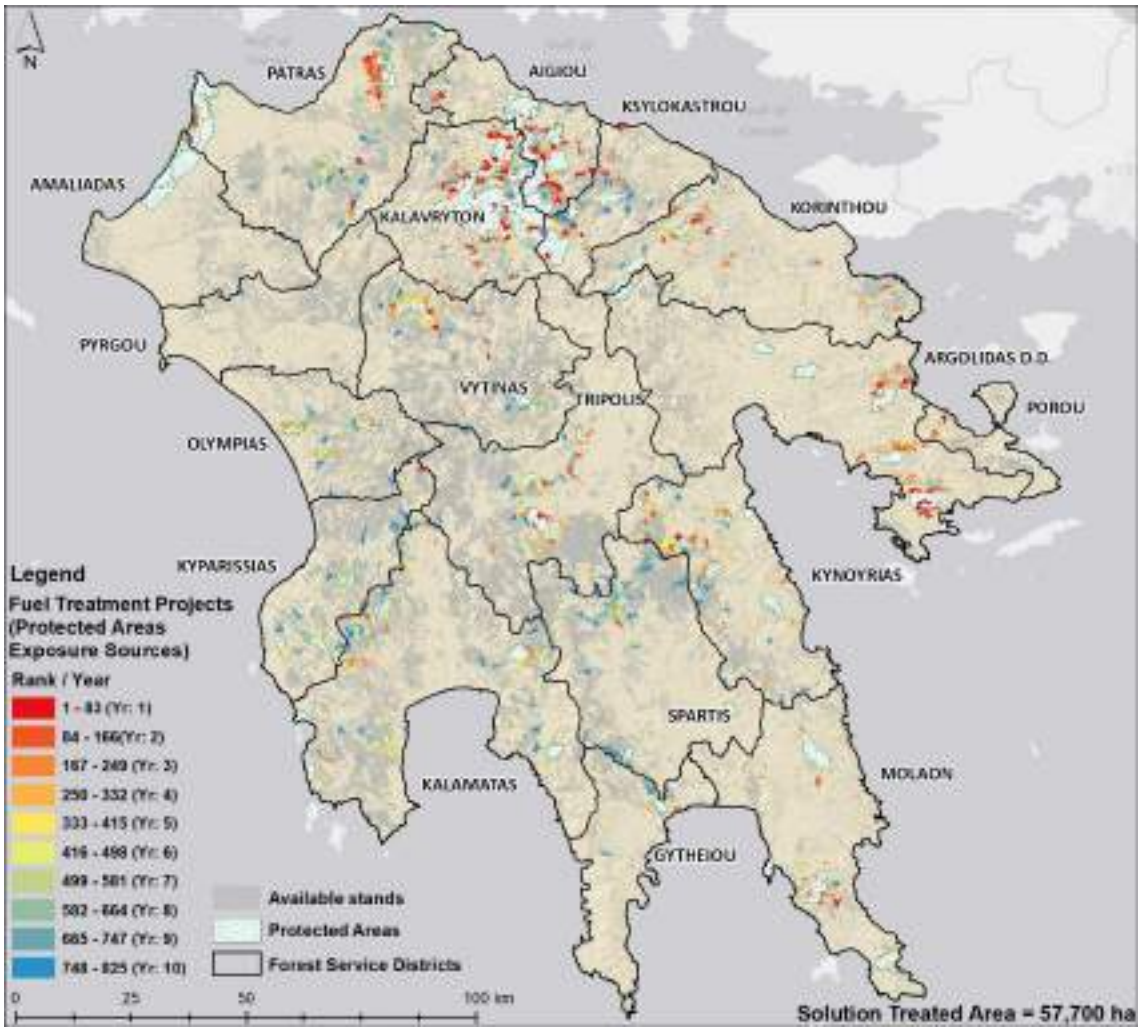

Figure 16 Map of the 825 projects ranked by the level of attainment they achieve and distributed evenly across each year of the 10-year implementation plan of fuel treatment with the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

The bulk of the projects are in the FS district of Kalamata (~6.5k ha), followed by Patra (~6.4k ha), Kalavryton (5.5k ha), Kynourias (~5k ha) and Spartis (~5k ha), with the rest FS districts receiving less than 4k ha of fuel treatments during the 10-year implementation plan (Figure 18-left). The highest attainment is achieved in the FS districts of Kalavryton (5.5%) and Argolidas (~2.5%), although the total treated area is much lower for Argolidas (~4k ha) compared to the other FS districts (e.g., Kalamata with 6.5k ha achieves ~1%). It

is notable that the projects planned to be implemented during the first year and are in the FS districts of Kalavryton and Aigiou achieve more than two thirds of their total attainment (Figure 18-right). This finding suggests that they should be among the first to receive fuel treatments to faster achieving the goals of the main objective.

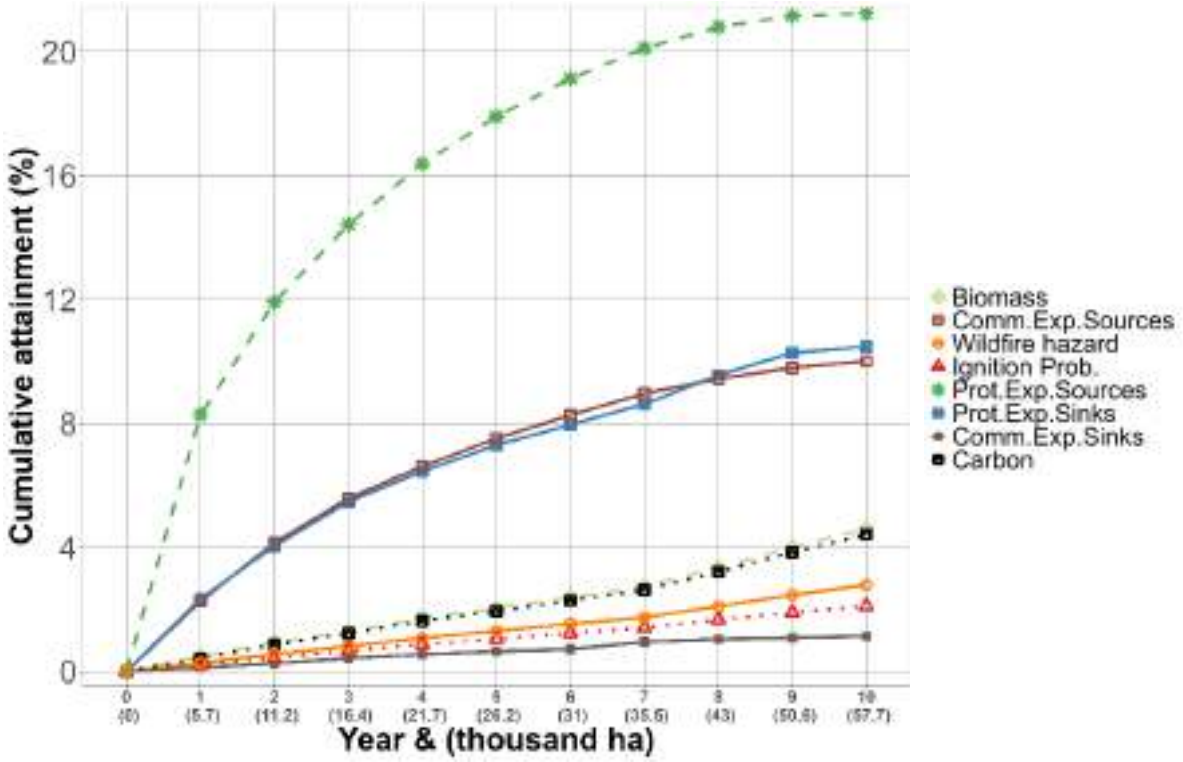

Figure 17 The 10-year implementation plan of fuel treatment with the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

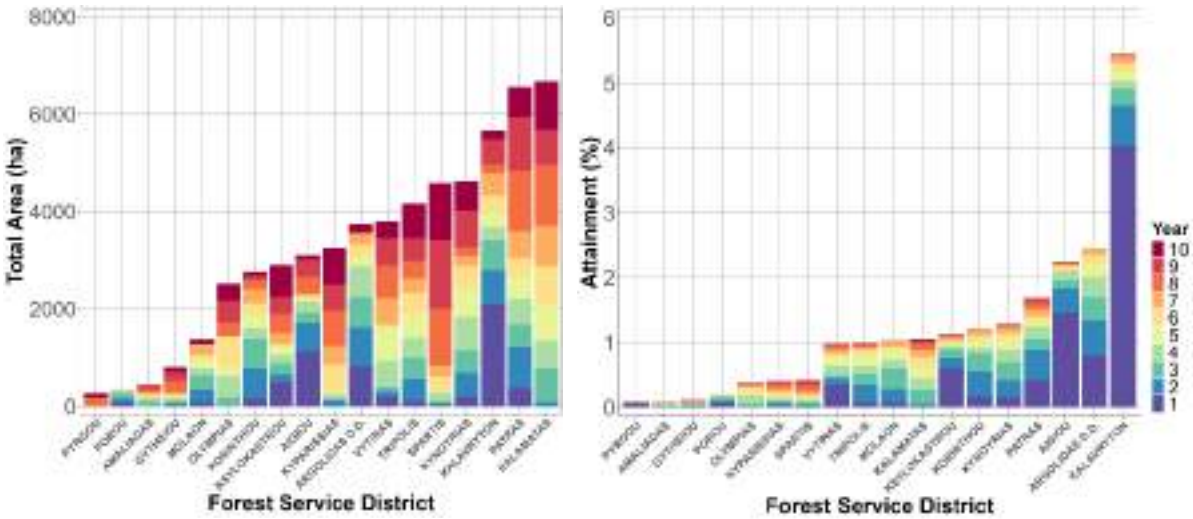

Figure 18 Left: area treated in ha for each Forest Service district by implementation year. Right: main prioritized objective attainment (%) for each Forest Service district by implementation year.

The implementation of a 10-year plan to reduce the ignition probability by treating half (i.e., 300,000 ha) of the lands that are available for treatment and has a value greater than zero for that objective (i.e., 600,000 ha), resulted to request the spatial optimization of

3000 projects (Figure 19). The total treated area returned from the spatial optimization solution is 282,300 ha. The proposed area for treatments is large since all the available stands had an ignition probability value attached that was greater than zero (the unavailable and non-burnable stands were already excluded). In this optimization run we did not consider any administrative boundary. Each year, approximately 28,000 ha should be treated (Figure 20), and during the first year the main objective (i.e., reduction of ignition probability) can reach an attainment of up to 3%. For the first five years, the attainment of the main objective can reach ~9% by treating 141,000 ha, with the attainment of the other objectives be at approximately the same levels (~8%) for community exposure sources, protected areas sources and biomass, while the other three objectives (wildfire hazard, protected areas sinks and community exposure sinks) achieve between 4-5% of attainment. After the fifth year, the attainment for the main objective is moderately increased to reach ~12% by the tenth year, while the three objectives rise linearly from the ~8% to >16% attainment, and the protected areas exposure sinks and wildfire hazard end up at about 11%, but after treating a massive area that reaches 282k ha.

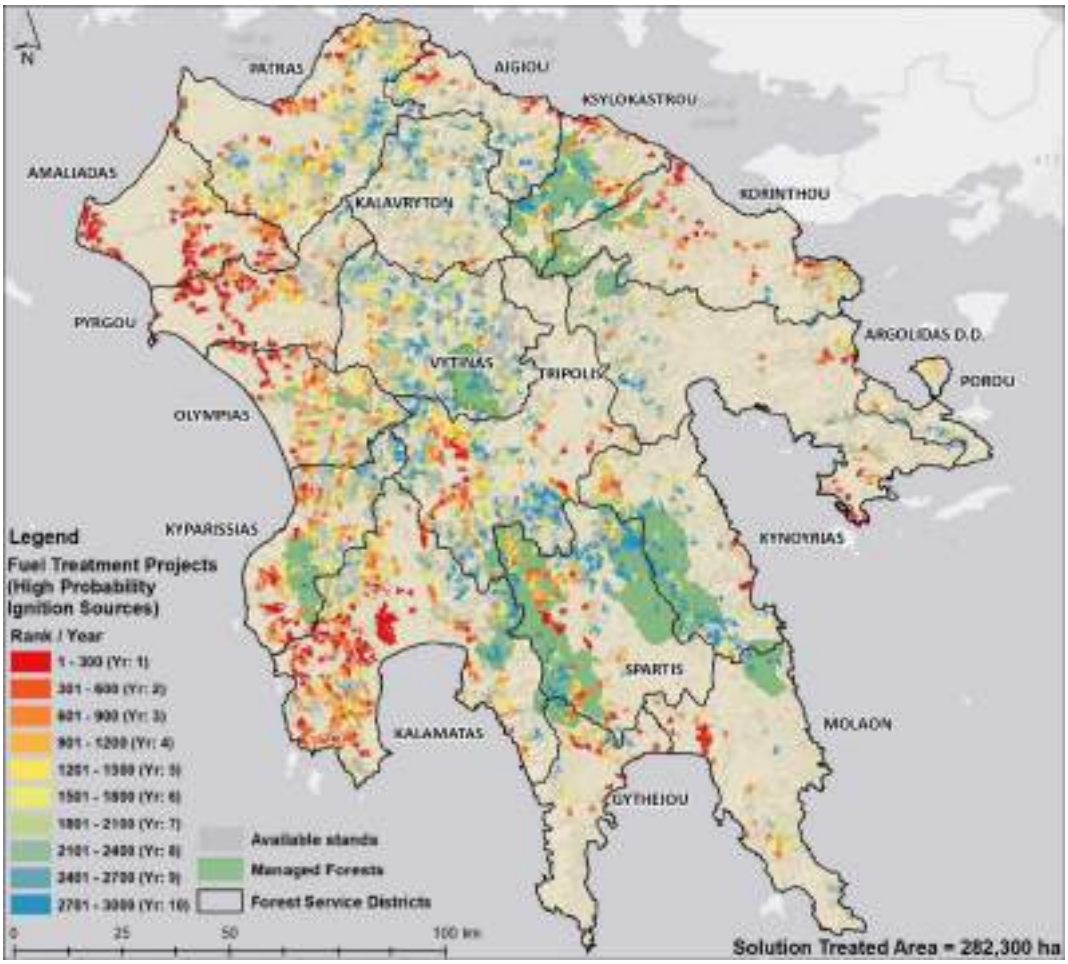

Figure 19 Map of the 3000 projects ranked by the level of attainment they achieve and distributed evenly across each year of the 10-year implementation plan of fuel treatment with the objective to reduce new ignitions by treated in areas with high ignition probability.

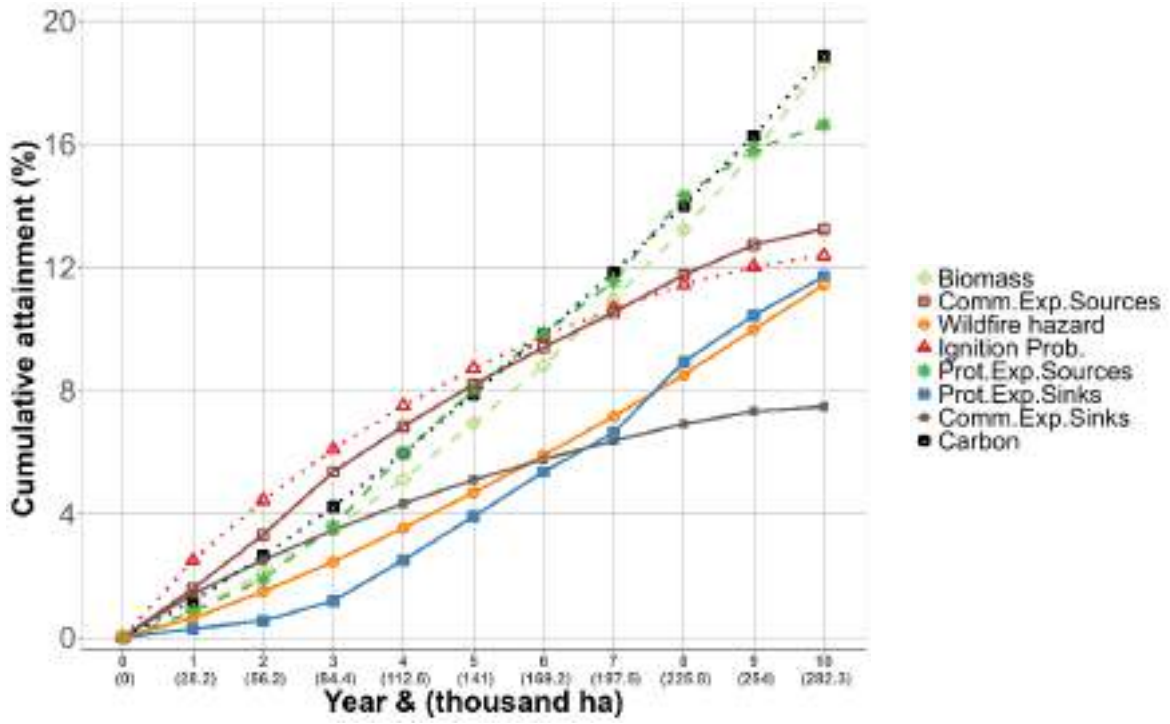

Figure 20 The 10-year implementation plan of fuel treatment with the objective to reduce new ignitions by treated in areas with high ignition probability.

The bulk of the projects are in the FS district of Kalamata (~37k ha), followed by Tripoli (~34k ha), Patra (29k ha) and Vytina (~25k ha), with the rest FS districts receiving less than 20k ha of fuel treatments during the 10-year implementation plan (Figure 21-left). The by far highest attainment is achieved in the FS districts of Kalamata (~2%), that also receives a high load of treatments, followed by Tripoli and Patra (~1.2%) (Figure 21-right). All other FS districts achieved attainment <0.8%. The attainment per year is almost evenly distributed among the 10-year period.

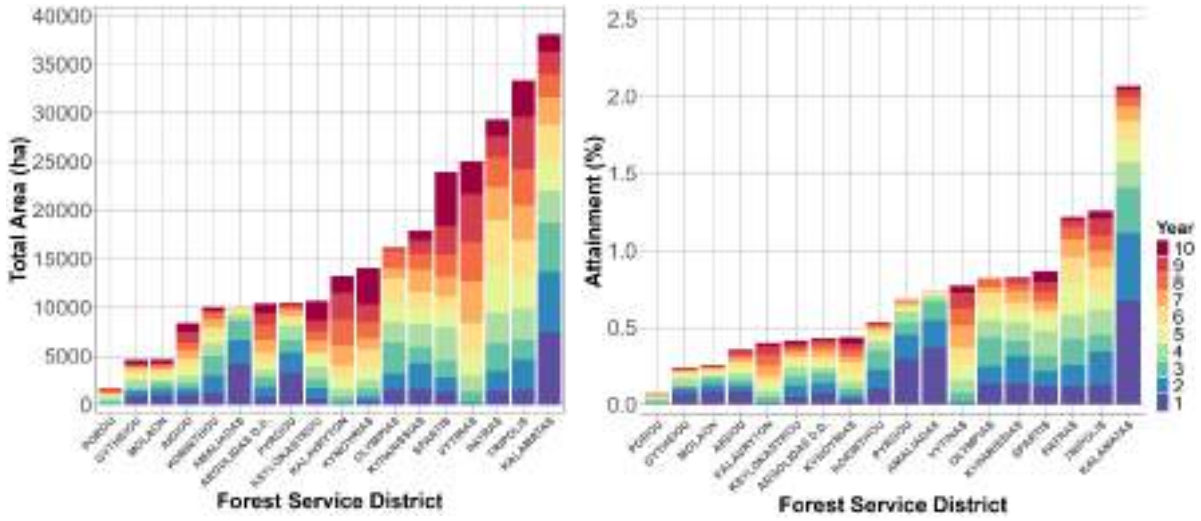

Figure 21 Left: area treated in ha for each Forest Service district by implementation year. Right: main prioritized objective attainment (%) for each Forest Service district by implementation year.

In Figure 22 we present all stands that met either more than two (orange) and three (red) objectives, but we do not suggest that spatial optimization allocation since the six out of eight objectives achieved very low attainments. There are about 160k ha of stands that meet at least two of the three main objectives examined above (community exposure sources, protected areas exposure sources and ignition probability), and 40k ha of stands that meet all three objectives (Figure 23). For the analysis, these stands are not grouped in projects. When we start selecting these stands that were part of the ForSys solutions for the three main objectives based on the best available stands for the objective of community exposure sources, we notice that by treating approximately 40k ha we can achieve a 12% for that objective, ~16% for the protected areas exposure sources, and less than 4% for the remaining objectives (Figure 23-left). By selecting with the same way, the stands that meet all three criteria, an attainment of community exposure sources of ~6% is achieved if we treat 15k ha, achieving a ~9% attainment for the protected areas sources and <2% for the other objectives (Figure 23-right). By treating the same amount of area (15k ha), we achieve larger attainments in the relevant optimization runs, i.e., 6% vs. 8% for community exposure sources and 9% vs. 15% for protected areas exposure sources.

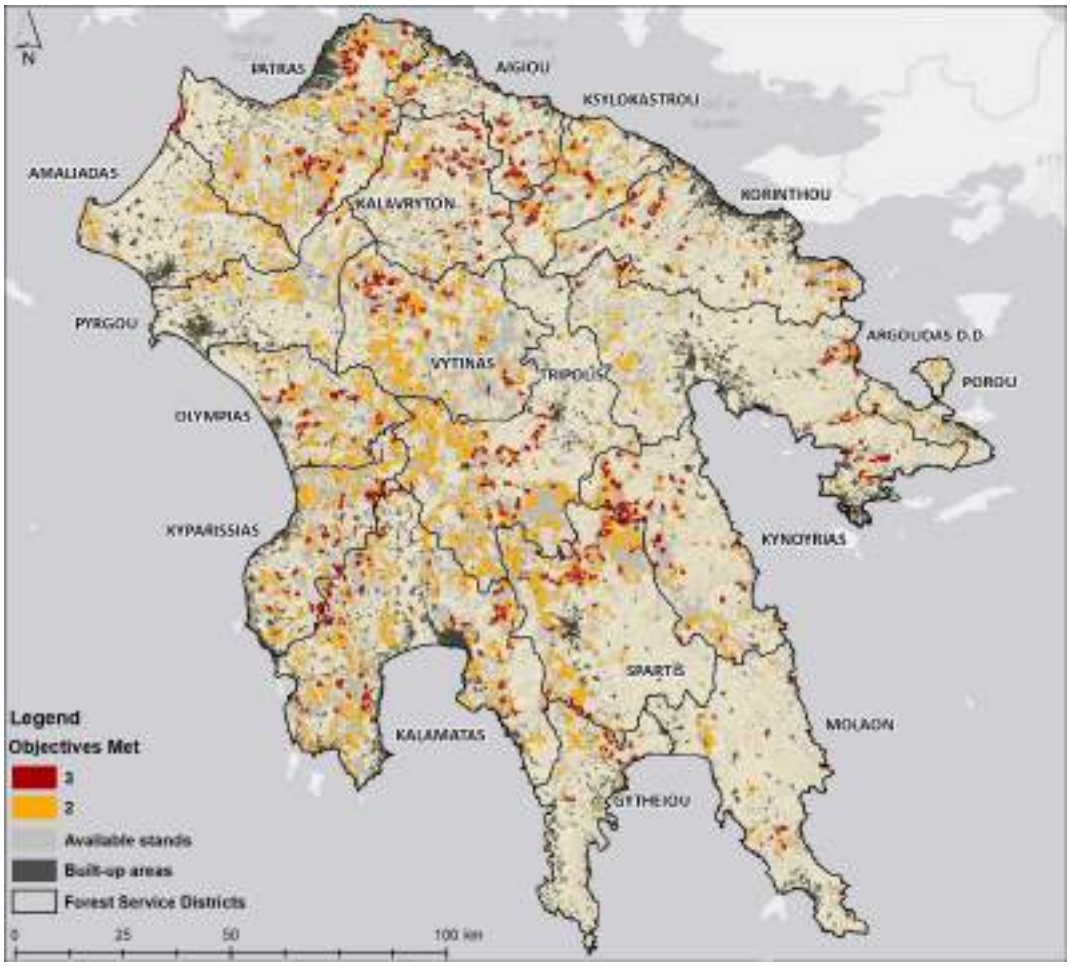

Figure 22 Allocation of stands that were selected from the three runs of SET1 that meet two or more objectives (orange) and three objectives (red).

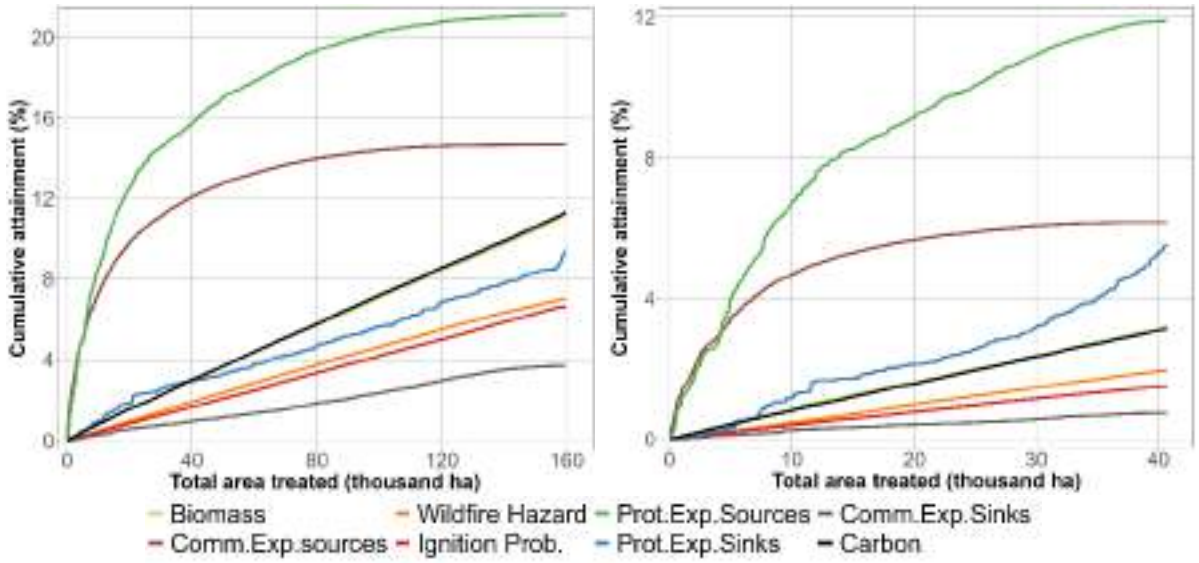

Figure 23 The attainment of the eight objectives analysed for the stands that were selected from the three runs of SET1 that a) meet two or more objectives (left) and b) meet three objectives (right). For graphing purposes, the stands selected first had the highest performance for the objective of community exposure sources.

4.1.3 SET2: Equity among planning areas

In this set of runs we chose to apply an equity approach among the different FS districts, meaning that we requested the same number of projects for each district with the same treated area. This set does not offer a 10-year management plan. ForSys, given that there are enough available stands, will return what was requested regardless of the area of each district (a district with 50k ha can potentially receive the same projects and area treated as one with 10k ha area). In Figure 24 the attainment curve of community exposure sources can achieve up to ~10% when all the solution area is treated (76,400 ha), with protected areas exposure sources achieving a roughly ~12% attainment. Biomass and Carbon are completely correlated and achieve a 5% attainment, with smaller achievements for the other four management objectives.

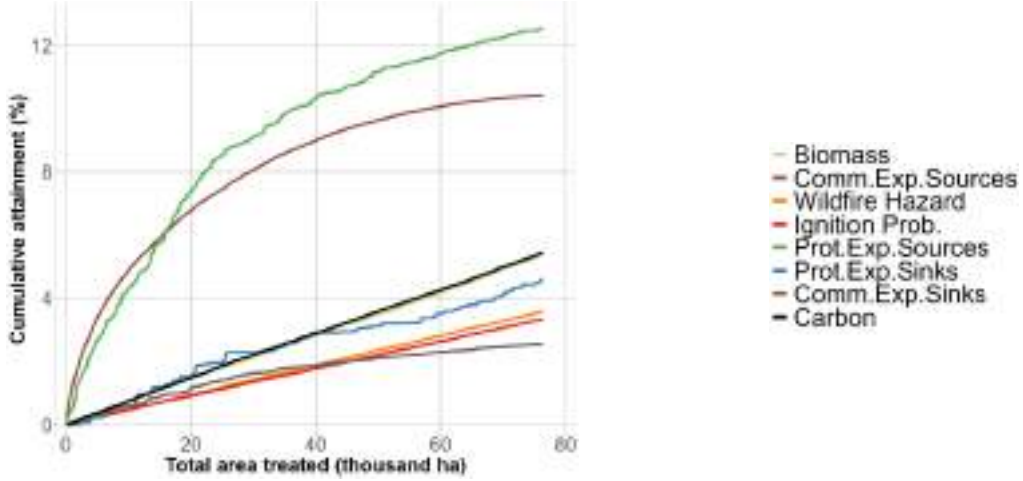

Figure 24 Area treated for all Forest Service Districts and the level of attainment for all objectives after prioritizing for the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

In Figure 25 we mapped the 50 projects of each FS districts, with warmer colours applied to the best performing projects when prioritized for the objective of community exposure sources.

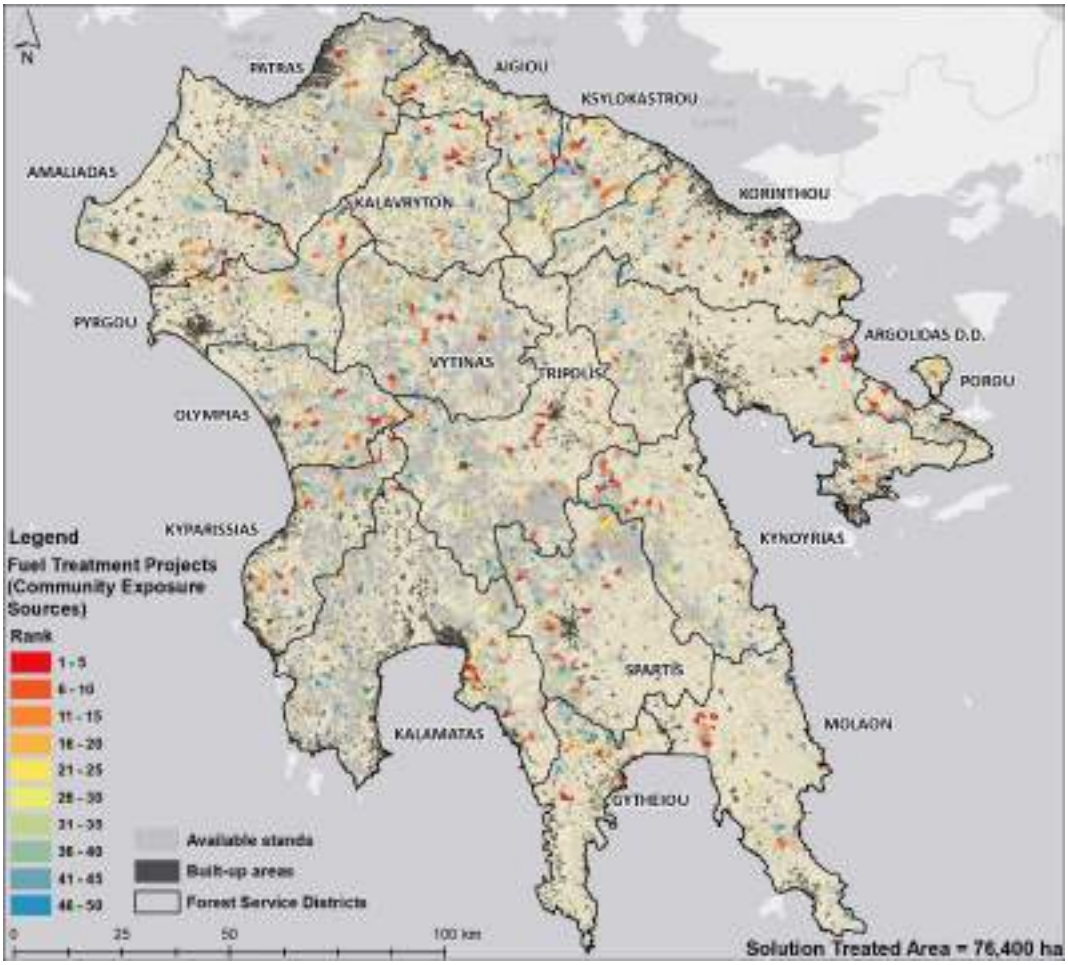

Figure 25 Map of the 50 best projects of each Forest Service District, ranked by the level of attainment they achieve, with the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

The FS district with the highest attainment for the main objective (community exposure sources) is Korinthou with ~1.5%, followed by Argolidas and Kynourias (~1%), with the remaining FS districts achieving < 0.75% attainment (Figure 26). Except for the two objectives that deal with the protected areas, where we notice that some districts are performing highly although not doing well with the main objective, all other management objectives achieved low attainment that is <0.5%.

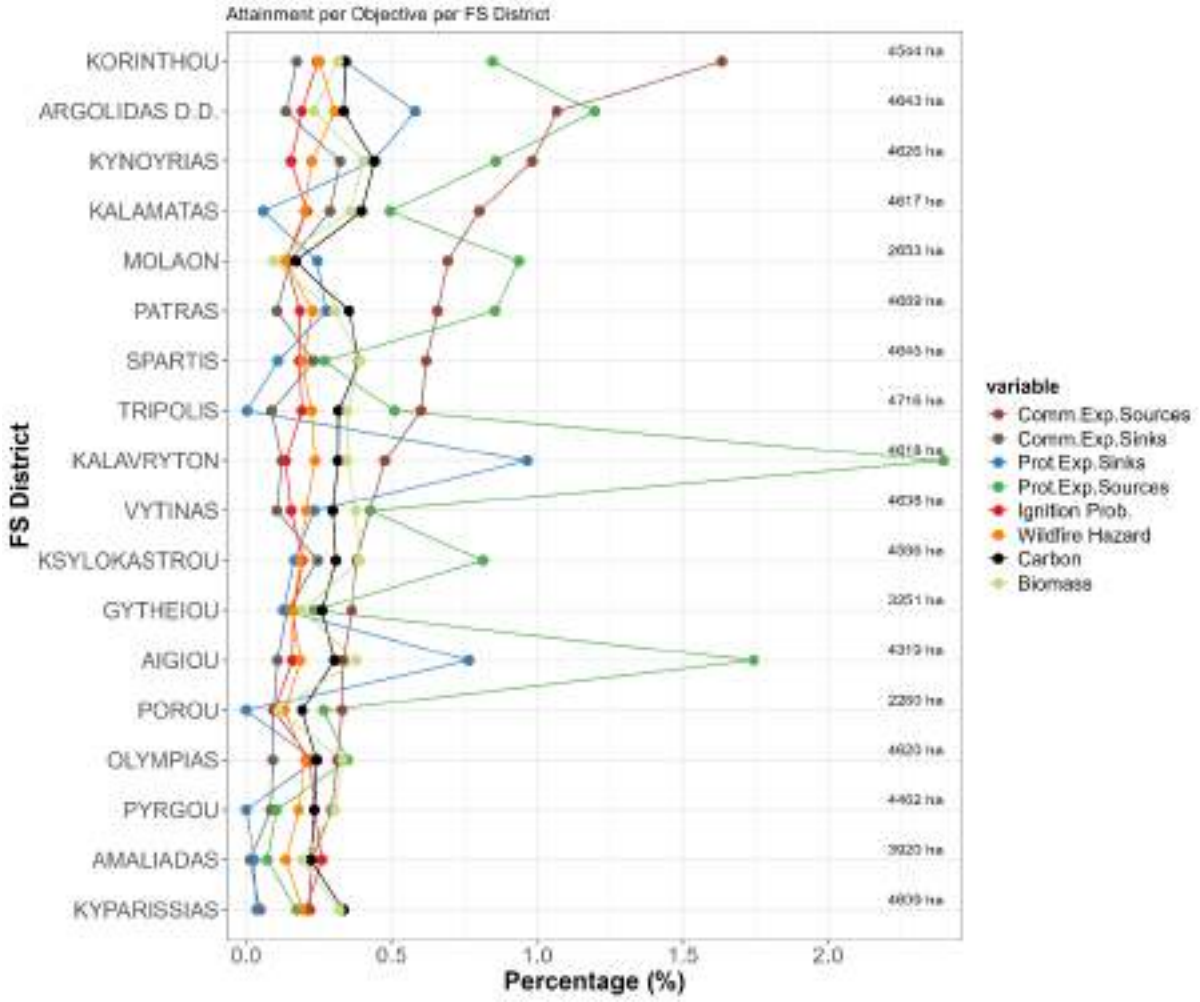

Figure 26 Attainment for each Forest Service District for the eight objectives when prioritized to reduce the exposure of developed areas from incoming wildfires (exposure sources).

The second run for this set prioritized fuel treatments for the management objective of limiting the exposure from the protected areas sources. In Figure 27 the attainment curve of the main objective can achieve up to ~18% when all the solution area is treated (52,600 ha), with community exposure sources and protected areas sinks achieving a roughly ~9% attainment. All the other management objectives achieved attainments <4%. In Figure 28 we noticed that the projects are, as expected, clustered around the protected areas, with three FS districts not receiving the number of 50 projects, due to their small area (Porou) or because there were no protected areas in proximity to or inside their boundaries or the available for treatment stands did not contributed enough to their exposure (Pyrgou and Amaliadas). Finally, in Figure 29 the FS district of Kalavryton achieved an impressive 3.5% attainment by treating ~4k ha in 50 projects, followed by Aigiou with 2.4% with 3.1k ha and Argolidas with 1.8% and 3.2k ha. All other FS districts achieved attainments < 1.3%. It is notable that for the FS districts of Korinthou and Kynourias, the objective of community exposure sources performed better than the main objective.

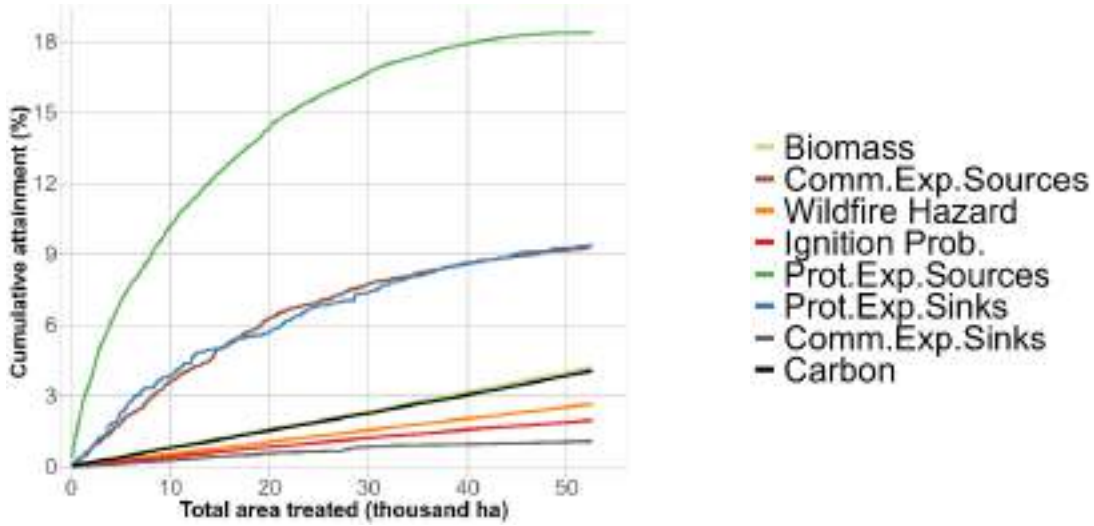

Figure 27 Area treated for all Forest Service Districts and the level of attainment for all objectives after prioritizing for the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

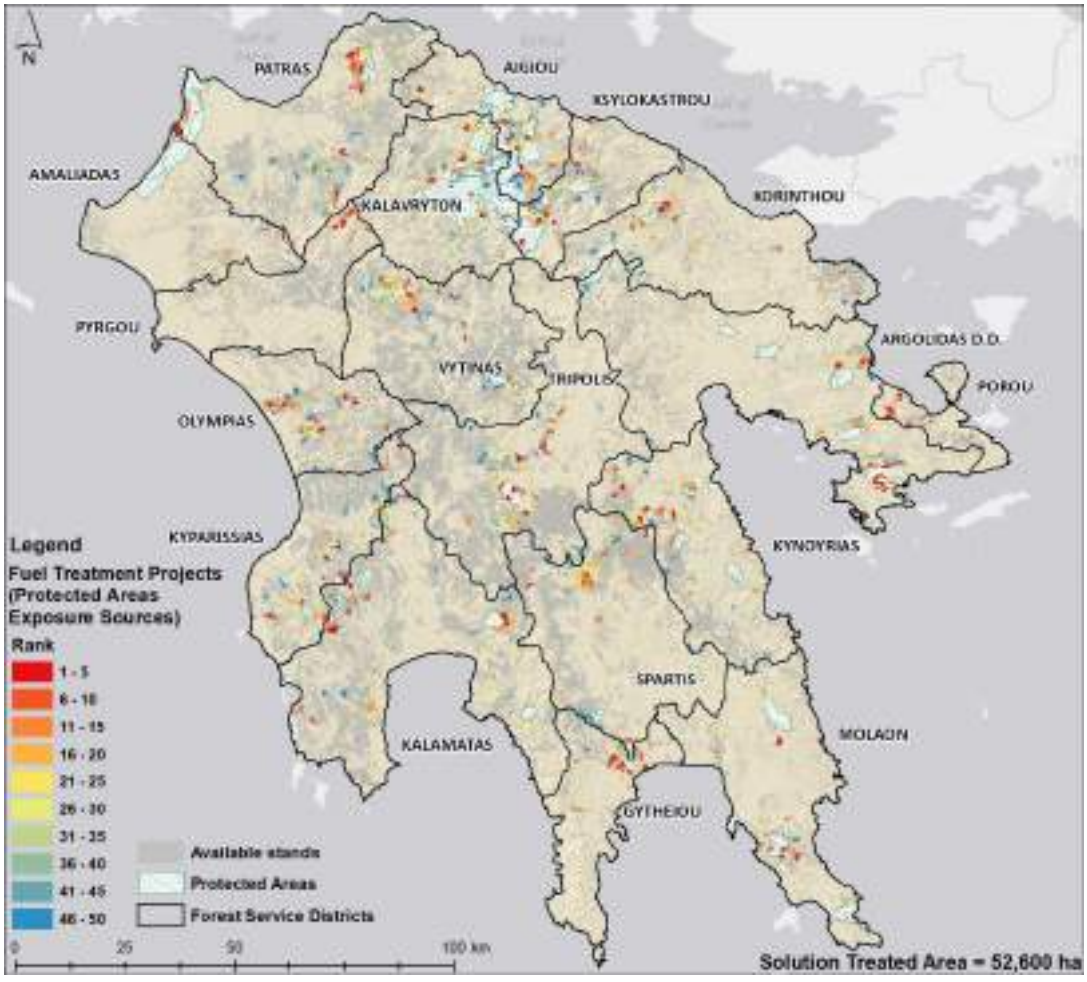

Figure 28 Map of the 50 best projects of each Forest Service District, ranked by the level of attainment they achieve, with the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

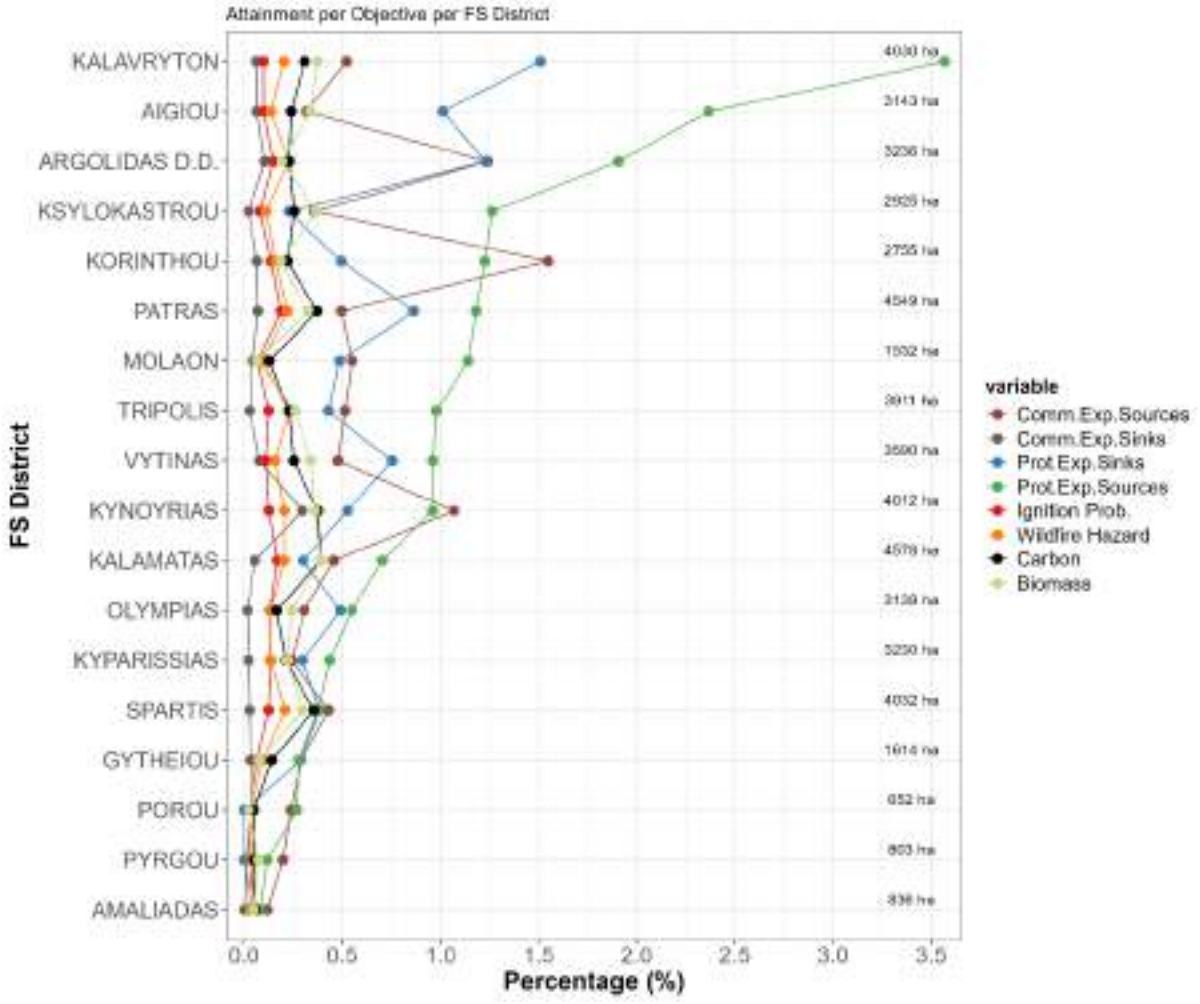

Figure 29 Attainment for each Forest Service District for the eight objectives when prioritized to reduce the exposure of protected areas from incoming wildfires (exposure sources).

The final run for this set prioritized fuel treatments for the management objective of limiting the ignition probability. In Figure 30 the attainment curve of the main objective (red line), although when starting and up to 10k ha is the best performing, as the treated areas increases and up to 40k ha is second in terms of attainment and behind the community exposure sources, to end up achieving ~4% when all the solution area is treated (83,700 ha), ranked fifth and behind protected areas sources (7%), community exposure sources (6%), carbon (~5.5%), biomass (~5%) and protected areas exposure sinks (~5%). In Figure 31 we can notice a good distribution of projects across the landscape, since all of the available stands had an ignition probability value greater than zero, so, there were plenty to select and build the projects. Finally, in Figure 32 the range of performance among the FS district is low, with the highest performing (Amaliada) achieving a ~0.3% and the lowest (Porou) a ~0.1% attainment. The treated area among the districts was quite similar and approximately at 4,000 ha. Some FS districts like Korinthou and Argolidas achieved high attainment for community exposure sources (due to their high population and building density), while others like Argolidas and Aigiou were high performing for protected areas exposure sources.

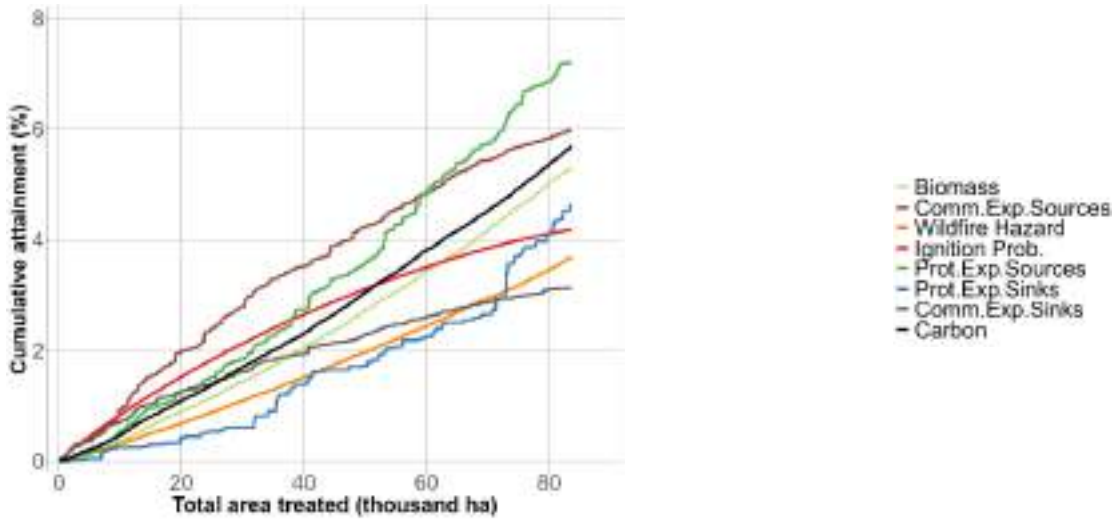

Figure 30 Area treated for all Forest Service Districts and the level of attainment for all objectives after prioritizing for the objective to reduce new ignitions by treating in areas with high ignition probability.

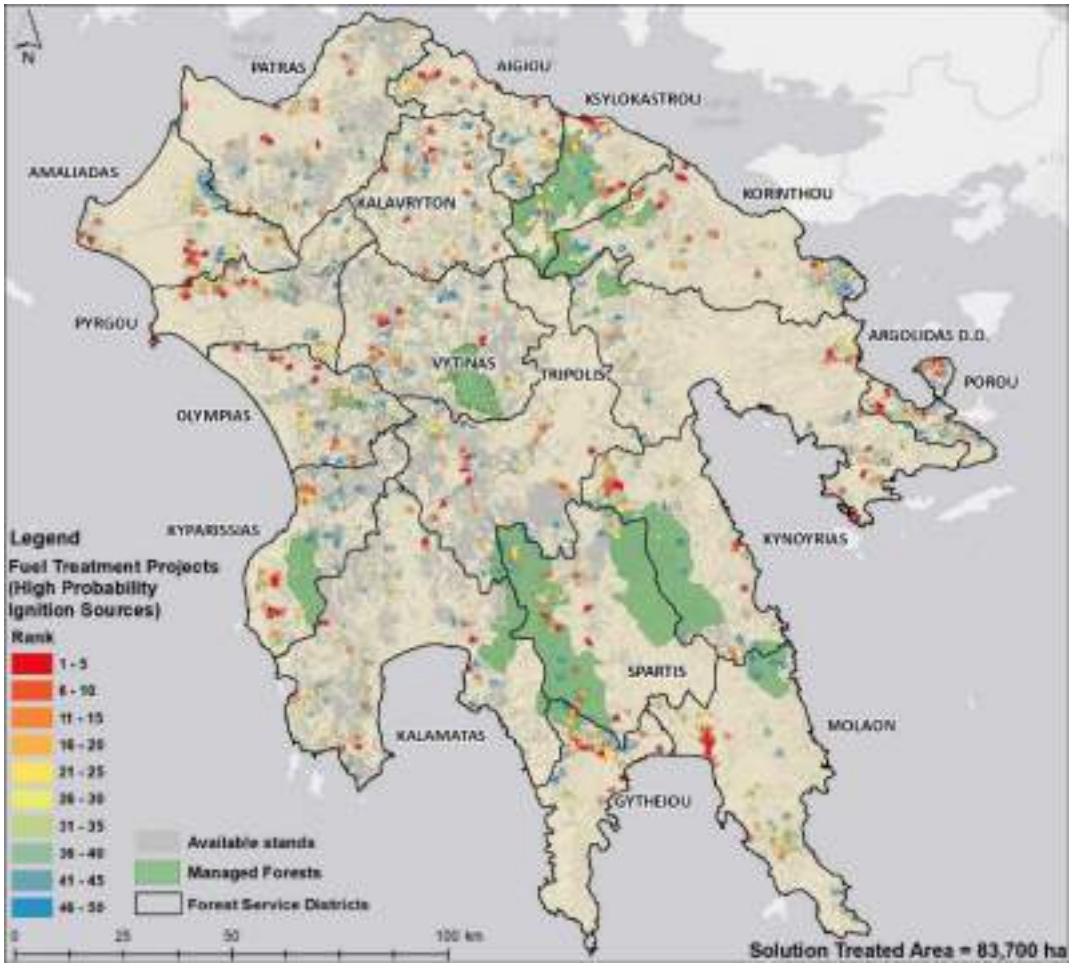

Figure 31 Map of the 50 best projects of each Forest Service District, ranked by the level of attainment they achieve, with the objective to reduce new ignitions by treating in areas with high ignition probability.

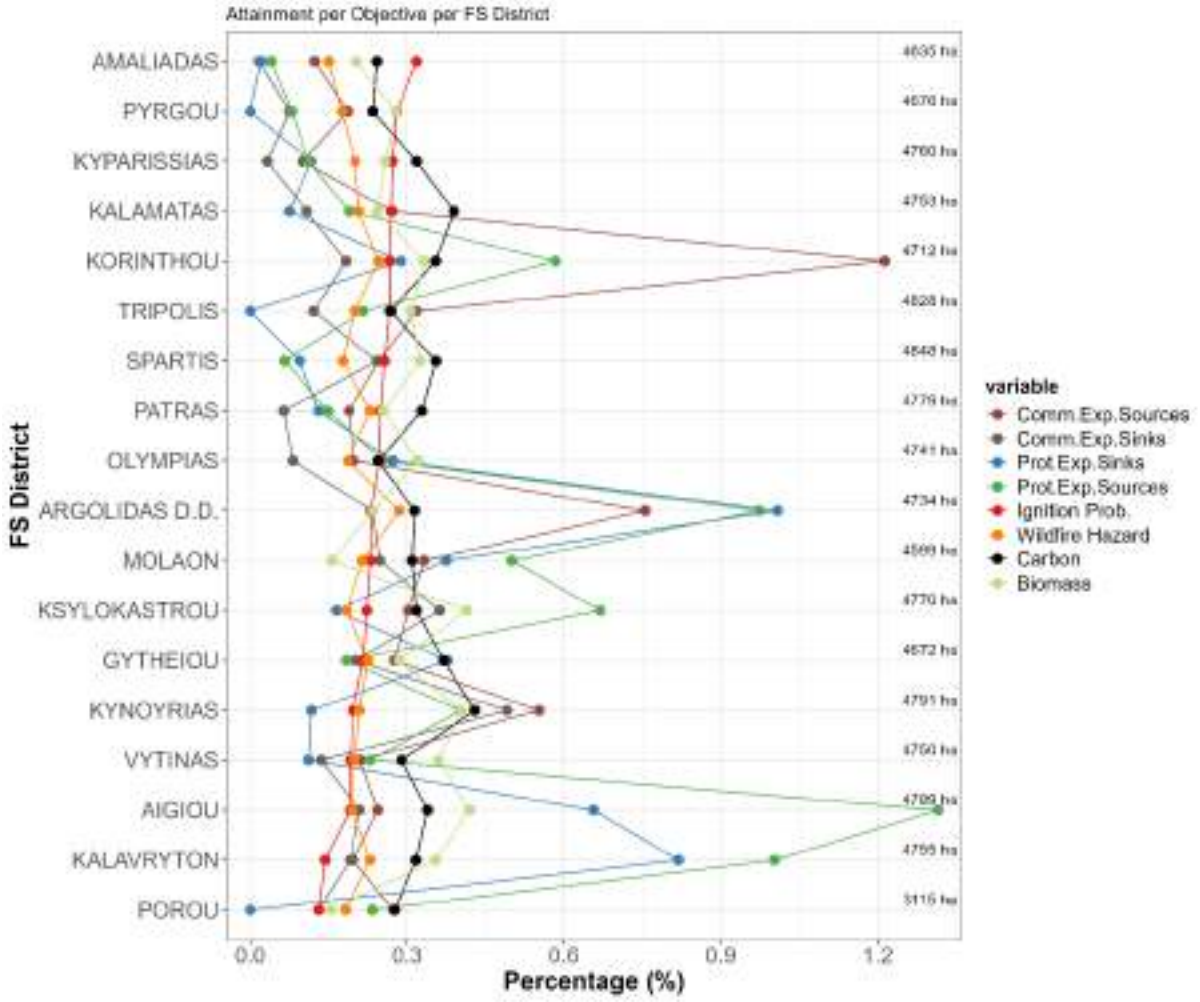

Figure 32 Attainment for each Forest Service District for the eight objectives when prioritized to reduce new ignitions by treated in areas with high ignition probability.

There are about 60k ha of stands that meet at least two of the three main objectives examined above (community exposure sources, protected areas exposure sources and ignition probability), and 15k ha of stands that meet all three objectives (Figure 33). When we start selecting these stands based on the best available stands for the objective of community exposure sources, we notice that by treating approximately 30k ha we can achieve a ~8% for that objective, ~10% for the protected areas exposure sources, and less than 3% for the remaining objectives (Figure 33-left). By selecting with the same way, the stands that meet all three criteria, an attainment of community exposure sources of ~3% is achieved if we treat 7k ha, achieving a ~3.5% attainment for the protected areas sources and <1% for the other objectives. For Greece, this is a typical and realistic scenario of how much area can be potentially get treated each year. Despite the fact that it seems a low percentage, if these stands are identified and receive treatments then a large measurable difference can be made in only one year for the objectives of community exposure sources and protected areas sources. In Figure 34 we present all stands that met either more than two (orange) and three (red) objectives.

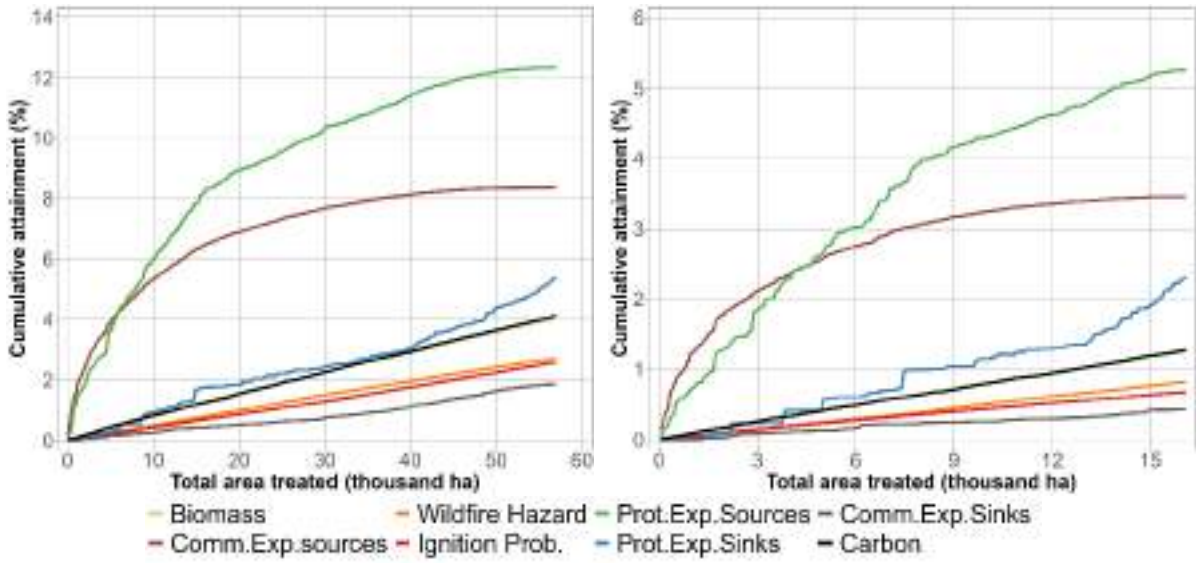

Figure 33 The attainment of the eight objectives analysed for the stands that were selected from the three runs of SET2 that a) meet two or more objectives (left) and b) meet three objectives (right). For graphing purposes, the stands selected first had the highest performance for the objective of community exposure sources.

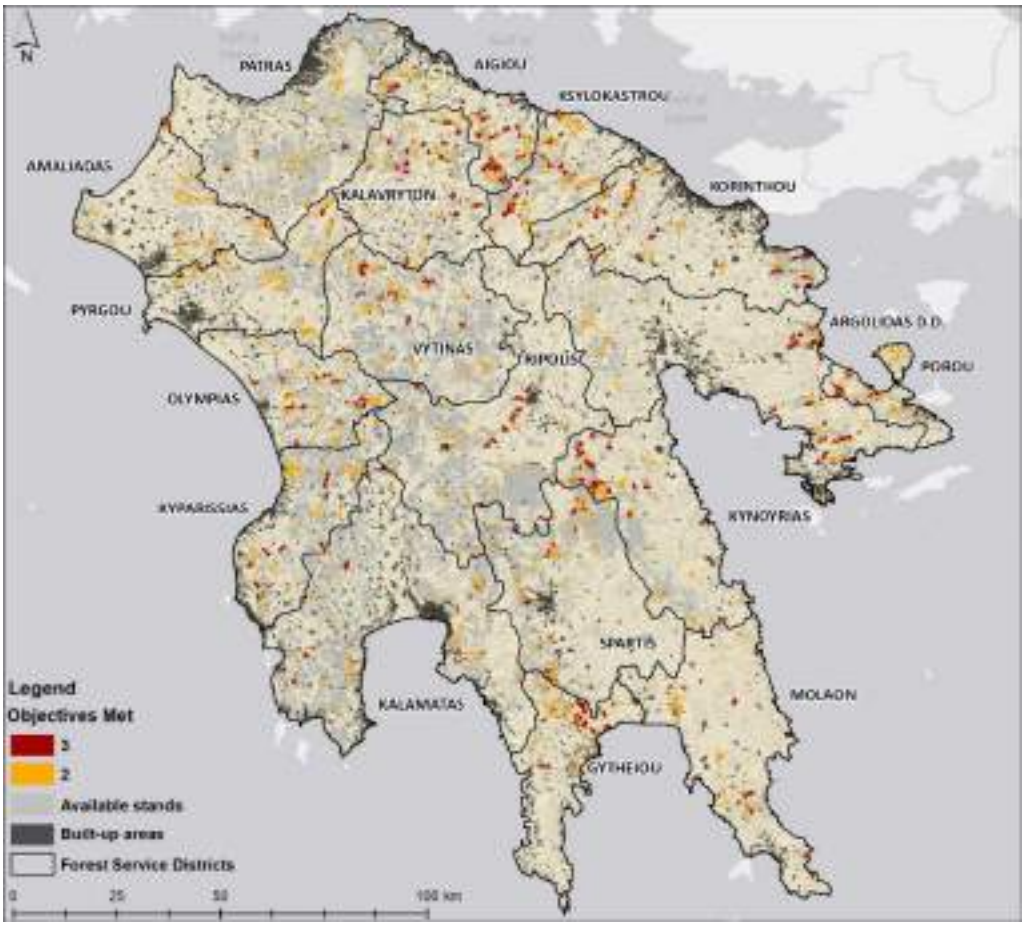

Figure 34 Allocation of stands that were selected from the three runs of SET2 that meet two or more objectives (orange) and three objectives (red).