FIRE-RES

Innovative technologies & socio-ecological-economic solutions for fire resilient territories in Europe

D2.5. IA brief 2.4: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE

www.fire-res.eu

fire-res@ctfc.cat

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Authors: Kostas Kalabokidis, Christos Vasilakos & Olga Rousou, University of the Aegean; Palaiologos Palaiologou, Agricultural University of Athens; José Calvão Borges, Susete Marques, Barbara Biju, Jean Magalhães, Dagm Abate, Sérgio Fernandéz, Srijana Poudel, Namrata Bhushal, Sandeep Timilsina & Sajal Saha, Instituto Superior de Agronomia – University of Lisbon; Sandra Pinto, Associação Florestal do Vale do Sousa; Christos Giannakopoulos, Anna Karali, George Katavoutas, Konstantinos V. Varotsos, Giannis Lemesios, National Observatory of Athens; José Ramón González Olabarría, Forest Science and Technology Centre of Catalonia; Andres Weintraub Pohorille & Rodrigo Mahaluf, Instituto de Sistemas Complejos de Ingeniería; Christophe Orazio, Lucas Moreews & Barry Gardiner, Institut Européen de la Forêt Cultivée; Jean-Yves Perez, SDIS 40; Marc-André Parisien, Canadian Forest Service; Alan Ager & Bruno Aparicio, USDA Forest Service; Fermín Alcasena, Public University of Navarre.

Abstract: Prioritizing investments in forest and fuel management projects and measuring outcomes is a significant challenge. As a result, the need to prioritize and strategically place fuel treatments requires a methodological approach that accounts for the implementation costs and prioritization based on different management objectives for different landscapes. For that purpose, the ForSys spatial planning system was used to modernize tools to prioritize forest and fuel management investments and understand trade-offs among alternative scenarios. In addition, a proposed methodological framework has been applied on a forest matrix scenario that reflects alternative spatial distributions of forest biophysical attributes, to obtain an optimized spatial landscape configuration to increase resilience and address concerns with EWE and, to minimize potential losses caused by EWE by the optimal allocation of management options over the landscape.

Key words: Scenario Planning; Fuel Treatments; Wildfire Simulations; Forest Management Policies; Trade-offs.

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1 Introduction

The scrutiny over fuel management programs requires a broader understanding of how abundance of often conflicting management objectives concerning conservation, restoration of fire-adapted forests and agency wood production targets influence the process of prioritizing limited budgets to conduct forest management activities. From a cost perspective, fuel treatment cannot be performed for very large areas, as the costs of the fuel treatment operations could exceed the benefits of the reduction in losses from wildfires (Schaaf et al., 2004; Thompson et al., 2013). As a result, the need to prioritize and strategically place fuel treatments requires a methodological approach that accounts for the implementation costs and prioritization based on different management objectives for different landscapes. This Innovation Action (IA) is comprised of two components: a) wildfire simulations and scenario planning for the optimal allocation of fuel treatment projects to achieve one or more forest management objectives and, b) development of a spatially explicit forest management problem formulation that recognize the risk of fire to occur and accounts for that the probability that a forest stand will burn depends on stand-level characteristics and biophysical factors. This probability also acknowledges neighbourhood relations, and the potential of wildfire spread between stands.

Since the main scope of this Innovation Action is to optimize landscape configuration and fire management policies to minimize expected losses from Extreme Wildfire Events (EWE), our research included a large-scale application of different fire spread modelling methods that include the Minimum Travel Time algorithm (MTT), as implemented through FSIM (for Greece) and FConstMTT for Portugal and Catalonia (Alcasena et al., 2021b; Finney et al., 2011), Cell2Fire for Chile (Cristobal Pais et al., 2019), and Burn P3 for France (Parisien et al., 2005) to assess the influence of potential fires to populated areas and the difficulty of fire suppression. The methodology is ideal to simulate a set of fuel management scenarios and analyse the performances of fuel treatments using objective measures like burn probability, flame length or fire size, and may therefore help forest management and fuel treatment planning. Moreover, this methodology provides a quantitative framework to analyse losses and benefits from wildfires and quantify the effectiveness of fuel management options, while considering wildfire propagation and intensity.

The use of wildfire simulators has provided a better understanding of forest fire dynamics and paved the way for the development of spatially explicit forest management problem formulations that recognize the risk of fire. In these formulations, the probability that a forest stand will burn depends on stand-level characteristics and biophysical factors. This probability also acknowledges neighbourhood relations, and the potential of wildfire spread between sets of neighbours. Yet, it does not consider the potential of a stand to burn because of ignitions in distant stands. This IA addresses this technological gap.

The scenario planning framework, and its pilot application in each Living Lab (LL), helps towards a better understanding of trade-offs and assesses the progress (and obstacles) towards nationally and regionally identified priorities and targets in forest restoration and fire risk management; and discovers the best investment strategies at the appropriate scale. ForSys, a Scenario Planning software developed by the USDA Forest Service, fills a

gap in current planning by Forest Management Services of each LL by providing a way to understand how specific cross-boundary priorities, such as reducing wildfire impacts to communities, lead to outcomes on the ground (Ager et al., 2019; Palaiologou, Kalabokidis, Ager, et al., 2021). The model is spatially explicit and uses multi-criteria prioritization and optimization created to design fuel treatment and restoration scenarios rapidly. Scenario planning has become a top-notch approach used by many agencies around the world [e.g. Shared Stewardship Strategy of the USDA Forest Service (2018)] for the prioritization of management on forested areas, helping them to decide how to deal with uncertainties in the future planning environment, including the identification of significant events, the main actors and their motivations.

Possible trade-offs among alternative fuel management strategies (e.g. address wildfire risk to the WUI originating from wildfires on public forests versus achieving the timber harvest targets) highlight the importance of careful prioritization when limited resources are available to manage fuels. For each Living Lab, ten fuel management allocation scenarios were tested, each considering one or more (for the cases of trade-off analysis) of the four major fire management objectives (ecological, firefighting, social and economic). Our goal was to explore the possibility of implementing alternative treatments and obtaining potential revenue from silvicultural treatments on different treatment units.

The main outcomes are presented in maps and summary charts and graphs to facilitate knowledge transfer, inform decision-making and assist ongoing landscape management plans in the different Living Labs. In addition, we present a management planning approach to allocate management options, i.e. fuel treatments to jointly optimize the provision of ecosystem services, namely wildfires regulatory services while accounting for fire dynamics.

For the second component of this IA, the design of resilient landscapes was built from the knowledge of key types of parameters such as the probability of an ignition occurring in a stand, the flammability of a stand, the tendency for a fire to spread to a given stand from each of the stands that are adjacent to it, and the value at risk in each stand. This design requires the use of effective, but simple, problem formulations in which the practitioners can fully understand the driving mechanisms of the models and algorithms involved. Each of these parameters are a function of the characteristics of the stand, the characteristics of the surrounding stands and the local climate and terrain.

The model of the system needs to be accurate and yet flexible and capable of providing feasible solutions for real and complex problems within a limited amount of computational time. The implementation of exact methods such as mixed integer programming can be constrained by problem size in the context of modern forest planning, and heuristics approaches are often preferred in the optimization arena to solve complex combinatorial problems, even though these approaches cannot guarantee global optimality. However, the tuning process can be optimized and nearly optimal outcomes for very complex formulations can be achieved at acceptable computational cost.

The questions addressed in this Innovation Action were where can fuel treatment projects be located to maximize the improvement in resiliency per area treated (meaning reduction in potential wildfire mortality of large diameter pine trees), and what is the trade-off between treatment intensity (amount of fuel removed) and total project area on predicted total mortality.

Based on a proposed methodological framework on a forest matrix scenario that reflects alternative spatial distributions of forest biophysical attributes, the specific objectives of this component of the IA are: i) to obtain an optimized spatial landscape configuration to increase resilience and address concerns with EWE ii) to minimize potential losses caused by EWE by the optimal allocation of management options over the landscape.

1.1 Study Areas Inside Living Labs

1.1.1 Living Lab Greece

Forest vegetation in Greece reflects the Mediterranean climate and mountainous topography of the landscape as well as the relatively poor soil conditions. The influence of humans, present in the area for more than three thousand years, is also reflected in the distribution and mainly the degraded condition of the forests. More than 21% of the area of Greece (about 2.8 million ha) is characterized as forested. However, less than half of this area is covered by "tall" timber producing forests; most of them are conifer forests. The remaining area is occupied by "low" or coppice forests that produce mostly fuelwood. In addition to the forest lands above, there are approximately 3.2 million ha of partially forested areas and shrublands (occupied mostly by evergreen broad-leaved shrubs). There are also approximately 1.9 million ha of grasslands and *phrygana*, the latter being the east Mediterranean version of *garrigue*, consisting of low, often thorny shrubs, such as *Sarcopoterium spinosum, Phlomis fruticosa, Euphorbia acanthothamnos, Thymus* spp., and *Cistus* spp.; they are mainly used for grazing and beekeeping.

Drought resistant evergreen broad-leaved species (*Quercus coccifera, Quercus ilex, Laurus nobilis*, *Ceratonia siliqua*, *Olea europaea*, *Arbutus* spp., *Cistus* spp., *Erica* spp., *Pistacia* spp., etc.) and pine trees (*Pinus halepensis*, *Pinus brutia*, *Pinus pinea*, etc.) occupy the lower elevations in the country (up to 300 m in northern Greece and 800 m in the south). Next, there is a zone of deciduous broad-leaved species (*Quercus* spp., *Fagus orientalis*, *Castanea vesca*, etc.) and conifers (*Pinus nigra, Pinus pinaster*, *Cupressus sempervirens*, *Abies cephalonica*, etc.) that reaches 900 m in the north and 1,200 m in the south of the country. At higher elevations, up to 1,800 m, vegetation includes cold-tolerant broad-leaved trees (*Fagus sylvatica*, *Fagus moesiaca*, *Quercus sessiliflora*, *Quercus pedunculata*, *Populus tremula*, *Betula pendula*, *Fraxinus excelsior*, *Acer* spp., etc.) and conifers *(Pinus nigra*, *Pinus sylvestris*, *Abies alba*, etc.). Finally, at elevations up to 2,200 m, vegetation includes mostly cold-tolerant conifers and a few broadleaves (*Picea abies*, *Abies alba*, *Pinus peuce*, *Pinus sylvestris*, *Pinus heldreichii*, *Populus tremula*, *Sorbus aucuparia*).

Considering the above, it is noteworthy that the changes occurred on the Greek landscapes during the past three decades are unprecedented. It is not only the three fire seasons (2007, 2021 & 2023) of Extreme Wildfire Events (EWE) that shook the societal and political status quo regarding the way Greece confronts, manage and live with fires, but

also the way that these EWE reshaped the biophysical and social realities. While the annually burned area in the country has been around 40 thousand hectares on the average in the last 40 years from approximately 1,500 fires per year, certain years stand out as exceptionally catastrophic. These are the years 1985 and 1988 in the 1980s, with 105,450 ha and 110,501 ha respectively, and then 2000 with 145,033 ha and 2007 with 225,734 ha burned in the 21st century. More than 2,500 ignitions occurred during the years 1992, 2000 and 2001. The largest fire events of history for the prefectures of Greece took place in the record year of 2007, namely in Achaea (30,000 ha), Messenia (11,000 ha), Laconia (22,000 ha) and Ilia with four wildfires (40,000, 32,000, 30,000 and 12,000 ha). Evia also experienced a large-scale event during 2007 with 18,000 ha burned. Attica experienced the largest fire event during 2009 with 20,500 ha burned and repeated catastrophic wildfire years in the vicinity of certain highly populated suburbs of Athens. More recently, in 2021, an Extreme Wildfire Event in Greece took place in northern Evia. It exceeded 50,000 ha in a year that the total burned area reached 108,418 ha, including agricultural areas, according to the statistical data of the European Forest Fire Information System (EFFIS). This wildfire destroyed the economic fabric of the region and huge funding were funnelled there by the Greek government to maintain the social balance and change the established economic paradigm. In addition, the destruction of so many hectares of forested lands in an isolated islandic system, and the years required to regenerate, is paving the ground for more natural disasters such as increase flooding and soil erosion, rockfalls and soil loss.

During the year 2022, the Hellenic Fire Service had to confront 9,856 ignitions (both agricultural and wildfire), i.e., about 27 fires per day and 28,500 ha burned. During the year 2023 the Hellenic Fire Service had to confront 8,257 ignitions, about 23 fires per day and 177,000 ha. It is worth noting that only two of these ignitions were enough to cause the 60% of the total annual burnt area for that year. During July 2023, and specifically between 15 and 31, seven major wildfires occurred in Greece in the areas of Corfu, Aigio, Dervenochoria, Attica/Kuvaras, Karystos, Nea Anchialos and Rhodes. These fires burned a total area of almost 47,000 ha. And while in 2022 the number of ignitions was higher by 1,600 incidents, the total burnt area in 2023 almost quadrupled. This is not only a statistical oxymoron but also a substantial problem. Another EWE example occurred in 2023, when the largest fire recorded for the past 20 years in Europe burned an area exceeding 93,500 ha in Evros, northern Greece, raging for two weeks and causing smoke issues 2000 km away from the burning front.

As we enter the era of mega-fires, we expect that similar wildfires will occur not only in regions prone to large fire propagation such as the Peloponnese, Attica and Evia, but also to high elevation ecosystems as those found in Central Greece and Epirus. By default, these ecosystems have reduced defences from both the non-fire-resistant vegetation species that cover them and by the intense depopulation that led to land abandonment and in turn, fire deficiencies that enhance fuel accumulation. To put it simply, there is not a single region in Greece that can claim that will remain “fire-proof” during the era of mega-fires. A fire of even one hour's duration can cause the death of dozens of people (example the fire in Mati, Attica) or one fire in a region with a small number of incidents and burnt areas can cause 100,000 ha of burnt forest vegetation.

1.1.1.1 The Peloponnese

The Peloponnese is geographically located in the southern part of mainland Greece and is the largest peninsula of the country and one of the nine geographical regions of Greece, covering an area of 21,549 km^2. Peloponnese has a population of approximately 700.000 inhabitants with Patras being the major urban center (approximately 171,000 inhabitants). Land uses are mainly agricultural whereas some mild tourist activities take place in the coastal areas. It consists of seven Prefectures, each having its own Forest Service District: Achaia, Corinthia, Argolida, Arcadia, Lakonia, Messinia and Ilia (Figure 1). For the management and assessment of aquatic systems, the Peloponnese is divided into three Water Departments. The topography of the geographical area is intense with large mountain ranges reaching a maximum of 2,407 m a.s.l. (Taygetos, Aronian Mountains, Mainalo, etc.) and large plains such as Ilia, Corinthia, and parts of Messinia. The percentage of lowland areas (up to 300 m altitude) is 38%, of semi-mountainous areas (300–600 m) is 22%, and of mountainous areas (over 600 m) is 40% (Tsagari et al., 2011). The climate is controlled by those terrain features, with the central part demonstrating a temperate climate and Mediterranean type climate at the coastal parts, with summer, i.e. June to August, being the dry period and precipitation demonstrating a seasonal pattern, with highest frequency and height during winter. Mean annual precipitation is higher in the west parts and reaches 800 mm, whereas in the eastern parts mean annual precipitation ranges from 600 to 700 mm during 1961–1990 (Pnevmatikos & Katsoulis, 2006).

Vegetation types follow the diverse topography with the typical Mediterranean Aleppo pine (*Pinus halepensis* Mill.) forests and the phryganic and evergreen sclerophyllous shrublands in the lowlands (Figure 1). In higher altitudes, above 800 m, Black pine (*Pinus nigra Arnold* subsp. *pallasiana* (Lamb.) Holmboe) and Greek fir (*Abies cephalonica Loudon*) dense forests are found. Local Stone pine (*Pinus pinea* L.) stands are found along the west coast and several dense groups of deciduous oaks can be seen in the hinterland.

The administrative region of Peloponnese is the third among all Greek regions in terms of ignition frequency (about 26,000 fires) and second in total area burned. The catastrophic fires in Corinthia in 2000 (20,000 ha burnt), in Zacharo in Ilia in 2007 with human losses (50,000 ha burnt), in Achaia in 2000 and 2007 and in Laconia and Messinia in 2007 are also mentioned.

The implementation of the ANTINERO Programme targeted to implement fuel treatments and apply fire protection measures that facilitate fire suppression, targeting to treat 5,200 ha of forests and maintain 2,000 km of firebreaks across Greece (budget of 72 million euros). For the Peloponnese, the first phase of the programme (ANTINERO 1) for the year 2022 took place in the Regional Units Ilia, Corinthia, Argolida, Arcadia and Laconia. The project applied clearings for biomass removal and tree removal on both sides (10 m wide) of the existing forest road network. Work intended to maintain and improve the forest road network accessibility and effectiveness of firebreaks. The ANTINERO 2 programme has been expanded to include erosion and flood control projects, with an 80% transfer of funds from afforestation to prevention. The project had an implementation schedule between 25/11/2022 to 31/12/2024, targeting to treat 6,500 ha of forests and maintain 1,000 km of firebreak zones (budget of 86 million euros). The work that had not been

carried out by ANTINERO 1 was transferred and supplemented to ANTINERO 2, making a more mature project with greater efficiency and planning. The project budget was larger than the previous one. In summary, the planned area of the above projects for the Regional Unit of the Peloponnese amounts to approximately 2,700 ha.

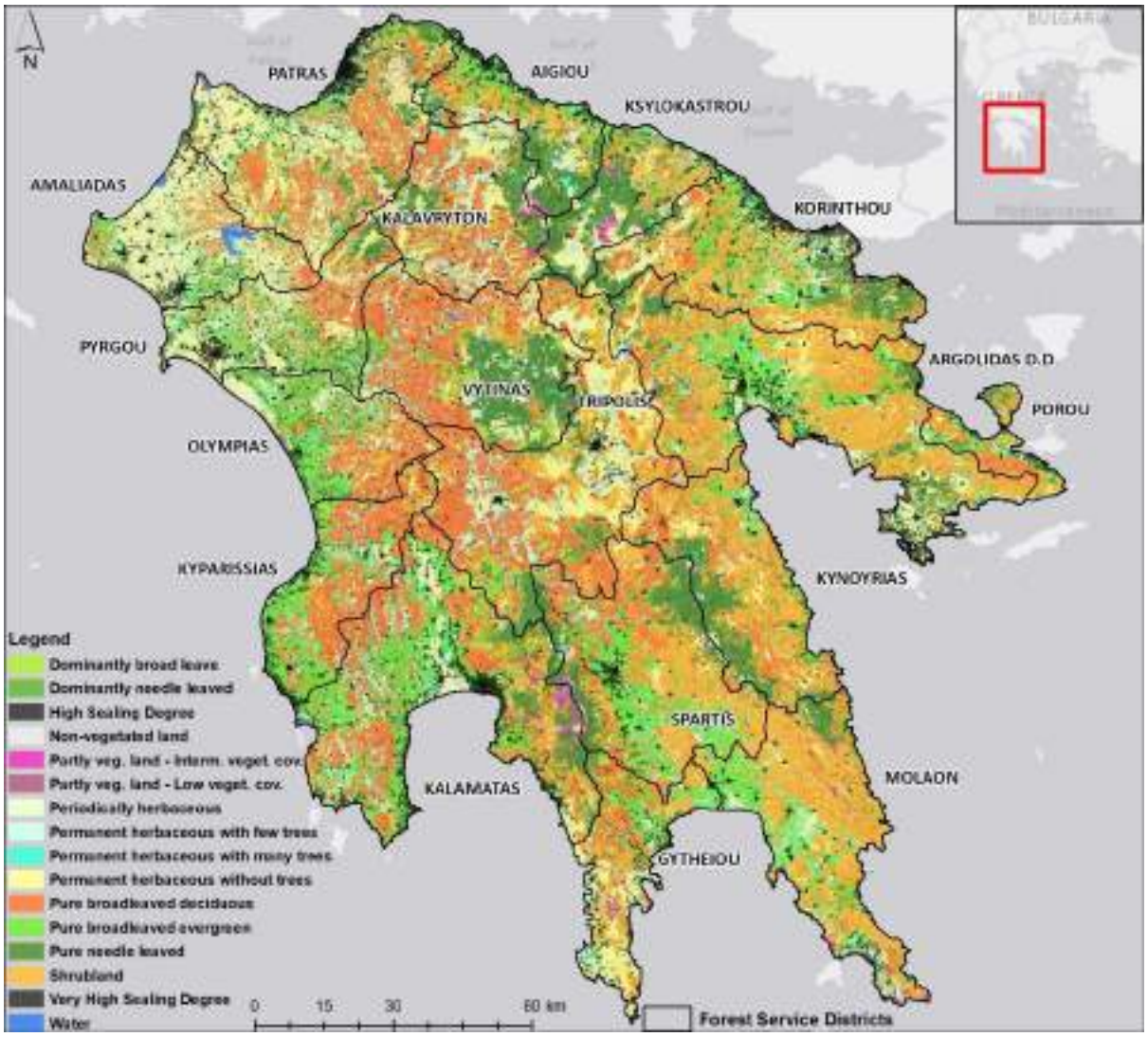

Figure 1 Land cover in the Peloponnese region, Living Lab Greece.

The ANTINERO 3 programme, targeted to prevention, implementation of fire protection and the conservation of forested ecosystems for the years 2024-2025, with the project starting on 06/11/2023 and ending on 31/12/2025. This project is ongoing and includes, in addition to the maintenance of the forest road network and construction of crossings and bridges in forested areas, the opening of new firebreak zones and the clearing on both sides of the forest road network in a radius of 30 m width (increased from the 10 m of ANTINERO 1 & 2), improving access and fire protection in the risk zones. This programme thus activates both pilot and indicative mixed firebreaks and the creation of mixed or pure stands of vegetation with broad-leaved species to reduce the spread of fire. The budget of the project is three times more (250 million euros) than ANTINERO 2 (targeted to treat 7,100 ha of forests, with additional 10,000 ha across the roads, and

create 6,500 ha of new and maintain 2,200 ha of firebreak zones across Greece – reaching an estimate of 26,000 ha of treated and intervened areas).

For the Peloponnese, eight forest management plans were commissioned, of which 2 were commissioned to the Forestry Department of Pyrgos for 30,236 ha, two to the Forestry Department of Olympia for 5,384 ha, three to the Forestry Department of Vytina for 29,405 ha and one to the Forestry Department of Tripoli for 17,750 ha. In the future, the proposal will include 27 more studies in 13 Forestry Offices of the Peloponnese. The usual practice followed so far for forest management in the large and productive forest complexes (e.g., Mt. Mainalo in Arcadia) is the harvesting for timber production. The tree species usually targeted for management by the abovementioned studies are *Abies cephalonica* (or Hybrid), mixed evergreen broadleaves, *Quercus ilex* and *Pinus nigra*.

1.1.1.2 Lesvos Island

Lesvos Island has three selected managed forests for which we estimated biomass and other relevant variables: Ampeliko forest, Agiasos forest and Vasilika forest (Figure 2). From a phytosociological perspective, the wider study area is part of the Euro-Mediterranean vegetation zone (*Quercetalia ilicis*), specifically the subzone *Oleo-Ceratonion* and the growth area *Oleo-lentiscetum*. The most common configurations are:

1. The coniferous vegetation (*Coni-silvae*), represented by the plant community of *Pinus spp.* (*Pinus brutia*).
2. Evergreen broad-leaved shrubs (*Duri-silvae*) that grow where the undergrowth is possible or in forest clearings.
3. The riparian vegetation (*Fluvi-silvae*) that dominates streams and creeks.
4. The grassland flora is composed of different types of grasses that belong to the *Graminae* and *Compositae* families.

The Ampeliko Forest is in the Plomari region, west of the city of Mytilene, at 40 km. It covers an area of 809 ha, of which 89% is wooded, 6% is partially wooded, 2% is bare, and 3% is barren. The Ampeliko Forest belongs to Management Class I – *Pinus brutia* and is divided into 12 sections. The soil has a medium-thick litter layer of decaying pine needles and is characterized as partially fertile. Even though the slopes range from 10% to 90%, with the dominant slope being 40–70%, there is sufficient forest cover to prevent erosion and torrents. The following species can be found in the Ampleliko forest: *Pinus brutia, Quercus coccifera, Juniperus oxycedrus, Pistacia lentiscus, Arbutus unedo, Myrtus communis, Olea oleaster, Erica verticilata, Erica arborea, Pyrus amygdaliformis, Prunus cocomilia, Phillyrea latifolia, Platanos orientalis, Nerium oleander, Vitex agnus-castus, Spartium junceum, Salix albra, Lavantula stoechas, Rubus fruticosus, Rubus ulmifolius, Rosa sempervirens, Cistus monspeliensis, Prtium spinosum, Origanus repacleoticum*, *Phlomis fruticose*. The major fire incidents occurred in this forest were minor in terms of burned area: 1921 (40 ha); 1950 (3 ha); 1952 (0.5 ha); 1957 (1 ha); 1962 (3 ha); and 1979 (9 ha).

The Agiasos forest, also called "Big Lake", is located at a distance of 27 km from the city of Mytilene, bordering on the south with the Ampeliko forest. It is part of the European Network of Protected Areas NATURA 2000, highlighting the environmental importance

and high biodiversity. It covers an area of 3,162 ha that is 88.4% wooded, 5.4% partially wooded, 4.1% agricultural land, 1.7% pastureland and 0.4% is barren soil. The main geological types are composed of limestone in the upper parts of the forest and clayey shales in the lower parts. Only one management class was distinguished in the Agiasos forest, with *Pinus brutia* be the dominant species in this single management class. It consists of 20 sections divided into 67 stands. The division was defined in forest management plans from the 80'-90's. The boundaries of stands and sections usually follow natural lines - firebreaks, streams and ridges. This way of dividing the forest makes it easier to monitor stand development and the results of management practices. Vegetation cover is typically 60-80% for trees (mostly *Pinus brutia*), 5-20% for shrubs (evergreen, broad-leaved species) and 10-60% for grasses. There are also agricultural areas within the forest, most of which are still cultivated. There were several past fires ignited or spread in the Agiasos forest. In 1923, a large fire burned a very large part of the forest, most of which was naturally reforested. The fires in the period 1941-1944 were small. In 1967, a fire destroyed completely two stands and partially two. In 1973 a fire destroyed a large part of one stand and a small part of two. It is also worth mentioning that a large part of the northern part of the forest burned in 1982, burning about 400 ha.

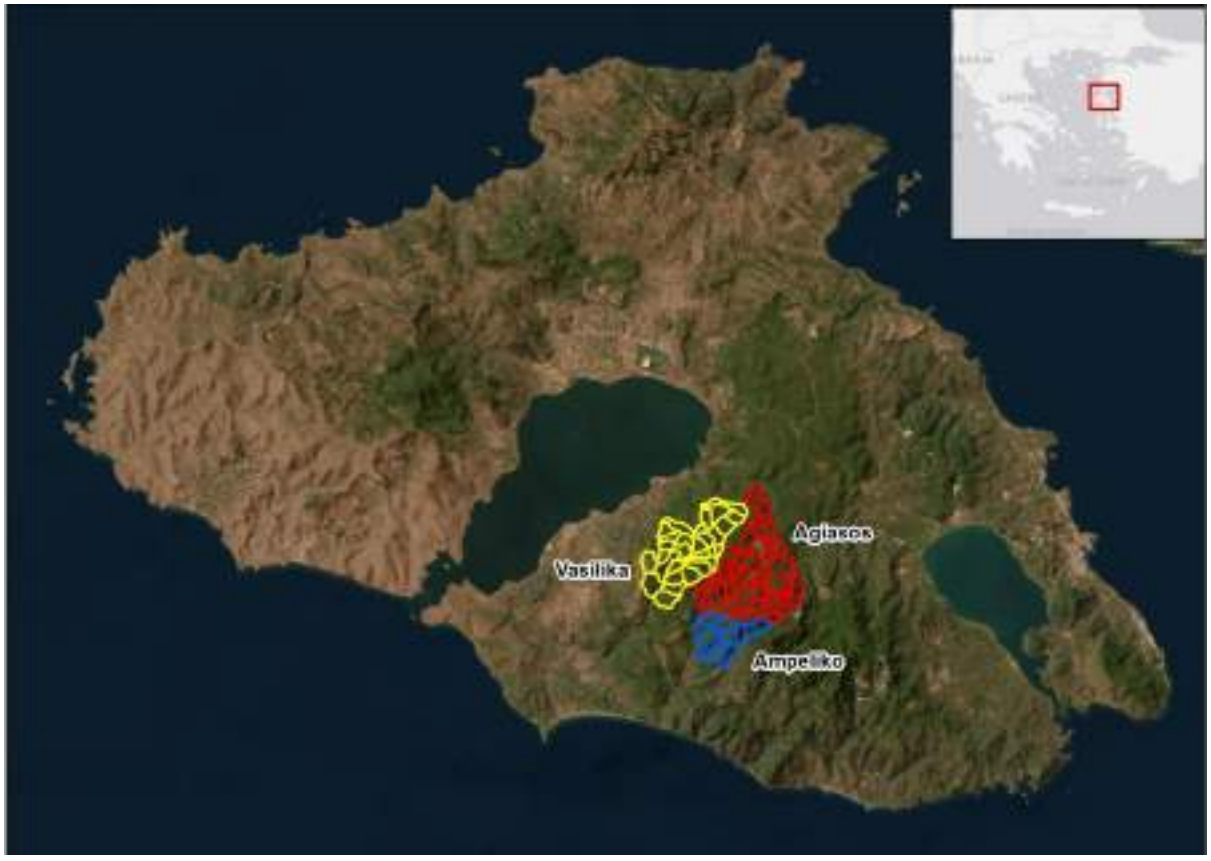

Figure 2 Lesvos Island with the stands of Agiasos forest (red), Vasilika forest (yellow) and Ampeliko forest (blue).

Vasilika forest occupies the northwestern side of Mount Olympus in Lesvos Island and borders on the east by the Agiasos forest and ranges at altitudes between 50 to 554 m. It covers an area of 2,118 ha that is 76% wooded, 11.5% partially wooded, 1.5% agricultural

land and 11% barren. Almost half of the forest has slopes between 20-60% and many agricultural areas that were abandoned in the past have started to reforest. In the Vasilika forest, only one management class was identified (*Pinus brutia*). The forest is divided into eight sections, comprising a total of 29 stands. When the coniferous formations became sparse, broad-leaved formations appear, interspersed with a few platanus trees along the streams. The main species identified are: *Olea europaea, Lavandula stoechas, Ononis spinosa, Juniperus spp., Genista acanthoclada, Euphorbia spp., Pinus amygdaliformis, Dactylis glomerata, Thymus vulgaris, Cistus incanus/ Cistus salviiefolius, Cytinus hypocistis, Quercus coccifera, Erica arborea, Asparagus aculeatus, Spartium junceum, Pinus brutia, Prunus spinosa, Limodorum abortivum, Phalaris tuberosa, Erica verticillata.*

1.1.2 Living Lab Portugal

Continental Portugal extends over 88,900 km^2 and is located on the western side of the Iberian Peninsula. Most of the population is in the northwestern coastal belt of the country, and the metropolitan areas of Lisbon, Coimbra, Braga, and Porto concentrate more than half the country's population (~5.27 million). Mainland Portugal is administratively divided into 278 municipalities or concelhos, ranging between 794 and 171,922 ha, and 32,031 ha on average. These are 2 to 6 times smaller in the northern areas where the valleys are enclosed within mountain ridges. The concelho is the minimum administrative division for the community protection plan implementation in Portugal. In addition, these communities are then internally subdivided into neighbourhoods or freguesias (n = 2883).

The northern mountainous orography with closed and deep valleys contrasts with the south's smooth terrain and extensive open plains. This topographic division is traced by the Tagus River, which also delineates the primary climatic separation between the warm-summer Mediterranean north (Köppen class Csb) and the hot-summer Mediterranean south (Köppen class Csa). Likewise, the coastal area presents milder winter and higher moisture levels than the colder and dryer inner lands due to the proximity and influence of the Atlantic Sea.

Forest (39.1%) and shrublands (12.4%) are the dominant land cover types in the northern portions and cover more than half of the country (Matoso et al., 2019). The conifer forests (*Pinus pinaster* Aiton. and *Pinus pinea* L.) and *Eucalyptus globulus* Labill. plantations are the main forest types in coastal sites and northern areas. Inner mountainous areas present a mosaic of grasslands and shrublands with deciduous forests of *Quercus pyrenaica* Willd. and *Castanea sativa* Mill. The complex agricultural patterns of olive groves and vineyards cover about 8% of the country and concentrate in some valleys such as the Douro and Mondego. Agricultural areas cover 26.1% of Portugal, locate in open landscapes, and occasionally intermix with *Quercus suber* L. and *Quercus ilex* L. open woodlands.

On average, some 18,345 fires in Portugal annually burned about 138,850 ha during 2009 to 2018 years (San-Miguel-Ayanz et al., 2019), 0.2–6% of the area per year. Still, the bulk of the fire is concentrated in a relatively small portion (~10%) located in the central and northern regions, where 906,000 ha have been burned at least twice in the last 30 years (i.e., average fire recurrence interval < 15 years) (Bergonse et al., 2021; Oliveira et al., 2020).

1.1.2.1 Rio Douro Valley

The study area is the Rio Douro Valley (DV) located in the north of continental Portugal, covers a region of over 1.8 million ha. DV experiences a Mediterranean climate, marked by hot, dry summers and cool, wet winters. January and December are the coldest months, with an average temperature of 6°C, while July and August are the warmest, reaching up to an average of 20-21°C. Rainfall varies significantly across seasons, with October experiencing the highest precipitation levels at 130 mm and July the lowest at 21 mm.

This region is defined by its steep slopes, which are often covered with terraced vineyards, olive groves, and other agricultural terraces, especially in the lower and middle parts of the valley. The Douro River itself flows through the valley from east to west, cutting through the landscape with deep, narrow gorges in some sections and broader, more gently sloping riverbanks in others. The river is flanked by rolling hills and high cliffs that are often dotted with small, traditional villages and towns. In the higher elevations, the region transitions into mountainous terrain, with steep peaks and rocky outcrops, particularly to the north and east of the valley.

The DV is administratively divided into 75 counties, not densely populated, with much of the area consisting of small towns, villages, and isolated rural communities. Population density is relatively low, especially in the more remote and mountainous areas. Most of the population lives in the valley's towns and villages, while the surrounding mountainous terrain remains sparsely populated. The population of the Douro Valley, like much of rural Portugal, has an aging demographic.

One of the primary economic activities in the DV is agriculture, particularly viticulture, covering an area of about 584,000 ha. Forests and woodlands cover over two-thirds of the study area. Maritime pine (*Pinus pinaster* Aiton.) and Blue gum (*Eucalyptus globulus* Labill.) stands are located mainly in the northern half of the region, occupying 258,000 and 87,500 ha respectively. Cork oak (*Q. suber* L.), Holm oak (*Q. ilex* L.) and other oaks are mostly in the northeast part and cover about 210,000 ha. Shrub understories are common in all these four main forest and woodland types. In Maritime pine and Blue gum stands, the main understory shrub genera are Gorse (*Ulex* sp.) and Heath (*Erica* sp. & *Calluna* sp.). *Cistus ladanifer* and *Cistus salviifolius* dominate the understory layer in evergreen oak woodlands. The aboveground biomass of the shrub layer ranges from ~10 tons per ha in Maritime pine stands, to 7.5 tons per ha in Blue gum plantations and Oak woodlands, and is lower (~5 tons per ha) in Holm oak woodlands (da Silva et al., 2006).

During the past 15 year about 491,000 ha were burned in the DV area from about 23,400 ignitions, making this region one of the most fire prone in Portugal, especially the Northwestern part, due to a wide variety of landscapes, vegetation types, physiographic gradients, climates, and fire ignition patterns. Only in 2017, about 55.7% of all the fire events in Portugal occurred there, burning the 18% of the total area of DV. The fire season of 2013 marked another dramatic year in terms of burned area for the region, with 1495 fire events that resulted in the burning 89,100 ha. On average, approximately 1700 fires burn about 35,100 ha each year, from which, the 3% exceeds a burned area of >100 ha and accounts for more than 38% of the burned area in DV. The few large-scale events

that burn more than 1,000 ha (0.3% of all recorded fire events) burn more than 32% of the total burned area. On the other hand, 71% of fires burned an area <5 ha, summing to a total of 21,000 ha during the past 14 years.

About 80% of fires have verified causes, most due to negligence (which includes the use of fire and accidents) or intentional causes (mainly arson). Intentional causes account for up to 30% of the number of fires but represent up to 50% of the total burned area. Negligence accounts for approximately 60% of fires but only for 40% of the burned area. Most negligent causes are linked to traditional agricultural, forestry, and pastoral tasks that involve fire and end up getting out of control, such as controlled burns, pasture renewal, fire clearing, and bonfires. Although legislation limits the period for burning and fire use for land clearing, the fact that these are traditional practices has a result that the law is often being overlooked and not imposed. The increase in the number of human-caused ignitions (both due to negligence and intentional actions) is one of the four key factors contributing to the rising fire risk across the Mediterranean region of Europe, including Portugal.

1.1.2.2 Vale do Sousa Forest

Vale do Sousa is a region located in the northern part of Portugal, within the Aveiro and Porto Districts and part of the larger Tâmega e Sousa subregion. It is known for its rich cultural heritage, natural landscapes, and significant agricultural and forestry activities. Vale do Sousa is situated in the central-northern part of Portugal, bordered by the Sousa River, which is a significant watercourse in the region. It lies south of the Douro River and is part of the greater Tâmega e Sousa region, an area that encompasses a variety of towns and villages with both rural and urban characteristics. The region is relatively close to the city of Porto, one of the major urban centers in Portugal, located approximately 30 km to the northwest.

The case study area, Vale do Sousa, is situated in the northwest region of Portugal, and comprises two Forest Intervention Zones (ZIFs): Entre-Douro-e-Sousa and Castelo de Paiva (Figure 3). Established in Portugal in 2005, ZIFs are defined as delimited and continuous areas mostly covered by forest, managed by a single organization in accordance with forest management and firefighting plans (ICNF, 2019). Additionally, the study area includes eight municipalities: Arouca, Castelo de Paiva, Cinfães, Gondomar, Marco de Canaveses, Paredes, Penafiel, and Santa Maria da Feira.

Forestry plays a significant role in Vale do Sousa's rural economy. Sustainable forest management practices are important in preserving the region's biodiversity and maintaining the balance between agricultural and forestry activities. The landscape is predominantly covered by eucalyptus (*Eucalyptus globulus* Labill), maritime pine (*Pinus pinaster* Aiton) (Marques et al., 2020), and sparse vegetation. A small portion of the study area is included in Natura 2000, a network of protected areas dedicated to preserving Europe's most important species and habitats, spanning the 27 European Union member states (Directive, 1992). Near the Douro River and its confluent rivers and streams, there is a presence of riparian species such as *Alnus glutinosa* (L.) Gaertn., *Salix atrocinera*, Brot, *Salix alba* L., *Fraxinus angustifolia* Vahl., and *Populus nigra* L. Due to recent wildfires and recent clearcuts, 16% of the forest area was classified as bare land or occupied by shrubs.

Understory vegetation is mainly composed of *Erica* spp., *Cistus ladanifer* L., *Ulex* spp., *Adenocarpus angyrophyllus* Caball., *Rubus fruticosus* L., and *Quercus lusitanica* Lam. A residual area, about 0.1% comprising hardwoods, namely chestnuts (*Castanea sativa* Mill.) and cork oak (*Quercus suber* L.), is present.

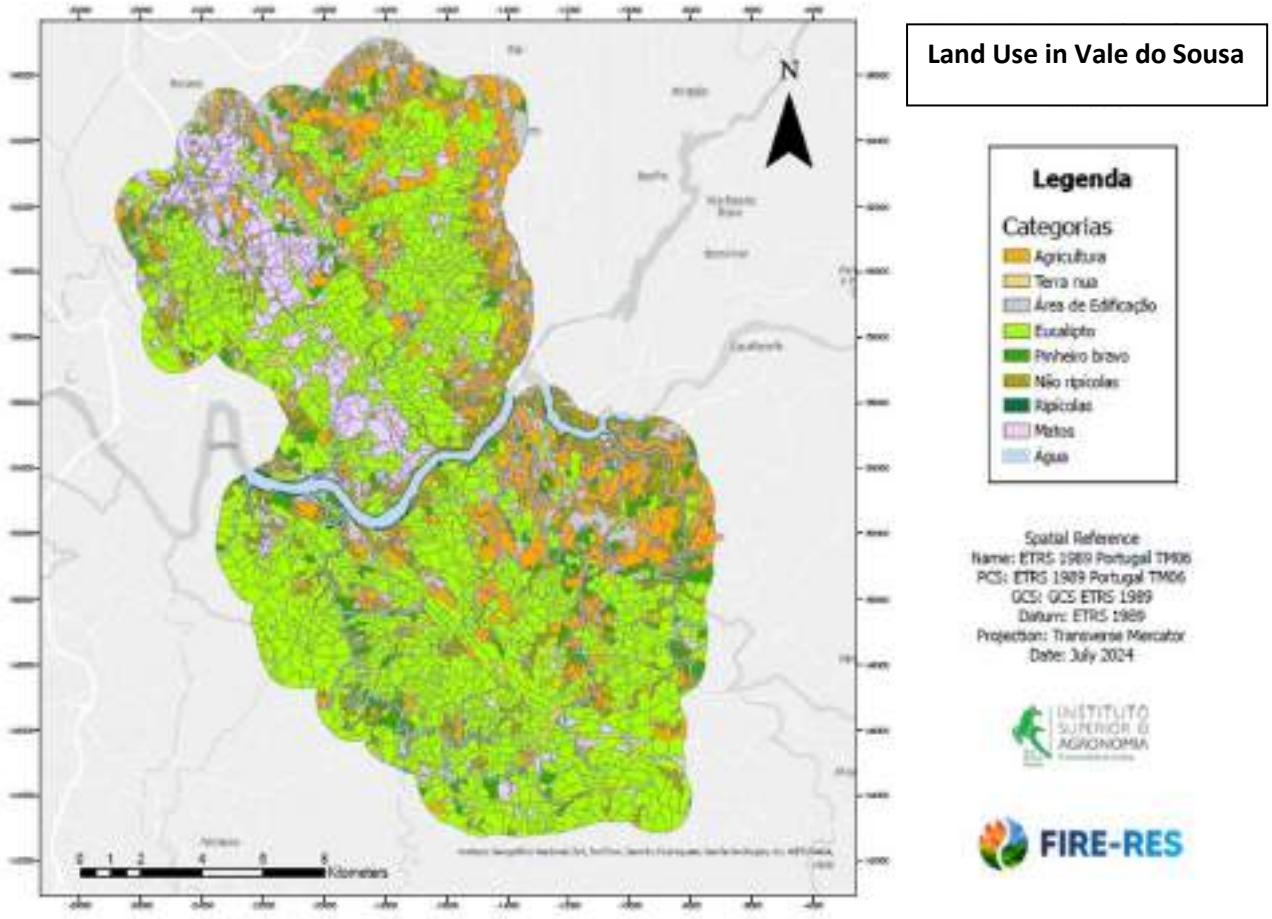

Figure 3 Land cover in the Living Lab Portugal where Agricultura is Agriculture, Terra Nua is Bareland, Area de Edificação is Built-up area, Eucalipto is Eucaliptus/Blue gum, Pinhiero bravo is Maritime pine, Não ripícolas is non-riparian, Ripicolas is Riparian, Matos is Shrubs, and Àgua is water.

Moreover, in recent years, the region has experienced recurring wildfires, with four of its municipalities ranking among the twenty with the highest number of fires in 2022 (Florestas, 2023). Additionally, the forest lands of Vale do Sousa are privately owned, fragmented, and typically small, with most areas covering less than 5 hectares (Marques et al., 2021).

The characterization of the Vale do Sousa landscape was carried out in previous studies (Botequim et al., 2021; Marques et al., 2024). A buffer zone was created around both ZIFs, and a Sentinel-2 image from 2022 was pre-processed and classified using a machine learning approach. This information was essential for identifying the dominant species and various land uses, including for agriculture, and built areas. The buffer zone was established due to nearby forested regions being susceptible to wildfires, with building

and agriculture being the most common categories within the buffer (Pavani-Biju et al., 2024).

The topography of Vale do Sousa is marked by rolling hills, valleys, and riverbanks, with the Sousa River playing a central role in the landscape. The region's natural features include vineyards, farmlands, and forests, offering picturesque views and varied terrain. The proximity to the mountainous regions of the north adds a level of scenic beauty to the area, with higher elevations to the north and gentler slopes to the south. The area is rich in biodiversity and is an important site for both agricultural activities and wildlife conservation.

Vale do Sousa enjoys a Mediterranean climate, characterized by hot, dry summers and mild, wet winters. The region benefits from moderate rainfall throughout the year, which supports its agricultural and forestry practices. Summers can be warm, with temperatures reaching the mid-30s Celsius, while winters are generally mild, with occasional frosts in the higher areas.

Vale do Sousa is home to a variety of historical landmarks, churches, and monuments, which reflect the rich cultural and architectural heritage of the region. Several Romanesque churches, medieval castles, and traditional villages are found throughout the area. The region's connection to the Roman Empire is evident in several archaeological sites and ancient infrastructures, such as old bridges and roads that are still visible today. Vale do Sousa is part of a biodiversity-rich zone, with forests and river systems providing important habitats for various species of flora and fauna. The region's forests support wildlife such as wild boar, deer, and a variety of bird species, making it a significant area for both conservation and eco-tourism. Several natural parks and protected areas are in or near the Vale do Sousa region, preserving its environmental integrity while allowing for recreational activities such as hiking, birdwatching, and cycling.

1.1.3 Living Lab Catalonia

The study area is in the northeastern extremity of the Iberian Peninsula and encompassed the 32,113 km^2 autonomous community of Catalonia (northeastern Spain). Catalonia is administratively divided into 948 municipalities, which are jurisdictionally aggregated into 42 counties and 4 provinces (Figure 4). Most of the 7.5 million inhabitants (>90%) concentrate in the highly developed metropolitan area of Barcelona and a few cities close to the coastline. The climate is predominantly Mediterranean with increasing rainfall on pre-littoral mountain ranges (precipitation > 500 mm yr^{-1}) and milder winters closer to the coastline to the east (average temperatures for January > 7 °C). The transition to high-mountain climate (precipitation > 750 mm yr^{-1} and average temperatures for January < 3 °C) is associated with the altitudinal gradient moving northwards to the Pyrenees mountain range above the 1,500 m. Irrigated agricultural lands, mosaics of shrublands (*Salsola vermiculata* L.) and herbaceous xerophytic vegetation edges cover the central depression of Lleida's plain below 450 m. Increasing elevations and rough reliefs to the north confine cultivated plots to valley bottoms, with forested areas dominated by Mediterranean oaks (e.g., *Quercus ilex* L.) and low shrublands on slopes (*Lavandula* spp.., *Rosmarinus officinalis* L. and *Quercus coccifera* L.).

These shrublands and forests are gradually replaced by tall-shrubland species (*Buxus sempervirens* L. and *Juniperus communis* L.), mid-mountain oak (*Quercus pubescens* Willd.) and conifer species (*Pinus nigra* Arn. and *Pinus sylvestris* L.) first on north-facing slopes, and then across on higher elevations (*Pinus uncinata* Ram.). The presence of broadleaved forests (*Fagus sylvatica* L.) and fir woods (*Abies alba* Mill.) is very limited. Mosaics of rocky outcrops, low shrublands (*Genista balansae* Boiss.) and pastures cover the high mountain tops above 1,400 m. On the pre-littoral mountain ranges, the Mediterranean maquis (*Pistacia lentiscus* L. and *Arbutus unedo* L.) appear in combinations with densely regenerated young Aleppo pine cohorts (*Pinus halepensis* Mill.). Silicicolous shrublands (*Cistus* ssp. and *Erica* ssp.) are frequently found in coastal lowlands sometimes with presence of stone pine (*Pinus pinea* L.). Cork oak (*Quercus suber* L.) is confined to the northeastern lowlands of the study area. Protected natural sites of special interest occupy about one-third of the study area and occasionally can represent a wildfire management constraint for the implementation of fuel reduction programs.

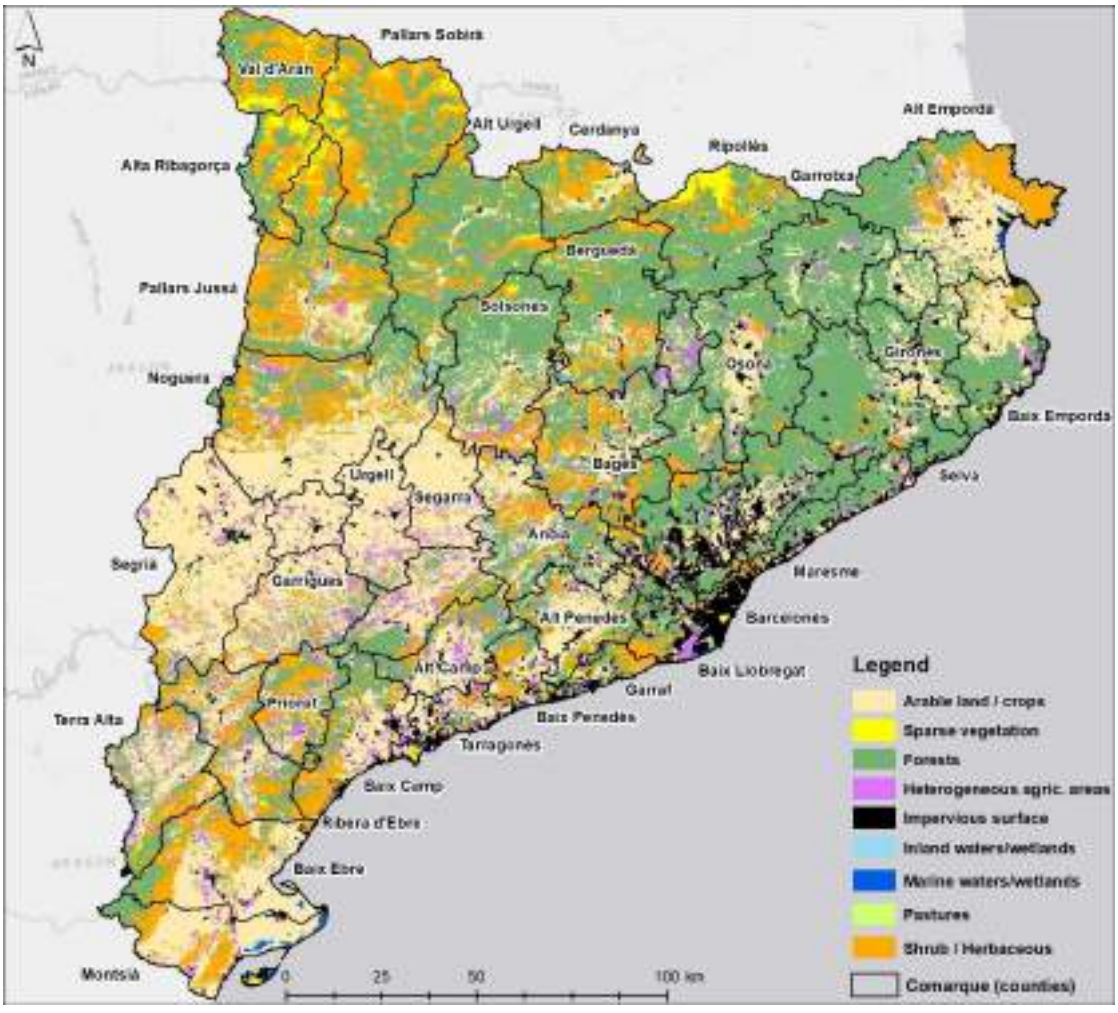

Figure 4 Land cover in the Catalonia region, Living Lab Catalonia-Spain.

Catalonia, together with the rest of the *Levante,* or easter part of the Iberian Peninsula, is one of the largest fire-prone areas in the Mediterranean basin and encompasses a wide variety of landscapes, vegetation types, physiographic gradients, climates, and fire

ignition patterns. On average some 650 fires burn about 11.5 thousand ha yr^{-1}, from which a low number (<2%) of large fires (>100 ha) account for more than the 88% of the burned area, and a few extreme events (>1.000 ha fire of 1986, 1994, 1998, 2003 and 2012) concentrate the bulk (>65%) of the burned area. Most fire ignitions (>90%) are caused by humans (1983–2014) (MAAyMA, 2015). Lightning activity is concentrated from June to August, and most natural fires start from cloud-to-ground flashes between 12:00 and 18:00 UTC (Pineda et al., 2014).

The climatic factors in the study area controlling large fire weather conditions are associated with spatial and temporal atmospheric circulation patterns presenting substantial region-wide differences (Duane & Brotons, 2018; Rasilla et al., 2010). The wildfire season was considered as the annual period concentrating 90% of the burned area from fires >100 ha. Apart from the typical summer wildfire season corresponding to the Mediterranean dry period, the Pyrenees also have a secondary winter fire season (Costafreda-Aumedes et al., 2018). We can observe wide differences in fire activity between the different regions of Catalonia in terms of large fire number and mean annual burn probability (fire database from 1983 to 2014). For instance, large fire number and mean annual burn probability in the northern coast are, respectively, 5 and 20 times higher than in the Pyrenees.

One of the main drivers for the occurrence of forest fires in the region is the accumulation of biomass fuel. While 65% of the region is considered as forestland (or better defined as rangeland), only 20% of that surface is actively managed. The abandonment of rural practices, other than forest management, like agricultural and cattle raising, has further increased fuel continuity further increasing fire hazard. There is an integrated plan for forest fires in the region, aiming at maintaining and creating, when necessary, infrastructures such as water points, roads and pathways and a network of areas of low fuel combustibility to support the suppression activities. At the landscape level, management aims for annual treatment rates >5 % of the landscapes to effectively control wildfire extents in forests, with 3–4 units of prescribed burning needed to reduce wildfire by one unit (Fernandes, 2015). Studies for the region indicate that management of approximately 15,000 hectares per year through prescribed fires or managed wildfires with a treatment frequency of 8-10 years could serve as a basis (Alcasena et al., 2018; Casals et al., 2009; Duane et al., 2019). In addition, the strategy in Catalonia includes the use of fire in the form of traditional fire use (burning agro-forestry remains, game management or other socio-cultural burning objectives), prescribed fire (planned use of fire to achieve precise and clearly defined management objectives and makes a vital contribution to the delivery of ecosystem goods and services), or managed wildfire (by its incorporation into the integrated fire management of Catalonia, it offers a series of technical decisions and actions aimed at monitoring an unplanned ignition and to conduct a fire to a predetermined limit of contention to achieve planned resource management objectives). The abovementioned strategies for Catalonia and elsewhere can be found in the FIRE-RES Deliverable 1.9 “Integrated fire management model: demonstration, training and piloting activities, including new fire prone areas”.

Additionally, it is highly recommended to enhance forest management activities that enhance the resistance and resilience of the forest to disturbances, especially the risk of

forest fires. Additional measures are considered depending on the season, to prevent undesirable human related ignitions, or specific fuel treatments around areas such as Wildland Urban Interface (WUI), electric network, railways, landfills.

1.1.4 Living Lab France (Nouvelle Aquitaine)

Nouvelle-Aquitaine is the largest administrative region in France by area, spanning the west and southwest of Metropolitan France (Figure 5). The region was created in 2014 by the merging of Aquitaine, Limousin, and Poitou-Charentes in a territorial reform. Nouvelle-Aquitaine has an area of 84,035 km^2 and has a population of 6,033,952 as of 2020. Its prefecture and largest city, Bordeaux, together with its suburbs and satellite cities, forms the seventh-largest metropolitan area of France, with 850,000 inhabitants. The region has 25 major urban areas, among which the most important after Bordeaux are Bayonne (288,000 inhabitants), Limoges (283,000), Poitiers (255,000), Pau (241,000) and La Rochelle (206,000), as well as eleven major clusters.

The Nouvelle-Aquitaine Living Lab (LL AQT) contributes in FIRE-RES by addressing the challenges posed by Extreme Weather Events (EWEs), such as prolonged droughts, heatwaves, and intense wildfire seasons. By focusing on optimizing landscape configurations and fire management policies in this IA (2.4), LL AQT seeks to minimize wildfire spread and losses.

The Nouvelle-Aquitaine Living Lab plays a pivotal role in addressing wildfire risks in one of France's most wildfire-prone regions. This region, renowned for its vast forested areas, has become increasingly vulnerable to catastrophic wildfires, especially under the changing climate. In the Nouvelle-Aquitaine region, megafires have been a relevant issue since the mid-20th century. To this day, a set of fires which occurred between 1946 and 1949, burning approximately 200,000 ha, remain commemorated historic events. The devastating fires of 2022 also underscore this vulnerability. The Landiras Fire, which burned over 20,000 hectares, and the La Teste-de-Buch Fire, which scorched 7,000 hectares, highlighted the region's susceptibility to drought, high temperatures, and strong winds. Together, these fires caused widespread evacuations, destroyed critical infrastructure, and demonstrated the escalating challenges posed by EWEs. As a result, local fire services were completely reorganised in South-Western France and tailored expertise to deal with wildfires was developed. Nowadays, about 5 000 fires breakout each year, mainly close to cities.

Overall, the territory is quite homogeneous, with sandy soils and maritime pine plantations. Nouvelle-Aquitaine is characterized by extensive forests dominated by Maritime pine (*Pinus pinaster*), interspersed with oaks such as *Quercus pyrenaica* and *Quercus suber*. About 95% of the forestlands is harvested and managed thanks to interactions with nature conservationists. Today, the presence of young maritime pines exposes the area to the risk of future fire occurrences. These forests, covering approximately 900,000 hectares, form one of the largest managed forest areas in Europe. The regional landscape includes a mosaic of dense pine plantations, transitional shrublands, and urban-wildland interfaces, all of which contribute to wildfire risk by providing continuous fuel for fire spread.

Forest fire management in Aquitaine is based on a complementarity between prevention and control. Forest owners have a very strong involvement in fire prevention through their membership and their daily action in forest protection associations (ASA DFCI). ASA DFCI Aquitaine, brings together 4 NUTS 3 level Unions, with 212 local ASA DFCI that rely on more than 2,500 active volunteers. Altogether, they maintain a network of very dense forest roads and water points allowing immediate and direct attack of each new wildfire.

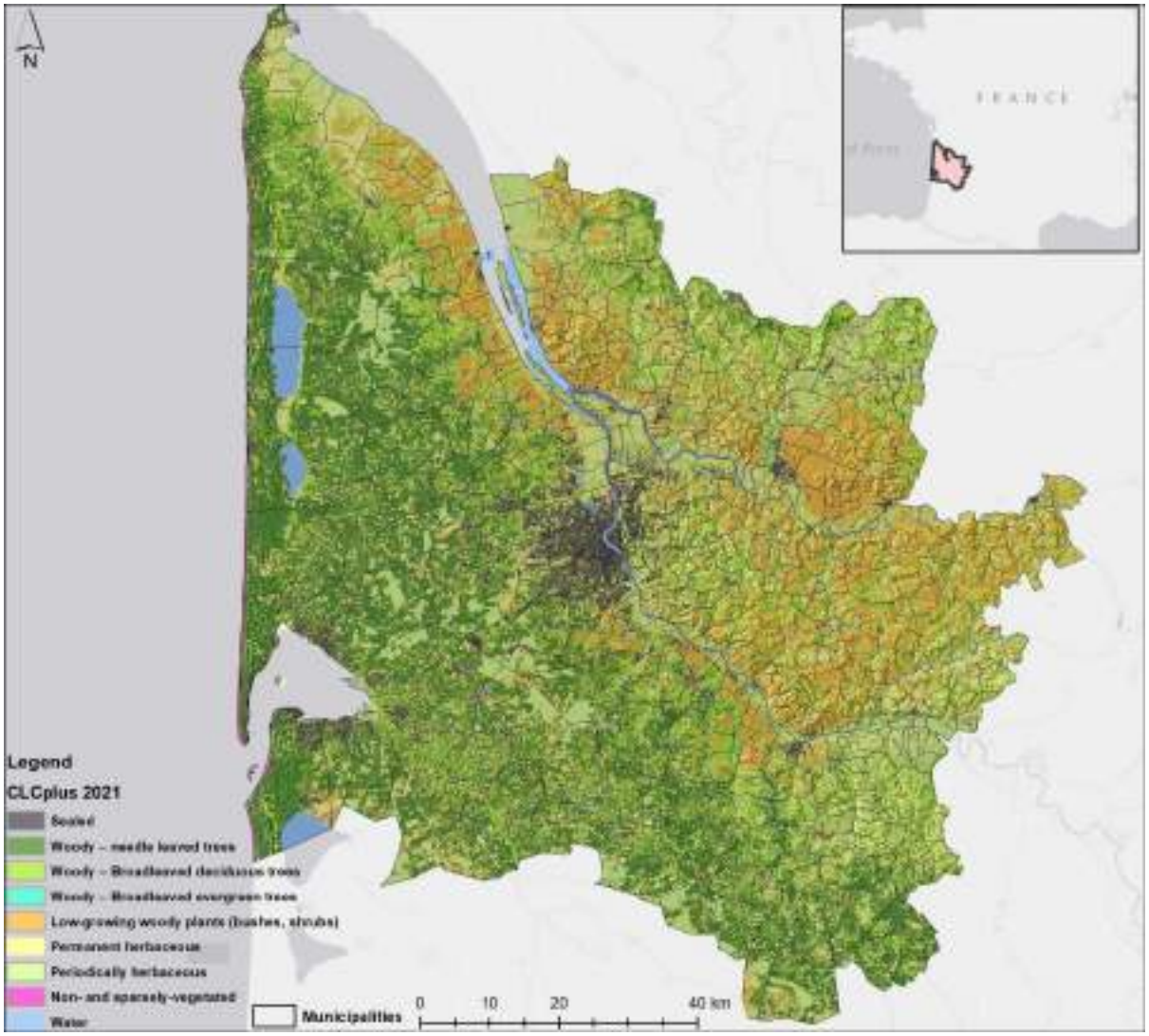

Figure 5 Land cover in the Nouvelle Aquitaine region, Living Lab Nouvelle Aquitaine- France.

Management practices in the region aim to balance timber production with wildfire risk mitigation. Traditional methods include fuel reduction treatments, such as the Landes roller chopper, which targets understory vegetation, and pruning in young stands, designed to minimize vertical connectivity of fuel and enhance fire resistance. However, the increasing frequency of extreme fires highlights the need for improved prevention strategies and tools, particularly for landscapes with high exposure to residential areas and critical infrastructure. Firefighters assisted by local representatives of ASA DFCI oversee the fire management. Moreover, the Civil Protection oversees fire suppression,

whereas ASA DFCI assists in fire detection. Windstorm and fire risks are covered for forest owners by MISSO-GROUPAMA insurance company.

The 2022 fires also highlighted the vulnerability of the WUI, where the proximity of forests to populated areas amplifies the potential for human and economic losses. Combined with worsening droughts, longer fire seasons, and high-value assets in harm's way, Nouvelle-Aquitaine shows the urgent need for innovative solutions to wildfire management.

1.1.5 Living Lab Chile (Biobío Region)

The Chilean Living Lab covers the entire Biobío region (Figure 6). It is in the southern part of Chile between latitudes 36°26' and 38°30' S and longitudes 73°42' and 70°59 W. It comprises of 33 communes separated into three provinces: Arauco, Biobío and Concepción. This region has 23,890 km^2 and a population of approximately 1,557,414 inhabitants, and its density reaches 64.38 inhabitants/km^2, making it the third most populated region in the country. The region is one of the main centers of important economic activities, with various sectors such as steel, agriculture, the cellulose industry and forestry.

The region represents a transitional zone between the dry temperate climates of central Chile and the rainy temperate climates found south of the Biobío River. It is bounded by two main mountain ranges: the Coastal Range and the Andes Mountains, leaving a valley in the center. These orographic features create significant climatic variations within the region. A humid temperate climate prevails in the coastal strip, as well as in the higher areas and the western slope of the Coastal Range. Annual precipitation ranges from 1,200 mm to 2,000 mm and increases from north to south within the Biobío region. Further inland, the climate remains humid temperate. However, the longitudinal valley experiences more significant thermal variability than areas closer to the coast. In the northern part of the region, a Mediterranean temperate climate predominates, extending from the eastern edge of the Coastal Range through the intermediate zone to the lower sections of the foothills. In the Andes Mountains, at altitudes above 1,500 meters, a cold high-altitude climate develops, characterized by abundant precipitation (over 2,000 mm annually) and low temperatures. These conditions allow for the presence of permanent snow on the highest peaks of the mountain range.

This climatic variability has shaped the vegetation composition and structure, characterized by Mediterranean shrubs and temperate evergreen forests. The study area is covered with exotic forest plantations, predominantly of *Pinus radiata* Don and in minor proportion *Eucalyptus* spp. and remanent native forest. The dominant native vegetation includes sclerophyllous shrubs, with representative species such as *Quillaja Saponaria* Molina, *Lithraea caustica* Molina, and *Peumus boldus* Molina (Duarte et al., 2024). Additionally, the study area hosts deciduous forests, primarily of the *Nothofagus* spp., and steppe vegetation at higher altitudes (Holz et al., 2012). In regions with higher precipitation and humidity, extensive mixed temperate deciduous–evergreen forests are found, with dominant species like *Nothofagus obliqua* Mirb, *Nothofagus alpina* Poepp. & Endl., and *Nothofagus dombeyi* Mirb (Veblen et al., 1996). Above 1,000 m above sea level,

the presence of *Araucaria araucana* Molina stands out, occasionally mixed with other *Nothofagus* species such as *Nothofagus*. *pumilio* Poepp. & Endl. and *N. dombeyi*.

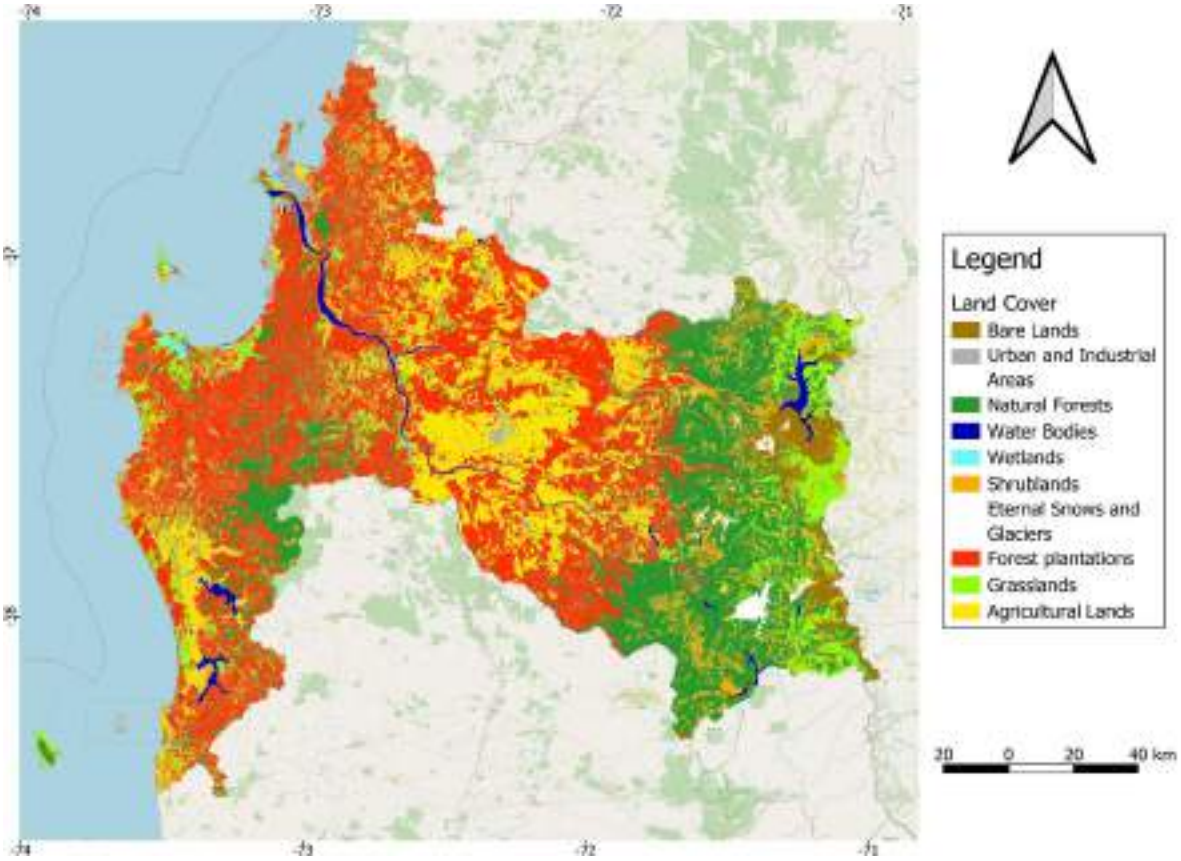

Figure 6 Land cover in Biobio region, Living Lab Chile.

In Chile most forests are native: 14.18 million ha of native forest vs. 2.96 million ha of plantations. The administrative region of Biobío feature vast extensions of forest plantations that provide an abundant and interconnected biomass, leading to an increased recurrence and severity of fires, especially during prolonged drought periods (McWethy et al., 2018). Since 1975, the mean growth rate recorded by plantations stands at 70,000 ha per year, with Biobío region presenting one of the largest areas dominated by the species of *Pinus radiate*, *Eucalyptus globulus* and, to a lesser extent, *Pseudotsuga menziesii* (Úbeda & Sarricolea, 2016). More than 8,700 km^2 corresponds to forest plantations, being the most common cover in the region (Figure 6). Natural forests reach almost 6,500 km^2 concentrated to the East in the Andes mountains and in the Nahuelbuta mountains. Shrublands cover 2,300 km^2 approximately spread over the whole region. Grasslands and agricultural lands are also important in the region, covering almost 1,300 km^2 and more than 3,270 km^2 respectively, but agricultural lands are concentrated in the valley and coastal areas, while grasslands are spread all over the region. Wetlands and water bodies reach approximately 100 km^2 and 450 km^2 respectively. Finally, urban areas cover 300 km^2 approximately and are concentrated in the valley and coastal areas. The Biobio region in southern Chile presents about 17 large size wetlands and another 30 of smaller sizes along the coastal border (Belmonte et al., 2015). Between the cities of

Talcahuano and Arauco wetland areas have been covered by urban expansion that has both occupied their surfaces and transformed the surficial sediments in those sites.

The Biobío region had the most forest fires in the last 10 years, both in terms of their number (23,199) and the affected area (377,096 ha). The season with the highest number of fires was 2014-2015, but it was the third in terms of area. Massive wildfires have occurred between December and February of 2016-2017 and for years later in 2022-2023 seasons; the so-called `mega-fires' or 'storm-fires' mainly in bioclimatic Mediterranean and Temperate Regions in the Coastal range where the exotic plantation dominate the landscape, compared to endemic forests remaining in the Andes range (Matus et al., 2023). Similarly, the 2020-2021 season was the second in terms of number of fires, but it was the seventh season regarding burned area. Mega-fires temporarily matched the maximum recorded air temperatures in central-south Chile, corresponding to Mediterranean and Temperate Regions. Crown fires are especially common in forest plantations given the dominant tree species, their highly inflammable leaves, plantation homogeneity and continuity, and the high levels of forest residues on the soil surface. Regarding fire management, it is overseen by the Ministry of Agriculture, which is applied through the National Forestry Corporation (CONAF). At the same time, some forest owners have their own specialized personnel to face forest fires. Both organizations work together in prevention and suppression.

2 Scenario Planning with ForSys

The ForSys spatial planning system (Day et al., 2023) was developed by USDA Forest Service Research and Development to modernize tools to prioritize forest and fuel management investments and understand trade-offs among alternative scenarios. ForSys is a multi-criteria spatial prioritization and optimization system to help design complex strategies and explore multifunctional fuel management scenarios in fire-prone landscapes. The program fills the gap between the large fire modelling programs and stand-level planning systems in the fuel treatment planning process. ForSys uses inputs on multiple objectives, budgetary constraints, and treatment thresholds to identify optimal fuel treatment solutions concerning the input data and user-defined parameters. The input data represent the treatment units attributed to the attainment of one or more landscape management objectives, activity constraints, and treatment thresholds. Constraints are the total possible investments in management activities, which can be specified as the total area treated or budgetary availability. The user can set varying objective priorities to assess different scenario planning options and explore existing trade-offs among them. The program can consider a pre-existing landscape subdivision such as an administrative boundary, sub-watershed, and planning areas to arrange treatments or generate new project areas by aggregating treatments into patches. ForSys can be used in several ways to assist restoration programs, facilitate the development of forest management plans, design strategic fire containment efforts, describe scenario planning options on shared stewardship programs, and explore any treatment opportunities and decision rules as spatially explicit treatment strategies. The model was developed with an emphasis on application by nontechnical users, and thus optimization is accomplished with a relatively simple greedy spatial heuristic instead of more complicated mathematical programming approaches (Beyer et al., 2016; Hof & Bevers, 2002; Tóth, 2020) that are not feasible to implement in the field in large land management agencies.

2.1 Basic Concepts

Using the ForSys, forest managers can easily explore the existing treatment collocation opportunities among multiple competing objectives and design the optimal fuel treatment allocation within vast landscapes (> 1 million hectares) at various operational scales. ForSys streamlines a cross-scale adaptive wildfire risk framework where resources are designated to manage large areas, but the treatment allocation requires a stand-level detailed design to facilitate the implementation of fuel reduction programs. ForSys is used for short-range tactical planning problems where invariant landscape conditions can be assumed, i.e., fire and forest succession are not going to significantly affect the outcome of the model run compared to prescribed management, although the potential impacts of treatment on the predicted outcomes are considered.

ForSys is designed around the concept that restoration and risk reduction activities occur at the stand polygon scale (1–20 ha) and need to be organized into project areas (2,000–10,000 ha) to achieve landscape scale management goals and meet logistical and administrative constraints. The input data represent treatment units that are attributed with the polygon's overall contribution to one or more landscape management

objectives, as well as information including: non-spatial attributes such as stand conditions (merchantable timber volume or revenue from thinning) and spatial attributes, including the distance to strategic fire contention areas (primary roads, firebreaks, and safety zones), operational constraints (slope limitations for mechanized timber retrieval, protection status of an area), expected losses from wildfires (post-fire soil runoff), pest risk (projected tree mortality due to insect outbreak), land tenure systems (private, public, municipal), and fire-susceptible landscape features (critical habitat or residential structures). Besides, the user supplies an activity constraint (the annual area treated or treatment cost) representing the maximum value that can be treated based on budget allocations or other restrictions such as fuel treatment rotation interval. Scenarios are designed by understanding spatially explicit values and constraints on landscape management. It is not simply a matter of where priorities overlap but how treatment is limited to particular locations or conditions (Figure 7).

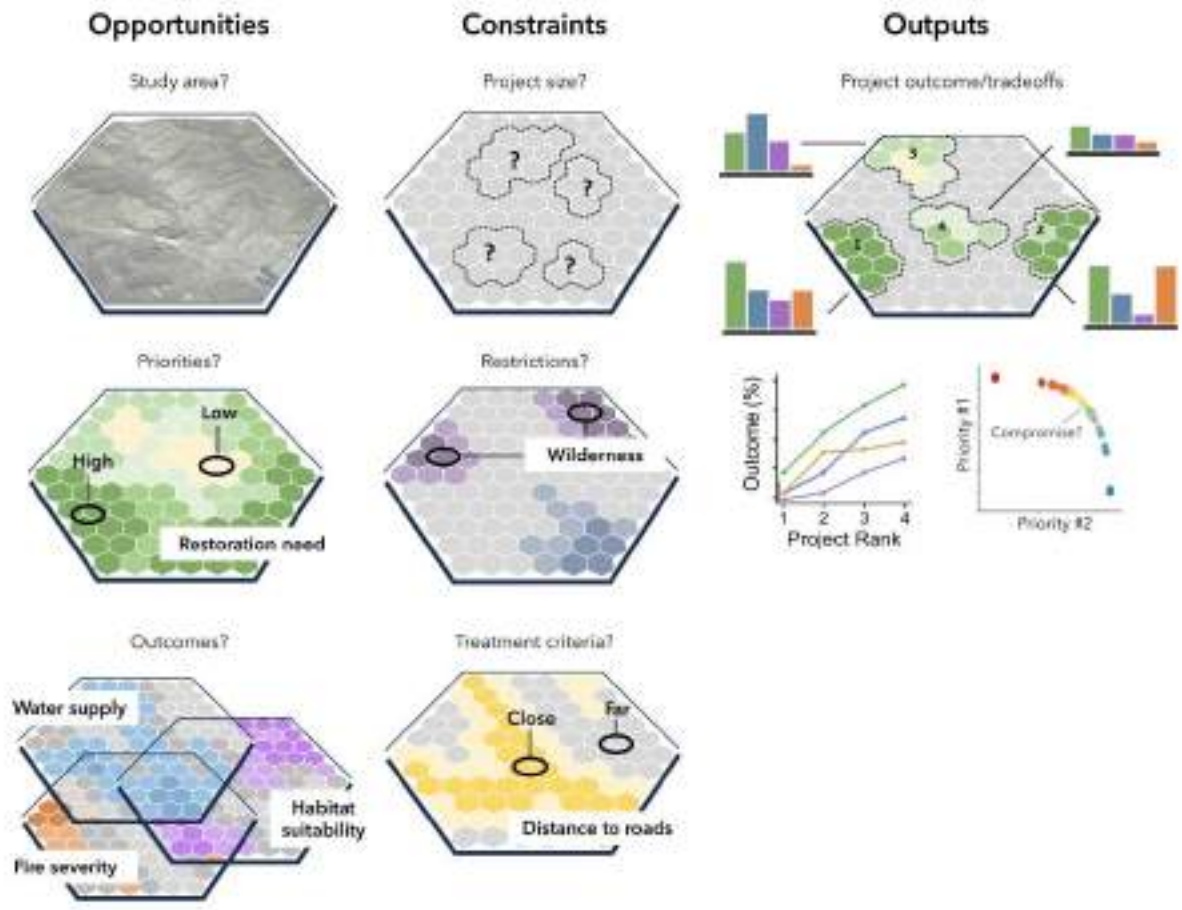

Figure 7 In this example, a single objective (restoration need) is prioritized for treatment to treat 30% of the landscape in 100-hectare projects. Treatments are prohibited from wilderness areas and "stands," or treatment decision units, must be close to roads to be selected for treatment. Other values are of interest as treatment outcomes (i.e., water supply, fire severity, habitat suitability) even though they were not priorities in the scenario. ForSys will determine where to locate projects and in what priority order, then assess outcomes. For multiple priorities, ForSys will also explore if there are opportunities for compromise solutions where projects can be located to target both objectives efficiently. (Source: Day et al. (2023)).

In a basic application, the program operates the same as sorting polygons based on fields of interest and selecting the polygons from the sorted list until some total area limit is met or budget availability is accomplished. However, ForSys automates the process and allows for combining several attributes in weighted combinations to generate and map treatment alternatives quickly.

Prioritization of stands for treatments and their organization into landscape-scale projects can be accomplished with four spatial strategies: (1) stands are selected to optimize one or more objectives within a predefined planning area; (2) stands are aggregated to create planning areas that optimize one or more objectives; (3) stands are maximally dispersed from a project centroid considering one or more objectives and distance from the centroid; and (4) project areas are maximally dispersed within a larger landscape considering both distance from other projects and one or more objectives (Day et al., 2023).

We used two objective values, blended with weighting factors, to build optimal fuel treatment hybrid scenarios that allocate investments to multiple values of interest. This functionality may help explore collocation opportunities among scenario planning options and find compromise solutions during collaborative planning or shared stewardship programs where human communities, private landowners, and forest managers have competing interests and different needs. In addition, ForSys can iterate through pre-existing planning areas (e.g., Forest Service districts for Greece, or Municipalities/Counties for the other Living Labs) to design the optimal treatment mosaic or use an aggregation option to generate new project areas. The aggregation constraint forces the program to build project areas as patches within which threshold conditions at the stand level are not exceeded, and stands that exceed fire behaviour thresholds are treated until the treatment constraint is reached. On the other hand, a non-adjacency problem would allocate treatments based on objective values regardless of their location relative to each other.

ForSys does not have embedded management response functions, thus it can incorporate any type of management prioritization problem from prescribed fire to thinning or clearcuts. End-users and forest managers are freely allowed to choose which fuel treatment prescription and mix will use to the stands selected by ForSys and grouped to create projects. ForSys reveal what can potentially be achieved if we apply the ideal management strategy for these projects to achieve a specified management goal.

The algorithm starts with a random stand in the input spatial dataset, and a list of adjacent candidate stands are identified using an adjacency matrix that is computed prior to the optimization process. The candidate stand with the highest objective value is added to the project. A new list of candidates is identified that now contains stands that are adjacent to the seed stand as well as stands that are adjacent to a prior selected candidate. Again, the patch with the highest objective is added to the project. Each time a candidate stand is selected, it is removed from the candidate list. This iteration continues, adding stands to the project, until either the specified project diameter or one of the constraints is exceeded. When all stands (or all available stands) have been tested as a seed for a project, the project with the highest objective is identified and stands

included are removed from consideration in subsequent projects. The project building process repeats until the number of projects specified by the user has been created. The spatial optimization section of ForSys allows the user to enter the maximum project diameter, which controls the potential size of the project.

2.2 Inputs

To run ForSys, several datasets should be considered and processed to produce the necessary geospatial vector layer that contains all the relevant and required information that the program needs to be run. The most important layer is the "stands" layer, which is actually a polygon layer that defines the spatial units that can form projects applicable to receive fuel treatments. In the USA, they used equally sized hexagonal polygons to produce these stands. Note that these spatial units are not the actual stands that usually comprise the managed forests (derived and defined from Forestry methods and techniques), but artificial "stands" that cover the entire study area (in contrast to the traditional forest stands that cover only small parts of the landscape).

After the stands are defined, the next step is to add information regarding pre-existing planning areas. These can be Municipalities, Counties, Forest Service Districts or Watersheds, among others. For the case of Greece we used Forest Service Districts, for Catalonia we used Comarques (similar to counties), and for Portugal, Chile and France we used Municipalities. The choice of the pre-existing planning areas depends on who actually is in charge of performing the fuel treatments, and on which spatial unit they are planned to be implemented. The next step is to define management barriers that can include restrictions of management in protected areas, distance to roads, exclusion of high slopes and non-forested areas, and removal of recently disturbed (e.g. from wildfires) areas. This information is stored in the fields of the attribute table of the spatial unit shapefile, and it must be ensured that all polygons will receive a value. The combination of exclusion criteria creates the stand availability field (0: unavailable; 1: available), and based on this field ForSys chooses which stands will participate in the formulation of the spatial solution of the scenario it was called to run.

The next step is to populate the attribute table with information regarding key forest management priorities. For the protection of developed areas, it is necessary to acquire the outputs of wildfire simulators and perform an analysis on where fires start, how they are transmitted and which developed areas are affected. The post-processing of wildfire simulations can create rasters of developed areas exposure that can be summarized or averaged at the scale of each stand using GIS functions. Similarly, the wildfire transmission to protected areas can be quantified for each stand and reveal which stands contribute more to the wildfire problem that these areas can face from potential fires, and which parts of the protected areas are affected the most by them. Other information that can be attributed to each stand includes the commercial timber volume or the average biomass, fire intensity, amount of carbon, ignition probability, burn probability and others. Refer to subchapter 2.3 for more information. The final step is to convert the raw stand values of each objective to percentages, so that we can know how much each stand is contributing to the solution of each objective considering all stands of the

landscape (including the unavailable). For a detailed explanation of how this is performed (it's a two-click process that occurs within ForSys), refer to subchapter 2.5.

ForSys also produces an adjacency file that estimates which stands are in proximity and neighbouring, using the spatial attributes that every shapefile inherently has. This is a required file when we want to avoid having a selection of random, but highly performed, stands of the landscape that cannot form a spatial contiguous project. In our runs, we used the aggregation function of ForSys to ensure that all projects meet the requested area and their spatially aggregated and not scattered. Specifically, the adjacency constraint forces the program to build a contiguous treatment aggregate patch that maximizes the objective function while not exceeding the investment constraint. Stands that exceed the established treatment threshold count against the investment constraint.

2.2.1 Spatial Inputs to define the analysis scale - stands

ForSys uses spatial information in the form of shapefiles that describe stands (hexcells) that can be also grouped into pre-defined operational planning areas (i.e., forest districts in our study). We used two datasets to define the stands: for all European Living Labs, the CLC+Backbone product in its vector form was chosen, while for Chile, we created 10-ha hexcells. The CLC+ Backbone product (2018 version) provides a detailed pan-European wall to wall geometric vector reference layer with 18 basic thematic classes and a 11-class 10 m spatial resolution raster product (Probeck et al., 2021). The CLC+ Backbone is an object-oriented, large scale, wall-to-wall (EEA-38 + UK), high-resolution (HR) inventory of European LC in a vector format accompanied by a raster product layer, providing a consistent pan-European geometric backbone of Landscape Objects with limited, but robust thematic detail, on which many other applications can be built. An object-based Vector Product with 0.5 ha MMU, derived from a combination of linear traffic and hydrological networks (Hardbone) and image segmentation (Softbone), and 18 landcover classes attributed with aggregated statistics from the Raster Product as well as various additional characteristics.

The following landcover classes exists in the vector version: 11: Very High Sealing Degree 12: High Sealing Degree 21: Pure needle leaved 22: Dominantly needle leaved 31: Pure broadleaved deciduous 32: Pure broadleaved evergreen 33: Dominantly broad leave 40: Shrubland 51: Permanent herbaceous without trees 52: Permanent herbaceous with few trees 53: Permanent herbaceous with many trees 60: Periodically herbaceous 70: Lichens and mosses 81: Partly vegetated land - Low vegetation cover 82: Partly vegetated land - Intermediate vegetation cover 90: Non-vegetated land 100: Water 110: Snow and ice. To define the forested areas, we used the following codes: 21, 22, 31, 32, 33, 53. All other classes were flagged as non-forested and were removed from the available stands for fuel treatments.

For Chile, we used the Moderate Dynamic Land Cover dataset from the Copernicus Global Land Operations at the spatial scale of 100 m (version 3) for the reference year 2020 (Buchhorn et al., 2020). The following classes defined whether a stand (hexcell) was characterized as forested: Closed forest, evergreen needle leaf; Closed forest, deciduous needle leaf; Closed forest, evergreen, broad leaf; Closed forest, deciduous broad leaf; Closed forest, deciduous broad leaf; Closed forest, unknown; Open forest, evergreen

needle leaf; Open forest, deciduous needle leaf; Open forest, evergreen broad leaf; Open forest, deciduous broad leaf; Open forest, mixed; Open forest, unknown.

Each stand was populated with the average values or binary flags from variables derived from fire behaviour modelling or other ecological and timber related data sources (e.g., protection status, available growing stock volume, disturbances etc.). In addition, each stand had a unique identifier, centroid coordinates, and an area field. For all Living Labs, all stands that were non-forested, had a road distance to each polygon centroid > 500 m, a slope >25 degrees and were disturbed from wildfire that occurred after the year 2018 were flagged as unavailable.

The total available area for fuel treatments varied for each Living Lab. For Greece, from the 2.13 million ha of the Peloponnese, the 600 thousand ha were available. For Catalonia, from the 3.21 million ha, the 1.06 million ha were available. For Portugal, from the 1.93 million ha of the Douro Valley study area, the 495 thousand ha were available. For Chile, from the 2.4 million ha of the Biobío study area, the 568 thousand ha were available. Finally, for France, from the 1,02 million ha of the Nouvelle Aquitaine study area, the 428 thousand ha were available.

2.3 Forest Management Priorities

Defining priorities in restoration, risk reduction, and conservation programs has become increasingly important to address a wide range of emerging resource management issues on public lands in the United States and elsewhere (Brudvig, 2017; Chazdon & Guariguata, 2018; Kukkala & Moilanen, 2013; Moilanen et al., 2011; Pohjanmies et al., 2019; Strassburg et al., 2020). Prioritization often involves multiple objectives and is constrained by limited resources and by restrictions on where management is directed. Ignored, these factors can have manifold impacts on expected outcomes from restoration, contributing to failed objectives and wasted financial resources (Brudvig, 2017; Iftekhar et al., 2017). Successful prioritization plans help allocate limited resources, often at multiple scales, and communicate restoration plans and estimated outcomes to key stakeholders (Eaton et al., 2019; Riddell et al., 2019). In the following subchapters, we present the selected forest management priorities for the five Living Labs and explain why they were chosen and how they were estimated at stand level to create the required inputs for ForSys.

2.3.1 Protection of Developed Areas

Protecting communities and structures in the Wildland-Urban Interface (WUI) is the primary goal of both fire suppression and annual fuel treatment programs, applying actions such as fuel breaks, fuel removal and to a lesser extent, thinning in the periphery of developed areas and along major roads. Recently, funding for such treatments has increased in the Mediterranean countries with protection of developed areas being the highest management priority for most fire management agencies.

We geometrically intersected all simulated fire perimeters with a point layer depicting the building locations of each study area, as produced by Microsoft from Bing Maps imagery between 2014 and 2021 including Maxar and Airbus imagery (Microsoft, 2018). For each ignition, we summed all predicted structures exposed to each simulated wildfire

perimeter, and for each building, we assessed how many of the simulated fires reached its boundaries and create exposure.

Then, a kernel density estimation was run twice with a search radius of 500 m at a 100 m spatial resolution, one on the ignition dataset using the structure exposure value and another on the structure dataset using the number of fires affecting them, producing two density rasters. For the first case, the target was to estimate community exposure sources areas, i.e., where fires are coming from to each region, while for the later, to estimate community exposure sinks, i.e., the areas inside the urban and peri-urban sites that receive the highest number and pressure from the simulated fires.

Finally, for each stand we estimated the average value of the sources and sinks of structure exposure from all pixels intersecting it, representing the number of structures exposed to wildfire from ignitions started within the stand. Each stand can have many ignitions that affect multiple developed areas. Structure exposure for sources and sinks were the metrics used to prioritize protection of developed areas.

2.3.2 Wildfire Transmission to Protected Areas

If an area is characterized with a protection status in National or European Union legislation (Wetlands-Ramsar; Specially Protected Areas under the Barcelona Convention; Biogenetic Inventories; Biosphere Reserves; World Heritage sites; NATURA 2000; Natural Parks and Forests), limitations on human interventions are imposed, including fuel and forest management. Restrictions can include limiting the quantity and quality of retrieved timber, allowing only specific mechanical treatment methods to be applied, controlling the opening of new roads, and forbidding the use of machinery, equipment, and vehicles. The role of protected areas is important in maintaining ecosystem services, ecological balance, aesthetic quality, and biogenetic reserves. A wildfire can impact the functioning of protected areas and years can be required to restore them to their pre-fire state. Large parts of each study area have some type of protection status, but this does not necessarily mean that fuel and forest management is restricted.

Like protection of developed areas, our goal was to understand where fires initiate and spread into these areas (sources), and which parts (stands) of the protected areas are most affected by these simulated fires. To achieve this, we geometrically intersected all simulated fire perimeters with a polygon layer depicting the major land tenures and protected areas. This enabled the estimation of outgoing fire (number of hectares) from each ignition that burned into protected area polygons (sources), and incoming fire received by the protected areas stands. Then, we applied the kernel density estimation process with 500 m search radius and 100 m spatial resolution on all ignitions that affected protected areas, with annual burned hectares value >0. Then, for each stand we estimated the average value of all pixels intersecting it. Each stand can have many ignitions that affect multiple protected areas. Higher stand level protected area exposure denotes a higher priority for receiving fuel treatments. Finally, for the protected areas exposure sinks we assigned the total number of hectares burned by all simulated fires that intersected it.

2.3.3 Probability of New Ignitions

By focusing on areas with high wildfire ignition probabilities, fire management agencies can effectively minimize the risks and damages associated with wildfires, helping protect both natural and human environments, and ultimately saving lives, property, and ecosystems. Areas with a high wildfire ignition probability are critical for fire management agencies because they help these agencies prioritize their resources, planning, and strategies to reduce wildfire risks. Knowing where fires are most likely to start allows them to position resources strategically, so they can respond quickly and effectively when a fire does ignite. High-risk areas are often prioritized for fire prevention efforts, like in Portugal, including public awareness campaigns, fuel reduction (clearing vegetation), and creating firebreaks. Fire management agencies can plan controlled burns or prescribed fires in high-ignition zones, which reduces available fuel (like dry brush and dead trees) that would otherwise help a wildfire spread.

We used an ignition probability grid for each Living Lab, created from the historical ignition points of at least the last five years (Greece), spanning to >20 years for Portugal and Spain. The ignition probability surface was created using all the ignitions, regardless of their origin and associated burned area, representing the overall ignition probability. For Portugal and Spain, the ignition probability surface was created using the tool kernel density with a fixed bandwidth of 10 km, which was proven to represent well fire events in Portugal (Tonini et al., 2016). For Greece, a cohesive modelling approach to model human-caused ignition probability was applied at a fine-grained spatial resolution (100 m). To do so, we ascertained which factors influence ignitions and delivered a spatial-explicit representation of ignition probability. Random Forest models were calibrated from historical fire records, and we used geospatial layers of land cover, accessibility, population density and dead fine-fuel moisture content (DFMC). The methodology is explained in detail in Gelabert et al. (2025). For Chile, a Random Forest model was used that relates topographic, climatic and anthropic variables (such as land use or distance from roads) with ignition sources. It considers ignitions from 2013 to 2015 but was validated with ignitions up to 2020.

2.3.4 Forest Production

Prioritizing forest production identifies locations where treatments can generate revenue that in turn can be used to subsidize non-economic fuels treatments (Ager et al., 2017). In addition, rural communities can also participate in the projects by retrieving fuelwood for household purposes. Accurate estimates of the timber volume available for harvesting, including the type and quality of the retrieved stocks, are only available for forest districts. To provide some examples of growing stock of common tree species found in the area, *P. halepensis* and *P. brutia* have a growing stock of about 26 m^3/ha, *P. nigra* about 54 m^3/ha, *P. sylvestris* about 123 m^3/ha, and *Picea abies* about 342 m^3/ha (Kazana & Kazaklis, 2005). One major drawback is that most of these plans were either not available to us or outdated (i.e., more than a decade old), requiring additional processing to approximate the level of current timber volume in each stand. In addition, information was available only for forests with forest management plans and not for the entire landscape.

We retrieved the raster layer (100 m cell size) of aboveground biomass (Mg ha^{-1}) created by an ensemble of machine learning algorithms that were trained using stratified sampling from an existing European-scale biomass map from 2018 to predict an updated version for 2020 (Pirotti et al., 2023). Aboveground biomass is defined as the mass, expressed as oven-dry weight of the woody parts (stem, bark, branches, and twigs) of all living trees, excluding stumps and roots. This is a product created by the FIRE-RES project. The sampled biomass values from 2018 were filtered to remove areas that did were subject to forest disturbances between 2018 and 2020. This information was available from forest cover/loss/gain maps derived from satellite imagery. Then, the authors (Pirotti et al., 2023) trained the algorithm using a total of 49 features derived from the following sources: bioclimatic data, maps of land-cover, tree cover, tree height, annual composites of vegetation indices per pixel (EVI and NDVI) obtained from Sentinel-2, radar backscatter median annual values from Sentinel-1 and ALOS-2, and the ALOS DSM (3D) elevation grid. A model was created dividing Europe into 19 tiles to limit variability due to very different bioclimatic zones. This dataset was used as a proxy to estimate the available biomass at any given stand, since commercial timber volume was not available, for all European Living Labs. For Chile, since the FIRE-RES dataset did not cover this region, we used the ESA CCI BIOMASS for the reference year 2020 (de Bruin et al., 2020).

This value represented the volume of all trees of the stand, regardless of their commercial value, stand structure and condition, and was the metric used to prioritize forest production. For each stand we assigned the average value of all pixels whose centers intersected it with the zonal statistics tool in ArcGIS.

2.3.5 Suppression Difficulty

Flame length is the distance measured from the average flame tip to the middle of the flaming zone at the base of the fire, measured on a slant when the flames are tilted due to effects of wind and slope, and serving as an indicator of fireline intensity. Fireline intensity is an important determinant of aboveground fire severity and can be used as an indicator of fire suppression difficulty. Despite serious considerations on how flame length can be accurately measured in the field (Alexander & Cruz, 2017), it is very apparent to fireline personnel and so readily conveys a sense of fire intensity that it is worth featuring as a primary variable representing the potential wildfire hazard on the landscape (Murphy et al., 1991). Higher flame length values represent fuels with a higher probability of experiencing torching, crowning, and other forms of extreme fire behaviour under conducive weather conditions. Treating stands with highest flame length values, especially in forested stands with low canopy base heights and adequate canopy fuels, can reduce the crown fire severity potential and increase future fire resistance.

From the above, a necessary condition for the development of EWE is a landscape with enough stored energy, i.e., a sufficient amount of available fuel. Under extreme weather conditions, available fine fuel loads greater than 10-12 t ha-1 might result in EWE exceeding firefighting capabilities (Fernandes et al., 2016). The threshold for available fine fuel load depends on vegetation type and meteorological conditions. Regarding aerial horizontal continuity, for the development of active crown fires a threshold for bulk density between 0.08 to 0.1 kg per m^3 has been identified (Botequim et al., 2019; Gómez-

Vázquez et al., 2014). In terms of vertical continuity, a threshold of 1.9 m of canopy base height for a crown value greater than 0.08 kg per m^3 resulted in active crown fires (when shrubs were medium or tall) while fire activity was low at a canopy base height greater than 1.9 m in stands with short shrubs (Botequim et al., 2019). In maritime pines, canopy base height of 7 m proved to be the most important threshold for dramatic changes in fire type (Botequim et al., 2017). For more information regarding how suppression efficiency can be increased through targeted fuel treatment measures, please refer to the FIRE-RES deliverable D1.11 "Ecological factors driving resistant and resilient landscapes to high intensity and extreme wildfire events".

The metric of flame length is a product of all the stochastic fire simulators used in this IA. For more details, please visit the fire simulations section in this document (Section 3). The values of the flame length raster were averaged at the stand level through the zonal statistics tool of ArcGIS. We hypothesized that if stands with high flame length values are treated, then a substantial reduction of the fire suppression difficulty can be achieved, and the higher this value is, the more important is this stand to receive fuel treatments that will reduce this value.

2.3.6 Carbon Stocks

Carbon can be emitted in large quantities during a wildfire. If a fire reaches an area rich in accumulated carbon, both in dead and live plant material, it can consume it for several days even after the main fire front has passed from the area with the process of smouldering. When vegetation burns, carbon stored in plant material (especially in trees and undergrowth) is rapidly released into the atmosphere in wide variety of C compounds including greenhouse gases (CO2, CH4, N2O, NMVOC, NOx) and fine and coarse particulate matter. This immediate release contributes to atmospheric carbon levels, impacting climate change. Intense fires can reduce carbon stored in soil layers. Organic matter in the soil, rich in carbon, can combust in a fire, especially if it burns deep into the soil layers. This reduces the carbon stored in the soil, which might take decades to rebuild. With the destruction of vegetation, the forest loses much of its ability to absorb CO_2 through photosynthesis. In sum, wildfires cause a rapid release of stored carbon, reduce the immediate capacity of the ecosystem to sequester future carbon, and may lead to long-term shifts in vegetation that lower the ecosystem's overall carbon storage potential.

We used a dataset that mapped aboveground and belowground biomass carbon to estimate the average values of each stand of the five Living Labs. This global dataset provides temporally consistent and harmonized maps of aboveground and belowground biomass carbon density for the year 2010 at a 300 m spatial resolution (Spawn & Gibbs, 2020). The aboveground biomass map integrates land-cover specific, remotely sensed maps of woody, grassland, cropland, and tundra biomass. Aboveground living biomass carbon density includes carbon stored in living plant tissues located above the earth's surface (stems, bark, branches, twigs). It does not include leaf litter or coarse woody debris that was once attached to living plants but have since been deposited and are no longer living.

The belowground biomass map similarly integrates matching maps derived from each aboveground biomass map and land-cover specific empirical models. Belowground living

biomass carbon density includes carbon stored in living plant tissues located below the earth's surface (roots). This does not include dead and/or dislocated root tissue, nor does it include soil organic matter. Woody cover includes any vegetation whose biomass is primarily composed of woody biomass (e.g. trees and shrubs). Herbaceous cover includes any vegetation whose biomass is primarily composed of leaf-like matter (e.g. grasses and many crops). Both above- and belowground biomass carbon maps were created using a novel method that overlayed vegetation-specific carbon density maps and proportionately allocate their estimates to each grid cell using ancillary maps of percent tree cover and landcover, and a rule-based decision tree. We hypothesized that if fuel treatments are applied in areas with high carbon stocks, then they can be protected by wildfires and these treatments can have a substantial impact on not releasing this accumulated carbon in atmosphere, and that the trees can continue their photosynthesis and storage of carbon in the future.

2.3.7 Downstream Protection Value

Downstream Protection Value (DPV) (Pais et al., 2021) is a flexible metric that measures and ranks the impact of treating a unit of the landscape to minimize wildfire losses, like the "node influence grid" introduced in FlamMap. Traveling times recorded inside the "shortest-path trees" from a wildfire simulator like MTT or Cell2Fire provide useful information regarding the shortest propagation paths inside the forest. Furthermore, average propagation time and rate of spread can be calculated, providing practical insights when developing the fuel treatment plan by also incorporating relevant elements for operational fire suppression (e.g., average propagation speed) that can be critical in the event of a future wildfire (Pais et al., 2021).

From these outputs, interesting conclusions can be extracted with respect to the role of different fuel types inside the propagation dynamic, as well as weather conditions that affect the effective rate of spread between cells. Following the idea of evaluating the level of protection given by treating a certain area, Pais et al. (2021) introduced the DPV, a new fire risk model that aims to measure the value of what is burned downstream, starting from a burning cell *i*. Thanks to this metric, the impact of treating cell *i* can be quantified in terms of an optimization problem defined by the decision maker, optimizing the fuel treatment plan when planning under wildfire uncertainty (Pais et al., 2021). From the previous definition, DPV is the summation of "node values" factors, defined as a common value unit used to represent the relative importance of each cell and prioritize the treatment within the landscape as we seek to minimize the impact of (e.g., expected losses) wildfires. This metric was estimated as an additional metric of the Cell2Fire simulations conducted for the Chilean Living Lab, accounting the influence that the stochastic wildfire simulations can have in given portions of the landscape, i.e., where are the locations that more often crossed by the simulated fires, for a value-at-risk, in this case, the exposure of populated areas to these simulated wildfires. We hypothesize that the higher the DPV value is in any given stand, the higher the impact of potential fuel treatments will be there for the protection of populated areas. DPV values were averaged from all cells falling in any given stand of the Chilean LL.

2.4 Multicriteria spatial prioritization and optimization

The ForSys algorithm uses a relatively simple search heuristic that tests each polygon as a seed to build a restoration project in the surrounding landscape, absorbing adjacent stands based on their potential contribution to the priority value, and treating those that meet the treatment thresholds. The user supplies a forest management scenario in terms of priorities, treatment constraints, and treatment thresholds, and the program identifies one or more project areas within the landscape that maximize the priority (Equation 1):

$$Max \sum_{j=1}^{k} (Z_j * \sum (W_i N_{ij})) \quad (1)$$

Subject to Equation 2:

$$\sum_{j=1}^{k} (Z_j A_j) \leq C \quad (2)$$

where C is a global constraint on investment level per project area (e.g., area treated), Z is a vector of binary variables indicating whether the *j*th stand is treated (e.g., Z*j* = 1 for treated stands and 0 for untreated stands), N*ij* is the contribution to objective *i* in stand *j* if treated, and A is the area of the *j*th treated stand. W*i* is a weighting coefficient that can be used to emphasize one objective versus another.

The fundamental idea is that if a substantial portion of a forest district is treated on an annual basis, it has a positive effect on reducing fire intensity for the entire forest district, while low treatment intensities or scattered projects have little or no influence on limiting large fire spread (Ager et al., 2019; Salis et al., 2016). Another assumption is that each restoration priority would be addressed by thinning for overstocked stands and surface fuel reduction with mastication, prescribed fire or fuel removal. Stands were added to each project based on the value of the priority for that stand, and when the area treatment constraint was met (projects of 100 ha with varying total treated area depending on the modelled scenario), the total priority value was summed. ForSys runs were aggregated, meaning that there were spatial constraints in having the selected stands with common boundaries.

2.5 Linking stands with fire behavior modelling outputs and other forestry metrics

Due to the various stand shapes and sizes each variable's raw value had to be converted to stand value with Eq. (3):

$$\boldsymbol{S\_ij = C\_ij * A\_i} \quad (3)$$

Where S*ij* is the stand value for the stand *i* and for the variable *j*, C*ij* is the raw averaged or summed value for the stand *i* and for the variable *j*, and A*i* is the area (hectares) of stand *i*. Then the percentage contribution with respect to the total problem of all treatment units (i.e., PCP) was calculated to standardize reporting across all priorities and assess the attainment degree of all treated units with Equation 4.

$$PCP_{ij} = \frac{S_{ij}}{\sum_{S \cup K} S_{ij}} * 100 \quad (4)$$

where PCP*ij* is the percent contribution to the total problem (sum of the data subset K) of the stand *i* and for the variable *j*. Finally, to assess the importance of each stand that defined whether it will be selected or not in a project, we estimated the percent difference from the maximum value of all stands for each priority's stand value with equation 5.

$$SPM_{ij} = \frac{S_{ij}}{\max_{S \cup K} S_{ij}} * 100 \quad (5)$$

where SPM*ij* is the percent difference from the maximum value of the data subset K (landbase) of the stand S*i* and for the variable *j*. PCP and SPM for each priority values were calculated for all stands of each land base, i.e., estimated not only for the available stands but for the entire landscape, and the estimations were performed with a point-and-click functionality offered within ForSys.

2.6 Modelled Fuel Treatment Scenarios with ForSys

2.6.1 SET0: Control and Evaluation

The first set of runs (SET0), conducted for all five Living Labs, tests the business-as-usual scenarios for fuel treatment project spatial allocation against the spatial optimization process of ForSys to evaluate whether we expect to receive better results (i.e., higher percent attainment) for three management priorities. The first run asks ForSys to randomly spatially allocate a different number for each LL of 100-ha projects and estimate the attainment for the three defined management priorities (can be different among the five LLs). This run replicates the important planning problem for allocating such projects, where governments fund projects conducted by municipalities or fire management agencies that they do not account for what is expected to be gained in terms of fire risk reduction and achievements of other ecological or management objectives. Usually, such projects are allocated in a "random" way across the landscape (i.e., with limited and very local knowledge), without considering the major flow paths of the fire and in locations that are easier to implement such projects. The second run asks ForSys to spatially allocate projects close to the road network so that the closer a stand is to a road, the higher the chances are for it getting selected. This is another business-as-usual scenario, where fire management agencies choose accessibility as their main considered parameter to choose where they will implement fuel treatment projects. The results of the attainment of these two runs for the three objectives are compared with the results of the SET1 to show how different is the cumulative attainment of the two control and evaluation allocation strategies, for the same area treated. To put it simply, if we treat 50,000 ha with a random allocation what we expect to gain in terms of developed areas exposure reduction compared to treating the same area, but with optimization of spatial allocation based on where are the stands with the best chances to achieve such reduction are located.