FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

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Executive Summary

Implications of future fire regimes for preparedness planning are explored and contextualised to derive and update policy guidelines. Adaptation options for expected changes in ecosystem services are identified and resulting management options are prioritized. The preparedness activities program at municipal scale is developed according to the future danger, vulnerability and risk of fire in the WUI.

This document provides informed recommendations for adapting ecosystems and populated areas (WUI), to the anticipated changes in ecosystem services and the future evolution of wildfire exposure. Since WP3 highlight that fire danger and exposure are expected to increase drastically in all regions, particularly in the Mediterranean, actions aiming to reduce both exposure and vulnerability are critical.

Fire adaptation measures can help maintaining ecosystem service provisions related to carbon, water and habitats. An online model to quantify future fire impacts is applied at pilot site (PS) scale; running the model with and without fuel management interventions aimed at reducing burned area indicates that treatments can substantially lower the risk to water quality, soil erosion and nutrient cycling in demo catchments; i.e. removing 20% of 1-hour dead fuels halves the expected burned area by 2050, which means a 31% reduction in soil erosion, and a 49% reduction in ash, carbon and nitrogen transport.

In the context of the future regimes predicted in Work Package 3 (WP3) and the associated operational characteristics (i.e. occurrence of extreme fires or simultaneous wildfires) first-response resources will be increasingly overwhelmed, rendering firefighting efforts ineffective. Preparedness activities in WUI areas (municipalities) are developed based upon the expected danger levels using seasonal forecasts; these activities include risk mitigation and rehearsals for good practices on prevention and self-protection in dedicated training and education sessions.
This last deliverable from WP3 for adaptation options to future fire preparedness planning is based on climate and stylized fuel management scenarios (SSP1) from D3.1 and D3.2. They are used to simulate future burned area, and population exposure to future fires and smoke, plus changes in ecosystems and their functioning, as described in D3.6. D3.7 has identified effective adaptation measures.

Given the late development of the related WP3 activities within the temporal frame of the project (M36-M48), conference papers and journal papers are under way, with some exceptions, i.e. Neris et al. 2024 (https://doi.org/10.5194/egusphere-egu24-16087).

Objectives not achieved:
The integration of three spatial scales was constrained by data availability. However, the proposed Self-Protection Plans for Residential Developments (SPRD, organization and mechanisms to establish protocols for the response of homeowners and residents to a wildfire) are framed within the Municipality Wildfire Action Plans (MWAP, a tool capable of coordinating the participation of public and private entities, businesses, and citizens within the Civil

Protection System). In turn, MWAPs are part of the regional plan for wildfire defence and prevention, not addressed here.

Key take away messages:

֍ ADDRESS REGULATIONS TO FACILITATE ACTION: Implementing adaptation strategies locally requires alignment with national and regional legislation. Policymakers must address regulatory barriers to facilitate fuel management, urban planning, and community engagement in fire-prone areas. *Section 2.*

֍ REFINE MODELS: While current models provide valuable insights, they may not fully capture the extreme events projected under harsher climate scenarios. The application of predictive tools such as WEPPcloud-EU-WATAR attests the importance of modelling future fire impacts. These tools enable informed decision-making by simulating scenarios of soil erosion, ash deposition, and nutrient losses, helping prioritize fuel intervention strategies. *Sections 3 and 4.*

֍ ENGAGE COMMUNITIES: Proposed Municipal Wildfire Action Plans provide a structured framework for coordinating public and private responses to wildfires. These plans include zoning for risk assessment, resource cataloguing, and establishing self-protection measures in WUI areas. Effective wildfire preparedness hinges on community engagement. Educating communities about prevention and self-protection, public awareness campaigns, drills, and tailored risk assessment tools are essential for fostering a culture of shared responsibility in WUI areas. *Section 5.*

Links to Key Related Deliverables:

D3.1 – Downscaled CMIP5 and CMIP6 climate scenarios for selected PS and DA
D3.2 – Continental land use change scenarios and stylized fuel management scenarios for the 21st century
D3.6 – Future vulnerability and exposure to future fire, incl. changes along WUI
D3.7 – Identification of effective adaptation measures

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List of Acronyms

Table 1: List of Acronyms

List of Acronyms	
C	Carbon
DA	Demonstration area
ET	European territory
MWAP	Municipality Wildfire Action Plans
NUTS	Nomenclature des Unités Territoriales Statistiques
PS	Pilot site
SPRD	Self-protection plans for residential development
SU	Swansea University
T	Tonne
VUA	Stichting VU
WUI	Wildland-Urban Interface
WP	Work Package

1 Introduction

The WP3 of FirEUrisk intended to adapt wildfire management strategies to expected future climate and socioeconomic changes. In this framework a risk-centred management strategy must integrate wildfire prevention, suppression and restoration practices and policies in a holistic conceptual framework, involving multiple stakeholders and addressing all relevant wildfire management tasks. This should provide protection of citizens and ecosystems exposed to future wildfires. In previous work and deliverables, FIREURISK has modelled socio-economic issues and human activity influencing fire ignition, vulnerability and exposure, and has evaluated the impact of National and EU policies on land use change, rural economy and development, in a context of expected future fire regime changes. Consequently, this allows FIREURISK to deliver adaptation options and preparedness planning within innovative risk-informed regional planning approaches that are effective in increasing the resilience of local communities, ensuring safety and enhancing protection of assets and economic activity.

1.1 Purpose of the document

The purpose of this document is to provide adaptation management options, with technical and methodological specifications, for future fire preparedness planning required to mitigate unwanted fires at three scales: European Territory (ET), Pilot Sites (PS) and municipalities or demonstration areas (DA).

1.2 Structure of the Document

The document structures the activities proposed in WP3-Task 3.3 and Activity 3.3.2, as follows:

- Explores the implications of future fire regimes for fire prevention and preparedness planning and contextualize them with PS and DA experts with WPs 5 and 6 to derive and update policy guidelines.
- Provides informed suggestions for adaptation in ecosystems based on changes in ecosystem services and future fire risk (from task 3.2), from which adaptation options to expected changes will be identified and resulting management options prioritized.
- Applies the online model developed by Swansea University in WP1 to quantify fire impacts at PS to estimate the effects of likely future fire severity scenarios on water quality, carbon and nutrient losses. Running the model with and without fuel management scenarios allows the effectiveness of fuel management measures to be evaluated, and fire prevention and preparedness planning adjusted.
- Quantifies how fire adaptation measures can help maintaining ecosystem service provision related to carbon, water and habitat (as explored in WP2)
- Develops preparedness activities in European municipalities based upon the expected danger levels using seasonal forecasts. These include risk mitigation and rehearsals for good practices on prevention and self-protection. The activities performed in dedicated training and education sessions include risk mitigation and self-protection drills. The preparedness activities program is developed according to the future danger, vulnerability and risk of fire along the WUI (from WP1 and activity 3.2.2).

2 Future fire regimes for fire prevention and preparedness planning and contextualization with pilot sites and demonstration areas to update policy guidelines

Multiple factors influence and are impacted by fires, observing within Europe a strong latitudinal variation of the FWI (Fire Weather Index) increasing toward the south, whereas tree cover increases towards the north (Bowman et al. 2020). The combined effect of climate and land use change is leading to more flammable landscapes across Europe, suggesting that climate, land use and socio-economic conditions are the main drivers for future fire projections that should be considered in the fire prevention measures across the demonstration areas and pilot sites of FireEUrisk.

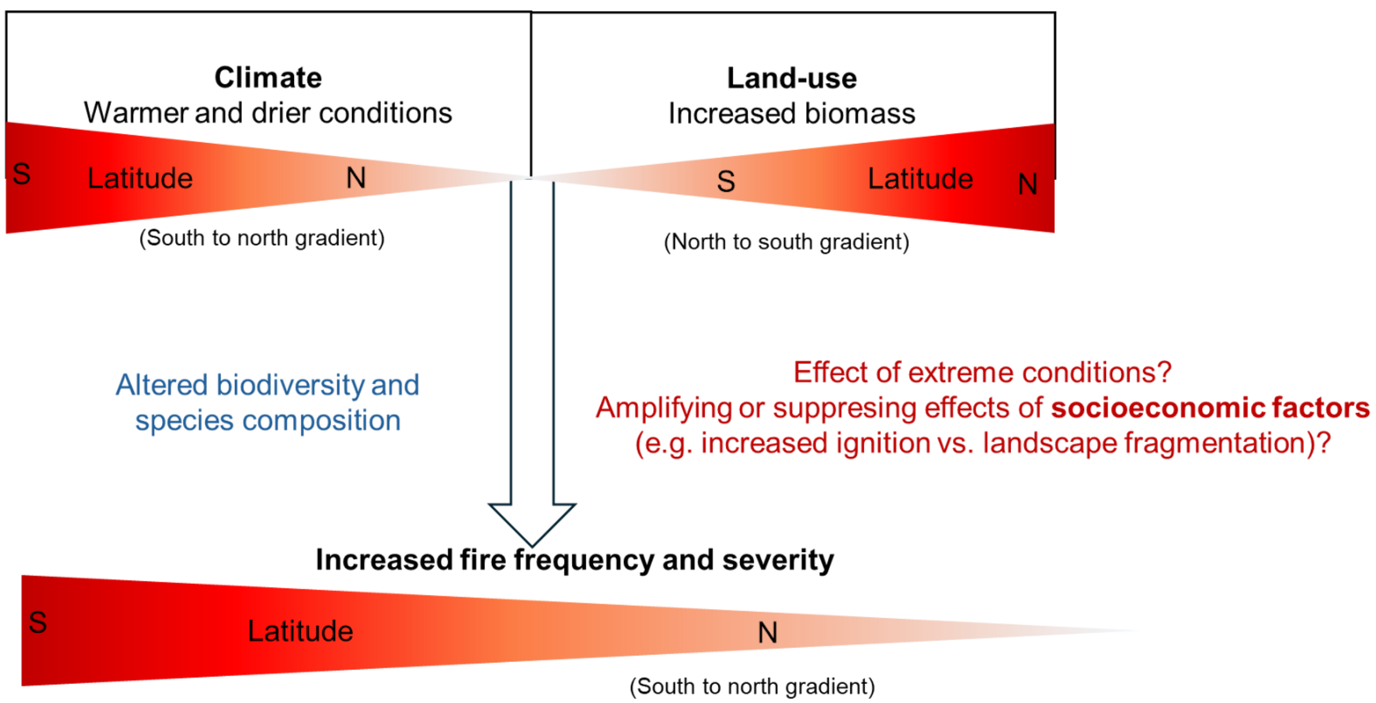

Figure 2.1. Schematic representation on how the latitudinal gradient of future changes in climate, land use and socio-economic conditions might affect fire regimes (fire occurrence, frequency and severity), generally mediated through altered biodiversity and species composition. Derived from FireEUrisk outcomes (see e.g. Figure 5 in deliverable 3.4).

The prevention and preparedness to future fire regimes should be focused on FirEUrisk risk assessment as proposed in Chuvieco et al. (2023) and shown in Figure 2.2, that can affect to the fire danger (i.e. ignition or propagation), exposure (i.e. population and assets, as well as ecosystems), and vulnerability (i.e. potential losses and resilience).

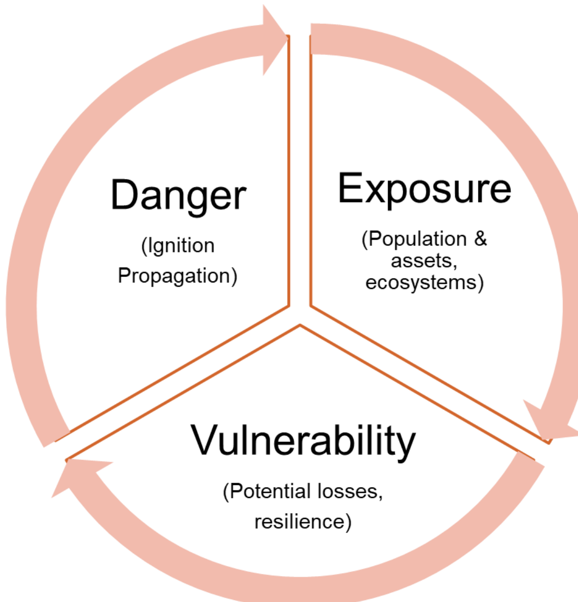

Figure 2.2. Wildfire fire risk assessment used in the FirEUrisk project, modified from Chuvieco et al. (2023). Potential losses include ecosystem services, ecological values, population and assets, whereas resilience the coping capacity and the recovery time.

The predictors used to predict fire regimes are based on fire danger including the fire occurrence, severity, frequency and duration are generally related to climate and abiotic conditions, socioeconomic conditions and land use conditions (Table 2.1), and several have been used to understand how fire regimes might change between pilot sites and demonstration areas across Europe.

Table 2.1. Abiotic, socio-economic and land-use predictors used within FireEUrisk to predict future fire regimes based on the danger of fires following Figure (see also Ochoa et al. 2024). The description of the variable and reasoning is included in the description.

Variable	Type	Description
Fire Weather index / Fire Danger index	Abiotic	Fire weather conditions. Fire danger index is based on vapour pressure deficit or Nesterov index. In other cases, aridity or evapotranspiration indices are being used.
Topographic Position Index or slope	Abiotic	Affects accessibility and fragmentation
GPP index	Land-use	Gross Primary Productivity of the month divided by the maximum monthly GPP of the last 12 months, with low values detecting drought-induced stress, low fuel moisture and high flammability.
Tree cover	Land-use	Biomass and fuel characteristics.

Dominant type	Land-use	Classification of the vegetation depending on their responses to fires or flammability (e.g. in deliverable 3.4 classified as "non-native broadleaved", "dry pines", "conifers" and "broadleaved".
Population density / distance to roads/ human-caused variables (e.g. WUI)	Socio-economic	Human starts fires
Human development index	Socio-economic	Investment in fire prevention and management, related to population awareness

The **occurrence of human-caused fire ignition** has been strongly linked to **population density** (people km^{-2}), but it has been also simulated with other **nine human predictor variables** in deliverable 3.3 including population older than 65 (%); distance to roads (m); fuel types (categorical); distance to wildland-urban, fores-agricultural or wildland-grassland interfaces (m); percentage of urban, agricultural or wildland land cover (%). From all the predictors population density was the most important variable for ignition occurrence in the three studied pilot sites (Spain, Portugal and central Europe), followed by distance to **forest-grassland** interface, population over 65 and distance to roads (see deliverable 3.3). The observed increased ignition probability with greater population densities, lower distances to **forest-grasslands**, lower percentage of population over 65 and lower distances to rows, suggest that in pilot sites and demonstration areas with these characteristics special fire prevention measures (as those suggested in Table 5.2) should be carefully considered and applied.

The **vulnerability and exposure to future fires** (see Table 2.2) following the wildfire risk assessment of FireEURisk depend on the population exposure to future fires and smoke; changes in the ecosystem and their functioning, as described in the deliverable 3.6. In future scenarios the **fire danger index** has been used in DGVMs to predict the proportion of human or lightning caused ignition events leading to **spreading fires**, based on wind speed, fire intensity and the availability, composition and wetness of vegetation (see deliverable 3.3 and Thonicke et al. 2010). The results from DGVMs in demonstration areas and pilot sites have shown that in southern Europe there are greater potential for human ignitions (e.g. Spain, France), and cause an actual fire; predicting less pronounced potential ignitions but a larger area burnt with the new SOFIA approach implemented in LPJmL-SPITFIRE when compared to the standard SPITFIRE.

Table 2.2. Potential effects of future fire regimes, with description of the effect and the expected value under future conditions. Summary to inform potential prevention and preparedness based on results from deliverable 3.6.

Variable	Description
Exposure to smoke	Increases in all regions, particularly in Mediterranean regions. Future situation in central Europe similar to current situation in the Mediterranean, with increased CO and NOx emissions
Ecosystem service provision	Carbon sequestration tends to increase in the north and mountain regions but decrease in highly managed regions dominated by agriculture (western Europe, British Islands).
Ecological vulnerability	Intensified fire regimes will affect plant abundance, diversity and fitness; particularly woody species as conifers in the short-term (≤ 2 years), decreasing biodiversity.

The EU objective of planting three billion trees as part of the biodiversity for 2030, as stated in the EU Green Deal, requires considering specific information as: consider forest canopy structure, introduction of maladapted or flammable species (e.g. Eucalyptus in Portugal, see Xanthopoulos et al. 2012). We propose to consider in the demonstration areas and pilot sites of the FireEUrisk project several fire prevention activities that are based on landscape planning and urban design principles, and particularly on fuel and fire management (see e.g. Bowman et al. 2020). The inclusion of specific actions for fire prevention and preparedness planning requires specific evaluations in the specific pilot sites and demonstration areas, where the scenario-based approaches, such as those considered in FirEUrisk project, where climate, socio-economic and land use changes are modelled. The development of fire-management interventions requires interdisciplinary research linking social and natural sciences, including engineering and technology. Specific considerations between diversity, climate change mitigation and adaptation and fire risk should be carefully considered.

Table 2.3. Fire prevention measures proposed for the demonstration areas and pilot sites based on landscape planning and urban principles (as decrease of WUI). A description of the specific measure is also included, were a specific local study needs to be developed for their implementation.

Fire prevention measurement	Description *Examples of development across Europe, pilot sites or demonstration areas*
Herbivory (Fuel management strategy)	Reduce biomass through activities such as grazing and browsing by wild or domesticated herbivores. *A strong south to north gradient of decreasing suitability is found (Neidermeir et al. 2023).*
Reduction of fuel load (Fuel management strategy)	Reduce biomass amount and continuity through direct management and mechanical removal (silviculture, pruning, and clearing). Consideration of fuel composition and distribution across landscapes. Aim to increase vegetation heterogeneity and decrease fire proneness. Mechanical fuel removal directly affects to fuel continuity, and it can affect to fuel composition.

	Medium to high suitability in most Europe (Neidermeir et al. 2023).
Prescribed fire use (Fuel management strategy)	Traditional burning practices, that can be professional and pastoral. *Suitability is observed in some Mediterranean regions (Neidermeir et al. 2023).* *Controlled fires in agropastoral areas have been developed in two demonstration areas (Sardinia and French Alps), where the specification of the practice according to each site needs, resources and regulations is changeling.*
Fuel composition	Species biomass, architectural structure and response to fire and climate strongly feedback with fire regimes. Considerate the adaptation and flammability of existing species to expected fire regimes.
Reduction of ignition points	Specific fuel management practices across power lines, roads, railroads. *Integration if PS5 – Attica, Grece described in D4.4.*
Model development and evaluation	Specific models to locally develop the response to fire under scenario-based approaches *Smoke releases has been simulated to extreme fire behaviour in several pilot sites (Portugal, Spain and Fires) and demonstration areas (Chernobyl region). Improved land use scenarios and fire-enabled DGVM.*

The management of future fire risks will require the integration of potential scenarios of land cover and global environmental change assessing the potential effects of expected exposure and reductions in the vulnerability (i.e. through reductions of potential losses and increases in the expected resilience). As the results for WP3 highlight that fire danger and exposure is expected to increase drastically in all regions, and particularly in the Mediterranean, actions aiming to reduce both exposure and vulnerability are critical.

3 Fire adaptation measures for ecosystem service provision

3.1 Overview of changes in ecosystem services and future fire risk

Water quality, soil erosion, and nutrient cycling are key ecosystem services that can be substantially altered by fire (Roces-Diaz et al., 2022). Soil and ash are sources of sediment, carbon, nitrogen, and associated pollutant movement following a fire. Their transport into freshwater systems, influenced by catchment characteristics and hydrological processes, can pose severe environmental and socio-economic implications including impacts on water quality, disruptions to drinking water supplies and high remediation costs, as well as the depletion of carbon and nutrients from areas affected by erosion (Gustine et al., 2022; Robinne et al., 2021). Future fire risk and fire impacts are presented in D3.5 for different future climate scenarios. They imply overall detrimental impacts on ecosystems services with increased warming and thus fire risk, especially for southern Europe.

We estimated the effects of likely future scenarios on water quality, soil erosion, carbon and nutrient losses using the WEPPcloud-EU-WATAR product (WP1) in three European catchments in North and South Portugal (i.e. Maciera and Monchique), and in Central Europe, which represent Atlantic mediterranean, mediterranean and continental climate zones respectively.

We used the stylized fuel management scenarios developed by project partner Stichting VU (3.2) to simulate future burned area. We selected two burn area simulation scenarios (SSP1) for 2050, i) no fuel management intervention; and ii) the removal of 20% of 1-hour dead fuels. We chose the removal of fine fuel (1-hour) scenario as this was identified as the most effective treatment for reducing burned area (see section 2.2). These simulations predicted that up to 75% of natural vegetation in the two Portuguese catchments would burn by 2050, with fuel reduction interventions reducing burned area by up to 50% (Fig. 3.1 and 3.2). We focus this overview on the Portuguese catchments since the simulations for the selected catchment in Central Europe predict no changes in burned area by 2050. However, irrespective of this specific simulation outcome, it is acknowledged that traditionally less fire-prone regions, like the broader Central Europe area, face a future increased risk of larger and more severe wildfires associated with ongoing increased in fire weather severity and fire season length (see D3.5 and Jones et al., 2022). Details of methods and scenarios are described in Chapter 4.

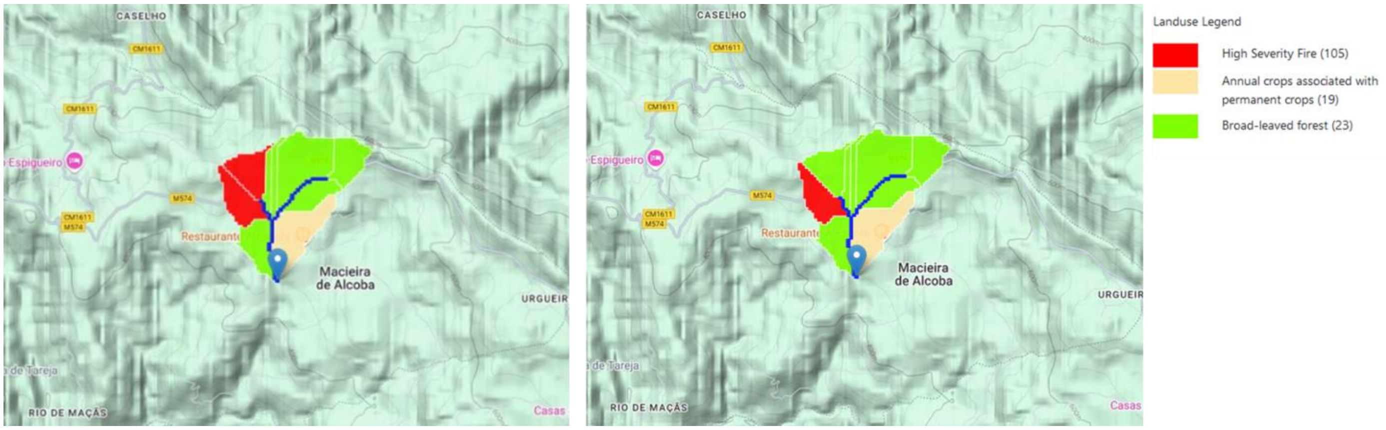

Fig. 3.1. Simulated burned area and severity for Scenario 1 (no fuel intervention; left) and Scenario 2 (fuel intervention; right) for the Macieira site (Portugal).

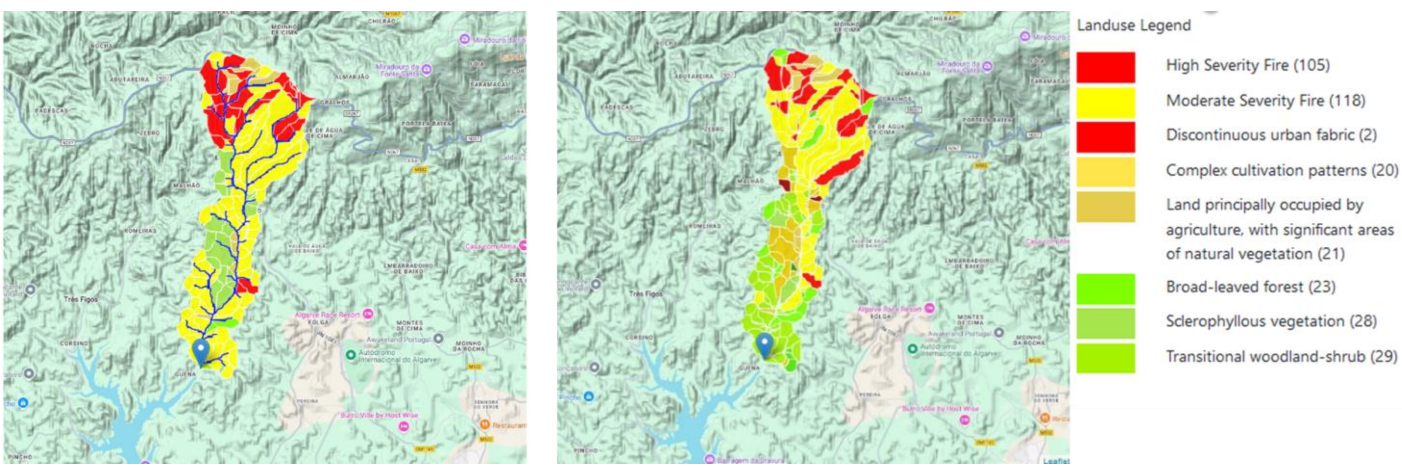

Fig. 3.2. Simulated burned area and severity for Scenario 1 (no fuel intervention; left) and Scenario 2 (fuel intervention; right) for the Monchique site (Portugal).

Without fuel management, our estimates suggest that between 0.96 and 4.4 T of wildfire ash per hectare could be delivered from burned catchments into water networks, potentially resulting in C losses ranging from 0.13 to 0.78 T of C per hectare in the studied catchments. We found that implementing fuel management interventions aimed at reducing burned area can substantially lower the risk to water quality, soil erosion and nutrient cycling in these catchments. For instance, in a catchment in South Portugal, the removal of 20% of 1-hour dead fuels led to a 17% reduction in the risk of soil erosion, ash transport and nutrient losses to receiving streams. Our analysis, therefore, highlights the importance of effective fuel management strategies, such as the reduction of fine fuels, especially in steep hillslopes with high fuel loads, in reducing fire-related risks to ecosystem services, particularly in fire-prone regions like Southern Europe.

3.2 Adaptation suggestions

We tested stylized fuel management scenarios that were developed by partner Stichting VU in WP2 in LPJmL-SPITFIRE for their effectiveness to reduce burned area under future climate change conditions. We tested 5 scenarios, where a certain percentage of either 1-hr, 10-hr, 100-hr or 1000-hr, or a certain percentage of fuel was reduced in each fuel class at the same time. By removing 1-hr to 100-hr fuel we expected direct reduction effects in rate of spread and thus burned area, whereas removing 1000-hr fuels would have indirect effects on area burnt by fuel availability being affected by fire intensity. We tested those fuel removal scenarios under two socio-economic pathways (and one related climate scenario) because we wanted to capture indirect effects of land-use change as well. A detailed description is found in Deliverable 3.7 "Identification of effective adaptation measures".

We found that removing fine fuels (1-hr fuel) has the most effective effect on reducing burned area in the Mediterranean region. This effect persisted also in the scenario with all fuel removals. Removing only wood fuel as 10-hr or 100-hr fuel as is discussed in temperate regions to avoid high-intensity fires, changed fuel compositions and thus the weighting of each fuel class's impact on rate of spread. It therefore led to increasing rate of spread and area burned across Europe. This effect was diminished when fuel was removed from all fuel classes, but the effect of reducing burned area by just removing 1-hr fuel was smaller in the Mediterranean region (see Fig. 3.3, more details in Deliverable D3.7).

Removing fuel under the SSP3 socio-economic pathway had a larger effect. Removing only 1-hr fuel led to larger reductions in burned area, increased burned area when only 10-hr fuel was removed, and the dominance of 1-hr removal persisted and still led to larger reductions in burned area (Fig. 3.3). Details of the methods and scenarios used, and all results are described in Deliverable D3.7.

Therefore, the potential to reduce fire risk via fuel management exists and seems to be robust also under harsher climate change conditions and socio-economic development in Europe, but it should be carefully assessed on how such fuel management can be implemented given national and subnational legislation and land-use configuration at the landscape scale, including wildland-urban interfaces. Given the fact that the climate scenarios cannot represent potential climate extreme conditions that could lead to single fire extreme events it is still possible that extreme fire events of high fire intensity occur and cause large damage to the affected vegetation. These conditions could not be captured with the current setting of scenarios and model configurations. It is further recommended to assess the local conditions where it is plausible to remove fuel, incl. fine fuel, e.g. in wildland-urban or wildland-rural interfaces, to have its maximum positive effects to reduce risks. The goal should be to avoid trade-offs with soil carbon storage, local shading effects on soil moisture and biodiversity to which decaying wood provides habitat. Preventing human-caused ignitions by raising awareness and through policy incentives should be the top priority with fuel management being a contributor in prevention. This way, one can reduce the risk that fire diminishes any other effort to mitigate climate change effects.

RCP2.6-SSP1	Burned area [ha]	Surface fire intensity [kW/m²]	Mean Fuel bulk density [kg/m³]	Mean Rate of spread [m/s]

Minimum	-15,701.0	-171.1	-308.5	-267.3
Maximum	1,153.2	12.1	269.1	49.6
Mean	-268.6	-4.7	-146.1	-6.4
Standard Deviation	1,086.4	10.5	104.8	18.0

RCP7.0-SSP3	Burned area [ha]	Surface fire intensity [kW/m²]	Mean Fuel bulk density [kg/m³]	Mean Rate of spread [m/s]
Minimum	-16,732.1	-137.4	-305.4	-258.7
Maximum	657.1	11.9	220.7	52.0
Mean	-244.0	-4.8	-144.5	-6.1
Standard Deviation	1,019.5	11.0	103.4	17.4

Table 3.1 Statistical summary of the difference from baseline for Scenario 5 (scheduled removal from all fuel classes) under RCP2.6-SSP1 (top) & RCP7.0-SSP3 (lower) on the variables Burned area [ha], Surface fire intensity [kW/m²], Mean Fuel bulk density [kg/m³], and Mean Rate of spread [m/s] accumulated across the period from 2025-2050 as simulated by the fire-enabled DGVM LPJmL-SPITFIRE.

4 Testing scenarios of the on-line model WEPPcloud-EU-WATAR to quantify future fire impacts on water quality, carbon and nutrient losses

4.1 Summary

Using the predictive modelling capability developed within WP1 (the WEPPcloud-EU-WATAR product; contribution to D1.5) across 3 European catchments (North Portugal, South Portugal and Central Europe), we estimated the effects of likely future fire scenarios on water quality, carbon and nitrogen losses. We run the model with and without fuel management scenarios to evaluate the effectiveness of fuel management measures. By 2050, 20-75% of the natural areas in the Portuguese catchments are projected to burn, with fuel management measures reducing burned area by 15-50%. Notably, simulations for the Central Europe catchment show 0% burned area by 2050.

4.2 The WEPPcloud-EU-WATAR model

WEPPcloud-EU-WATAR is a physically-based, probabilistic model designed to predict post-fire soil, ash, nutrient and pollutant transport from burned hillslopes to water bodies. The tool is built on the well-established WEPP model and offers spatially distributed, comprehensive predictions of nutrient and contaminant transport from burned catchments. It is accessible and user-friendly, requiring minimal data inputs since it integrates topographic, soil, land cover, and climate data from sources like EU-DEM, CORINE and ESDAC, with weather simulations generated via CLIGEN. Nutrient and pollutant concentrations in wildfire ash have been sourced from a comprehensive global dataset of wildfire ash chemical composition from the *Centre for Wildfire Research* at Swansea University (Sánchez-García et al., 2023).

4.3 Study areas

We have applied WEPPcloud-EU-WATAR to three European catchments, two in Portugal (Maciera and Monchique), representative of the Portuguese Pilot Site conditions, and one in the Central Europe Pilot Site (Bad Schandau Fire 2022). We have previously calibrated and validated the WEPPcloud-EU-WATAR product using actual fires in these catchments (Neris et al. 2024). Location and details of study catchments and actual fires can be found in Fig. 4.1 and Table 4.1.

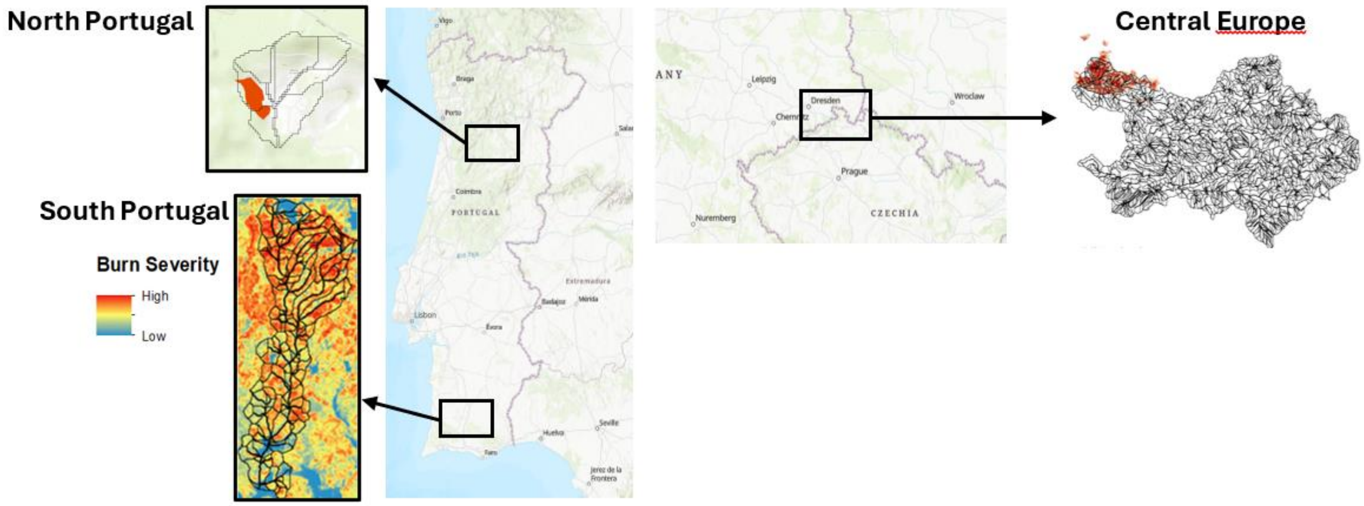

Fig. 4.1. Location of the three catchments with hillslope delineation and burn severity maps of the actual fires.

Table 4.1. Characteristics of the three study catchments and the actual fires.

Location	Catchment name	Catchment size (ha)	Fire date	Burned area (%)	Dominant vegetation	Dominant soil
North Portugal	Macieira	1900	August 2003	100	Evergreen broadleaf forest and shrubs	Loam (67%), sandy loam (30.4%)
South Portugal	Monchique	100	August 2011	10	Eucalypt and pine forest	Loam (7.7%), sandy loam (19%)
Saxon Switzerland National Park	Central Europe	21000	July 2022	5	Mixed conifer and deciduous broadleaf forest	Sandy loam (50%), loam (58%)

4.4 Simulating future fire scenarios (burned area and severity)

To simulate **future burned area**, we have used the burned area changes simulated as part of the stylised fuel management scenarios (SSP1) developed by project partners VUA and PIK (contribution to D3.2). Here, burned area is calculated as the fraction of natural area within a 9x9 km grid cell that burned calculated monthly by the Dynamic Global Vegetation Models (DGVMs; for more details, see D3.2). The stylised fuel management scenarios (SSP1) predict changes in burned area fraction for all months of all years from 2025 to 2050 under the following scenarios:

- Scenario 1: burned area simulations by 2050 without fuel management intervention.
- Scenario 2: burned area simulations by 2050 reducing 20% of 1-hour dead fuels.

Simulating **future fire severity** bears a very high degree of uncertainly due to the highly dynamic factors governing fire behaviour and ecosystem responses, amongst others. To not introduce excessive uncertainty to the analysis, we are assuming burn severity to be similar to the burn severity observed during the actual fires that have occurred in the study catchments (Fig. 4.1). That stated, it is not unreasonable to assume that future fire severity will be above that observed to date given the anticipated increases in fire weather severity across Europe (Jones et al., 2022). Hence the model simulation outputs provided below can be considered conservative. The results of the burned area simulations for Scenarios 1 and 2 for the three study catchments are summarised in Table 4.2.

Table 4.2. Burned area fraction simulations for the three study catchments under the two fuel management scenarios.

Site	Burned area (%)	
	Scenario 1	Scenario 2
North Portugal	17 – 21	8 - 11
South Portugal	Up to 75	50
Central Europe	0	0

4.5 Effect of future fire scenarios on post-fire soil erosion, ash, carbon and nitrogen losses

Future changes in burned area for the Macieira site by 2050 without fuel management intervention (Scenario 1) predicts the burning of around 20% of natural area within the catchment. According to our simulations, this would result in approx. 64 and 96 tonnes of soil and ash transported downstream at the outlet of the catchment, which translates into the potential transport of 13 and 0.5 tonnes of carbon and nitrogen into the river network (Table 4.3). With fuel management intervention (Scenario 2: removing 20% of 1-hour dead fuels), the burned area by 2050 would be halved compared to Scenario 1, i.e. between 8-11% of natural area in the catchment would burn. This reduction in burned area means a 31% reduction in soil erosion, and a 49% reduction in ash, carbon and nitrogen transport.

Table 4.3. Predictions of eroded soil, ash, and carbon and nitrogen at the outlet of the Macieira catchment for the two future fire scenarios.

	Soil		Ash		Carbon		Nitrogen	
	T	T ha^{-1}	T	T ha^{-1}	T	T ha^{-1}	T	T ha^{-1}
Scenario 1	64	0.64	96	0.96	13	0.13	0.5	0.005
Scenario 2	44	0.44	49	0.49	6.7	0.07	0.2	0.002

In the Monchique catchment, simulations in area burned by 2050 without fuel management scenario predict up to 75% of the natural area would burn. Fuel management interventions under Scenario 2 (removing 20% of 1-hour dead fuels) reduces burn area fraction by 15%. The reduction in burned area fraction would translate in a 17% reduction in soil erosion, ash transport, carbon and nitrogen transport to water systems (Table 4.4).

Table 4.4. Predictions of eroded soil, ash, and carbon and nitrogen at the outlet of the Monchique catchment for the two future fire scenarios.

	Soil		Ash		Carbon		Nitrogen	
	T	T ha^{-1}	T	T ha^{-1}	T	T ha^{-1}	T	T ha^{-1}
Scenario 1	41	0.023	7900	4.4	1070	0.59	37.3	0.020
Scenario 2	34	0.018	6570	3.6	893	0.49	31.3	0.017

Simulations for Scenario 1 and 2 in the Central Europe Pilot Site predict 0% burned area fraction. Therefore, we are only quantifying water quality impacts of the actual 2022 Bad Schandau fire (Table 4.5).

Table 4.5. Predictions of eroded soil, ash, and carbon and nitrogen at the outlet of the Bad Schandau catchment for the two future fire scenarios.

	Soil		Ash		Carbon		Nitrogen	
	T	T ha^{-1}	T	T ha^{-1}	T	T ha^{-1}	T	T ha^{-1}
Scenario 1	20	0.02	3175	2.6	945	0.78	36	0.03

5 Design of preparedness plans according to future fires

5.1 Justification of Municipal Wildfire Action Plans (MWAP)

In the context of the future regimes studied in the previous sections and the associated operational characteristics such as the occurrence of extreme fires or simultaneous wildfires, it is to be expected that first response resources will be increasingly overwhelmed, leaving communities to witness how firefighting efforts become ineffective. In this situation, community self-protection is of paramount importance, and its organization at the local level municipality is the most effective and direct approach for prevention and protection. Indeed, preventive land management includes not only the mitigation of wildland fuels but also the management of vegetation surrounding and within urbanized areas, such as common green spaces and private gardens. Furthermore, property owners must be involved in the design and maintenance of their parcels and the adaptation of their homes and infrastructure. To achieve this, it is essential to establish clear and well defined protocols for the development of municipal wildfire defense action plans and self-protection plans for residential developments and other facilities, which are outlined in this document. These plans must take into account the significant effects of climate evolution, both in vegetation and atmospheric conditions, and prepare communities for the protection against extreme wildfire events.

The Municipality Wildfire Action Plans (MWAP) aim to provide a tool capable of coordinating the participation of public and private entities, businesses, and citizens within the Civil Protection System in response to situations arising from wildfires. This will enhance the ability to act and respond effectively to wildfires, striving to provide maximum protection for people, property, and natural resources within the municipal territory. Ultimately, the development of this plan seeks to establish the MWAP as a tool capable of integrating the participation of public and private entities, businesses, and citizens into the Civil Protection System.

The MWAP is developed to provide the following basic functions:

- Anticipate the organizational structure and procedures for the initial municipal response to wildfire emergencies within the territory of the corresponding local entity, understanding that these will be subordinated to the structure of provincial or regional planning once they assume command of the emergency or situation.
- Establish systems for coordination with organizations from other local administrations within the surrounding or territorial area, in accordance with the provisions of the Regional Plan into which they are integrated.
- Zone the territory based on wildfire risk and its potential consequences, aligning with the guidelines of the Regional or Provincial Plan. Define areas according to potential prevention and intervention requirements, resource and equipment deployment, and the location of physical infrastructure to be utilized in emergency operations.
- To achieve this, measures may be established aimed at preventing the consequences outlined in the Municipal Wildfire Emergency Action Plan (MWAP) or supporting operational deployment during emergencies.
- Plan the organization of local groups for wildfire prevention and initial response, which may include volunteer personnel, while promoting and encouraging self-protection.
- Establish public information and training measures about wildfire risk and self-protection actions to take in the event of a wildfire emergency.
- Catalog specific resources and means for implementing the planned activities.
- Implement self-protection measures for urban areas and buildings, aimed at reducing risk in the urban-forest and agricultural-forest interfaces, through the creation and maintenance of perimeter firebreak zones.
- Create an inventory and characterization of urban-forest interface areas.

5.2 Basic content of the MWAP plans

The basic content of the MWAP plans can be resumed in the following list:

Introduction
1. Purpose and scope of the action plan

2. Territorial description and risk analysis
   2.1 Municipal Territorial Boundaries and Geographic Location
   2.1.1 General Characteristics of the Municipality
   2.1.2 Natural Environment
   2.1.3 Meteorology
   2.2 Distribution of Forest Mass, Urban Areas, and Agricultural Land
   2.3 Location and Description of Wildfire Suppression Support Infrastructure

2.3.1 General Communication Network. Road Network
2.3.2 Public Utility Supply Network Infrastructure
2.4 Wildfire Risk Analysis
2.4.1 Zoning and Classification of High Wildfire Risk or Priority Protection Areas
2.4.2 Zoning and Classification of Urban-Forest (WUI) and Agricultural-Forest Interfaces
2.4.3 Historical Analysis of Municipal Wildfires
2.5 Risk Periods

3. Resources available for wildfire suppression
3.1 Human Resources
3.2 Wildfire Suppression Support Infrastructure
3.2.1 Hydrological Infrastructure
3.2.2 Preventive Forestry
3.2.3 Road Infrastructure
3.2.4 Helipads and Helicopter Landing Sites
3.2.5 Meeting Points for Suppression Resources
3.3 Material and Support Resources

4. Local organization for wildfire suppression
4.1 Plan Director: Municipal Mayor
4.2 Provincial/Regional Coordination Center
4.3 Advanced Command Post (ACP)
4.4 Advisory Committee
4.5 Emergency Response and Suppression Group
4.6 Medical Group
4.7 Security Group
4.8 Logistical Support Group
4.9 Information Office

5. Operational procedures for wildfire response
5.1 Detection and Alarm
5.2 Initial Fire Attack
5.3 Initiation of Safety, Logistical, and Medical Tasks
5.3.1 Safety Actions
5.3.2 Medical Actions
5.3.3 Logistical Support Actions
5.4 Protective Measures for the Population
5.4.1 Public Information
5.4.2 Evacuation

5.4.3 Sheltering
5.5 End of Emergency
5.6 Handover of Command and Information to Provincial/Regional Resources
5.7 Integration of the Local Action Plan into the Regional Plan
5.8 Integration of Self-Protection Plans for Residential Developments (see content below)
5.9 Intervention Record

6. Information for the public on wildfire response
6.1 Before the Emergency: Preventive Information, Awareness, and Training Actions
6.2 At the Moment of Fire Detection: Alarm
6.3 During the Emergency
6.4 Evacuation Routes

7. Actions to promote and disseminate self-protection
7.1 Public information through the corresponding municipality's website
7.2 Use of social media
7.3 Development of informational brochures and best practices pamphlets
7.4 Organization of meetings and informational conferences
7.5 Door-to-door visits
7.6 Information through mobile public address systems
7.7 Personalized mobile phone calls and dedicated visits
7.8 Participation in fairs and exhibitions
7.9 Celebration of Preparedness Day
7.10 Dissemination of wildfire danger periods
7.11 Promotion of preventive measures

8. Action plan
8.1 Hydrological Infrastructure
8.2 Preventive Forestry and Fuel Mitigation
8.2.1 Priority Forestry Measures
8.2.2 Complementary Forestry Measures
8.3 Road Infrastructure
8.4 Other Measures
8.5 Budget and Temporal Planning
9. Plan implementation, maintenance, and updating

Annexes
A. Phone Directory
B. Economic Report

C. Preventive Action Program
D. Maps
E. Records
F. Photos
G. Executive Summary
H. Self-Protection Plans for Residential Developments (SPRD)
I. Recommendations for the Population in Case of Wildfire

5.3 Implementation Plan of MWAP

The organization of the implementation of local action plans involves developing a schedule of activities and drafting self-protection plans for residential developments within the municipality, which are included as annexes to the main document. These activities are aimed at implementing specific actions, following a schedule based on urgency and importance, aligned with a budget allocation, and executed using municipal funds. A significant number of these activities focus on integrating the population into the cycle of prevention, preparation, and best practices.

An essential part of the MWAP is its implementation, particularly the communication of its content to residents and property owners, ensuring that the strategies and actions to follow are understood and assimilated by the community to secure their cooperation. This is especially critical for parcel owners in residential areas potentially affected by wildfires, as previously discussed.
The proposed list of actions is as follows:

- Technical meetings and awareness sessions for education
- Technical meetings with intervention agents
- Meetings with municipal agents for prevention
- Awareness and education sessions with property owners and the public
- Campaign for risk assessment and evaluation of properties
- Preparation of communication materials
- Brochures, guides for best practices
- Presence on social media
- Self-assessment risk application
- Sandbox exercises
- Conducting drills of scenarios

The first step will involve informing the community about the content, scope, and strategies of the municipal wildfire action plan, as well as the municipality's commitment to its implementation through ordinances and actions designed to improve emergency response and ensure proper prevention efforts.

To achieve this, informational meetings should be held with residents to explain wildfire risks in the municipality, their characteristics, the firefighting capabilities of the resources deployed (whether municipal, regional, or national), and the prevention strategies and actions planned for the coming years. These meetings will emphasize the importance of collaboration in self-protection and prevention efforts, particularly in urban-forest interface zones. Informational brochures will be developed, as outlined in this document, addressing vegetation management on parcels and preparing homes and facilities for potential fire passage. Additionally, a guide to best practices will be provided, aimed at educating the public on appropriate behaviors before, during, and after wildfires, highlighting the importance of recognizing high-risk wildfire days and what actions should or should not be taken. These informational and educational meetings will include real-life examples of wildfires in the province or region, the country, and the European region to illustrate the consequences of inaction and the benefits of a committed approach to prevention.

A continuous campaign is also proposed through social media, where short informational messages will be shared on key aspects of risk culture, prevention, and self-protection. Social media will also be used to inform residents about the various actions being carried out in the municipality and to stress the importance of parcel owners in residential developments strengthening their self-protection efforts.

A door-to-door risk advisory campaign is proposed for property owners who request an evaluation of their property's risk and identification of potential actions to improve prevention. This campaign will be accompanied by targeted mailings, particularly emphasizing the gradual replacement of highly flammable vegetation in the municipality, especially in areas most exposed to wildfires, as highlighted in the risk analysis. A key process within this initiative is the development of Self-Protection Plans. Alternatively, awareness and advisory campaigns can be designed and implemented through mobile phone communication networks. This method has already been successfully tested in some parts of southern Spain after a wildfire with the affected communities.

A second line of action focuses on training municipal action groups through tabletop sandbox exercises and simulations of the scenarios analyzed in this document. To this end, it is proposed to conduct training sessions with the collaboration of the regional or provincial firefighters and other regional and national resources. These exercises underscore the role of Local Action Groups in managing emergencies and how they are integrated into the overall emergency management structure. Furthermore, these exercises serve as a starting point for awareness campaigns in the areas of the municipality most at risk from wildfires. They also help to identify the strengths and weaknesses of the current MWAP plan, enabling its scope and content to be adjusted accordingly to address any gaps.

The 1:1 scale drills aim to exercise some of the protocols and functions of local action groups in wildfire scenarios. They will be based on scenarios that have been previously identified, studied, and simulated, highlighting the challenges and difficulties that may arise.

The proposed drills are highly localized exercises that require minimal deployment and are relatively simple to organize. Similar to what is developed in sandbox problems, the following skills will be practiced:

- Information gathering
- Assessment
- Decision-making
- Communication
- Operations

The difference from the sandbox lies, first, in scale, as the exercises are conducted at specific locations within the residential areas being worked on. Additionally, there is a physical component to the actions, particularly movements, communications, and operations conducted on-site with real resources. Like the sandbox, time constraints will also be applied.

The operations and situations to be addressed in the exercises include, but are not limited to:

- Mobilization of resources and identification of meeting points
- Deployment of firefighting and fire control operations
- Blocking streets and roads
- Defending homes
- Evacuation / Shelter in Place
- Self-protection in entrapment scenarios
- Monitoring of LPG tanks
- Medical emergencies
- Communication with the public and media

To simplify and reinforce the lessons learned, the drills will be developed based on possible scenarios that have already been simulated in the sandbox.

During the exercises, standard communication channels will be used, but a protocol must be established to ensure it is clear that these are drills. It is also recommended to create a WhatsApp group or use similar applications for the exchange of graphical information (simulated photos) and weather updates provided by the exercise instructor. Alternatively, printed materials will be provided. All images and messages should include the word "DRILL."

5.4 Self-Protection Plans for Residential Developments (SPRD)

Description

The self-protection plans for residential developments (SPRD) include both the organization and mechanisms to establish protocols for the response of homeowners and residents to a wildfire event. The SPRD are framed within the municipal strategy for wildfire emergency management through its Local Wildfire Emergency Action Plan, which is, in turn, part of the regional plan for wildfire defense and prevention.

Basic content of the SPRD

1. Fundamentals

1.2 Purpose and Territorial Scope of the Plan
1.3 Definitions
1.4 Legal Framework
- National Legislation
- Regional Legislation
- Local Regulations and Ordinances

2. Description of the Environment

2.1 Territorial Description
2.2 Administrative and Legal Environment
2.3 Natural and Forest Environment
- Topography
- Forest Environment
- Vegetation
- Forest Fuels
- Protected Areas

2.4 Demographic Characteristics
2.5 Description of the Residential Area
- Urban-Forest Interface
- Buildings
- Parcels
- Vegetation and Other Fuels within the Residential Area
- Common Areas

2.6 Description of the Road Network and Accessibility
- Road Network
- Street Network
- Access Points
- External Access Points to the Residential Area
- Forest Roads and Trails
- Paths and Routes

2.7 Other Infrastructure
- Electrical Transport Network and Transformers
- LPG Stations
- Water Treatment Facilities
- Critical Infrastructure in the Municipality

2.8 Artistic and Cultural Assets
2.9 Directory of Individuals with Special Needs

3. Identification of Risk Scenarios

3.1 Historical Fire Study

3.2 Risk Periods

3.3 Identification of Meteorological Conditions

3.4 Description of Potential Wildfire Scenarios

3.5 Assessment of Parcel Exposure and Risk

- General Exposure to Wildfires
- Perimeter Exposure
- Risk: WUIX Interface Index

4. Wildfire Defense Resources and Means

4.1 Firefighting Resources

- Regional Resources
- Local Resources
- Private Resources

4.2 Support Infrastructure for Wildfire Suppression

- Internal Hydrant Network
- Water Points
- Firebreak Belts and Areas
- Heliports
- Civil Protection Support Infrastructure in the Municipality
- Evacuation Reception Points
- Surveillance Points
- Communications

5. Proposed Preventive Measures and Maintenance

5.1 Forest Fuel Management

5.2 Perimeter Firebreak Belts

5.3 Self-Prevention Measures for Parcels

- Design and Maintenance of Developed Parcels
- Preparation and Maintenance of Homes
- Maintenance of Undeveloped Parcels

5.4 Improvement of Road Network and Assembly Points

- Conditioning Alternative Tracks
- Conditioning Assembly Points
- Signage

5.5 Evacuation and Shelter-In-Place Plan

5.6 Improvement of the Hydrant Network

- Existing and Proposed Hydrants
- Alternative Water Points

5.7 Plan Implementation, Training, and Education on Risk Culture and Self-Protection

5.8 Mobile and Preventive Surveillance Plan

5.9 Recommendations and Best Practices for Fire Prevention

- Prevention in Perimeter Parcels
- General Recommendations for All Parcels

6. Organization of Wildfire Defense in the Residential Area

6.1 Operational Mechanism of the Plan

- Municipal Wildfire Action Plan (MWAP)
- Operational Situations
- Organization of the SPRD

6.2 Operational Procedures

- Detection and Alarm
- Protocol Activation
- Protocol Deactivation
- Coordination and Integration of Plans

6.3 Evacuation and Shelter-In-Place Operations

- Evacuations
- Shelter-In-place
- Relocations

6.4 Processes for Informing the Population in Case of Fire

6.5 Recommendations and Best Practices in Case of a Fire Emergency

- High-Risk Fire Days
- Evacuation of the Residential Area in Case of Fire

- Shelter-in-place in the Home

7. Annexes

7.1 Directory of Plan Staff
7.2 Telephone Directory
7.3 Photographic Archive
7.4 Cartography

5.5 Preparation of communication material

Since the safety of a dwelling depends on its preparation, the maintenance of fuel throughout the property, the maintenance of adjacent parcels and the conditions of the WUI which can be considered the environment in which the dwelling is inserted, three different and complementary dimensions that communication materials must contain must be considered:

- Self-responsibility: WUI inhabitants living in fire-prone areas must be willing to accept a high degree of self-responsibility to protect their own homes from wildfires by insuring their properties.
- Shared responsibility: the maintenance of the WUI's common spaces and services (road network, safe spaces, undeveloped plots and refugees) requires the assumption of shared responsibility by community members.
- Mutual responsibility: a dimension of mutual responsibility and commitment among inhabitants is implicit whenever securing one's own property means contributing to the security of others in a respective and mutual relationship.

Under the above premises, two perspectives are proposed for the realization of communication materials: urbanized environments, on houses and plots. The following are the key points to complete these communication materials:

Residential Developments

Access routes and roads

- Access routes should be more than one so that, in the event of an emergency, at least one of them is safe and avoids the risk of entrapment. The access routes must be sufficient to support the evacuation flow and, in the opposite direction, the simultaneous access of emergency vehicles.
- The internal road network should be planned to allow the circulation of large trucks (emergency vehicles). The width should be adequate to ensure a smooth flow of traffic, even if the sides can be used for parking. During the construction phase, trees rooted within 5 m of the road should be uprooted to avoid costly continuous pruning operations to raise the base of the crowns that may obstruct or slow down the circulation of trucks and to avoid trees falling on the roadway that may hinder the evacuation and/or access of emergency vehicles. The frequent presence of traffic circles (e.g. every 100-200m) facilitates quick U-turns in case of retreat avoiding the risk due to

time-consuming maneuvers of large trucks (driving in reverse or U-turns requiring many front-rear maneuvers in too narrow streets).

- Road lighting and signage must be well refined. Street lights are critical for emergencies that occur at night, especially in the presence of dense smoke. Signs and directions should be clear and visible with frequent street name panels. House numbers should be clearly displayed because they can be very useful especially for radio communications during the event between operators and the operations coordinator.
- A perimeter road encompassing the entire parcel will provide a second access to the peripheral parcels and function as a firebreak, reducing exposure to direct flames from houses in direct contact with the undeveloped land. It can function as a good opportunity for firefighters to act safely and effectively.
- The perimeter is the direct interface of the WUI with the undeveloped land. Curly shapes should be avoided and it should be regular and as short as possible.

Services and other actions

- Safe zones and construction of shelters: the presence of safe zones is very important and some of the commune's spaces (such as paved parking lots or large paved squares or parks with irrigated lawns) should be located within the WUI and should be thought out and pre-established also taking into account their usefulness in case of wildfire. Street lighting is very important and sprinklers can also be installed in these areas to increase safety. In addition, municipal buildings (schools, kindergartens, oratories, etc.) can be planned to be used as shelters and, in this case, the structures should be particularly well maintained and prepared.
- Common amenities and temporary use spaces such as playgrounds, sports facilities, viewpoint plazas, nature trails and paths may be located in the belt surrounding the WUI. These are usually maintained spaces where vegetation is cleared, grass is mowed and watered, which helps to decrease the intensity of the wildfire front approaching the WUI.
- A water supply network with frequent hydrants can be very useful in making water available to firefighters. The construction of several water tanks where helicopters can fill their bucket should be planned to reduce response time.
- The laying of the electrical network must be planned underground to exclude possible causes of ignition and to avoid problems of aerial intervention with water droplets.
- Housing density can be regulated by prescribing the size and proportion of plots or the distance of dwellings. Depending on the local hazard level, thresholds may be different: high hazard levels may be compatible with very dense housing.

Interior and exterior vegetation of the urbanized area.

- A firewall surrounding the entire WUI should be planned and maintained. Its usefulness is proportional to its width which, to be effective, must be at least three times the length of the local flame. It should be organized as a fire buffer zone with the nearest belt completely devoid of any fuel, while the intensity of treatment (thinning, clearing and pruning) decreases with distance from the houses. Conversely, it is often the case that the immediate surroundings of WUIs have higher fuel loads because the inhabitants like to enjoy the feeling of naturalness and because of the firefighters' defense that in the immediate surroundings is the maximum possible and if no fire occurs, fuels accumulate. Although the creation of a firebreak often provokes negative reactions from the inhabitants, it is essential that the intensity of the fire decreases as it approaches a populated area.
- Property boundaries between plots should be separated by non-combustible fences and hedges should be avoided.
- Peri-urban agriculture can be favored through subsidy programs or better with an urban garden program that can be implemented by assigning peri-urban lots or fallow plots within the WUI to users. The presence and contiguity of vegetation within the WUI should be controlled through a fuel management program so that in the event of a fire the flame intensity is kept low. Particular attention should be paid to inter-parcel hedgerows that provide privacy for dwellers but at the same time have high linear contiguity and significant amounts of dead fuels. They are a preferred pathway for wildfire advancement within the WUI also because they create a network of connections. The flammability of the species is very different. More detail can be seen in the fire sensitivity table in the plot structure section.

Homes and plots of land

In Mediterranean countries, houses are usually built of brick or concrete and the structures tend to be inherently fireproof. However, during forest fires, direct flame contact with openings in the structure (vents, windows, doors) or embers reaching the shingled roofs of wooden structures can cause ignition and destruction of the house. It should be taken into account that the resistance of the house is conditioned to the resistance of the most vulnerable material/part.

Housing structure

- **Construction materials**: the perimeter wall and roof structure should preferably be constructed in brick/concrete or at least in other fire-resistant materials, e.g. wood treated with high threshold fire resistance. The European Union provides a set of standards that classify all building materials into fire resistance classes. Urban planning can require that, depending on the level of danger, materials belong to at least a certain class (or higher) and exclude the use of materials belonging to lower classes. Architects and engineers may choose any material that meets the requirements prescribed in the zoning plan for that specific area. During the construction phase, provision may be made for the grubbing of trees within a 5 m buffer strip from the structure (if located on a slope, the grubbing strip on the downhill side may be 10 m or more).

- **Roofs and rooftops**: Roofs constructed with shingles laid on a wooden structure may be vulnerable to flying embers, while roofs constructed with shingles laid on a sloping brick and concrete floor are completely safe. Tar paper covering the roof should be avoided on both pitched and flat roofs. Metal gutters should be preferred to those made of other more vulnerable materials such as plastic. The roof overhang is the most vulnerable part of the element and requires special attention in terms of materials and construction.
- **Doors and windows**: Openings are a vulnerable part of the house and many house fires occur through windows. Traditional Mediterranean constructions were characterized by small windows to reduce heat transfer and to make the interior warmer in winter and cooler in summer. With the generalization of air conditioning, the simultaneous thermal-energetic characteristics of windows have improved and the construction style has evolved towards brighter rooms with larger windows overlooking panoramic views. Fireproofing requirements have become essential for doors, frames and glazing. For the construction material of doors and windows, it is advisable that the urban plan refers to the legal framework of the European Union which makes available an extensive fire classification of building materials. A compatible fire resistance class threshold should be chosen for each hazard level. The more hazardous the areas, the higher the fire resistance requirements of the permitted materials. Although metal structures (e.g. aluminum) cannot meet the thermal requirements, they are among the most fire resistant. Materials such as wood or PVC may even be involved in the combustion process and may be prohibited in the most dangerous situations. The vulnerability of glass lies in the possibility that it may break due to deformation caused by heat, especially if it comes into contact with direct flames. The urban plan may provide for the use of fireproof tempered double-glazed windows in new constructions that meet thermo-energetic, acoustic and fireproof requirements. Their diffusion in existing structures can be improved through a public funding program. Roller shutters can be another weak point if their material is not suitable because they burn when flames come into contact with the glass or degrade by exposing the opening to direct radiation. Aluminum roller shutters should be preferred to wooden ones and, in very dangerous places, PVC shutters should be avoided.
- **Protection in fans, chimneys and other openings**: flying embers can also enter the house through small openings and it is safe to cover them with systems that prevent their entry (it may be sufficient to cover them with a fine wire mesh).
- **Gazebos, eaves, overhanging roofs, balconies, wooden or retractable roofs**: these types of complementary architectural details are vulnerable elements and capable of bringing flames closer to the house. They require careful maintenance and special consideration in the event of a forest fire: wooden elements must be treated with fire-resistant paints, especially on their underside, which traps hot combustion air.
- **Wooden carports, tool sheds, garden furniture**: garden furniture, other equipment and ancillary constructions are often made of wood or other highly flammable materials (e.g. plastic) and if placed close to the house are capable of bringing flames into contact with it. It is safe to build these small structures at some distance from the main structure, in an area that should be kept clear of combustibles to avoid igniting them (and the car) by direct contact with the flames. In any case, they remain exposed and vulnerable to flying embers.

Plot structure

- **Barbecue**: it represents a possible source of ignition especially if it is surrounded by dry hay characterized by an extreme flammability. It should preferably be built in brick-concrete material on a paved area.
- **Paved belt**: it may be advantageous to integrate into the architectural structure a paved area surrounding the building that can serve as additional protection for the house.
- **Fuel oil or firewood storage**: in relation to the risk of forest fires, they are additional fuels and can create very dangerous situations. It is common to store firewood in the garden surrounding the house. In the event of a forest fire, it can create a very intense and long-lasting combustion. If the stored firewood is in contact with the house (usually on the first floor or protected by an overhanging balcony) prolonged exposure of the walls and especially the roof to high temperatures can severely damage the structure. It is safe to place firewood away from the house and, if possible, store it in an additional brick and concrete structure. It is also safe to place gas tanks some distance from the house and bury them in an area completely devoid of combustibles. Exposing a gas tank to high temperatures for a long time can cause it to explode with disastrous consequences.
- **Gardens**: Vegetation inside the plots is a very important element for the spread of wildfires in a WUI and for its capacity to bring flames closer to or in contact with the houses. The design of the gardens, the density of the trees, the composition of the species, irrigation and maintenance should be carefully studied avoiding the most flammable species, the direct contact of the canopy with the structure and all creeping plants on the walls. The immediate surroundings of the house must be completely devoid of combustibles and, during the planning phase, many possibilities can be taken into account to integrate fire protection with other requirements, such as the nearby placement of the swimming pool, or paved areas for car parking and barbecue, or large belts of irrigated lawn. Particular attention should be paid to boundary hedges which are the direct interface with the exterior and can be a weak point representing the entry of fire into the property or, conversely, can be the opportunity to remain protected. They are usually characterized by linear contiguity, high apparent density due to the presence of live and dead leaves (useful for privacy but detrimental to wildfire risk). Particularly flammable species such as *Cupressus* sp. can spread intensely creating a "wall of flames" effect capable of igniting the other plants within the plot by direct contact of the flames, by radiant heat flow or with the embers flying with the vertical air flow. It is essential not only to choose the least flammable species (e.g. privet, oleander, boxwood, pyracantha, ivy, pittosporum), but also copious watering and careful maintenance including canopy clearing to reduce dead fuel.
- The table below shows the **sensitivity to burn** of different plant species, categorized in a reduced scale of discrete values: low, medium, high and extreme, which conveys a fairly clear idea of their relationship with fire. Species with high or extreme fire sensitivity are strongly discouraged for use in WUI areas.

Scientific name	Fire proneness
Cupressocyparis leylandii	Extreme
Cupressus arizonica	Extreme
Cupressus sempervirens	Extreme
Laurus nobilis	Extreme
Salvia rosmarinus.	Extreme
Thuja plicata	Extreme
Euonymus japonicus	High
Nerium oleander	High
Prunus laurocerasus	High
Viburnum tinus	High
Arbutus unedo	Medium
Buxus sempervirens	Medium
Cotoneaster franchetii	Medium
Crataegus monogyna	Medium
Elaeagnus pungens	Medium
Ligustrum ovalifolium	Medium
Ligustrum vulgare	Medium
Photinia fraseri	Medium
Sorbus aucuparia	Medium
Coryllus avellana	Low
Fagus sylvatica	Low
Hedera helix	Low
Lonicera sp	Low
Parthenocissus quinquefolia	Low
Pittosporum tobira	Low
Prunus avium	Low
Pyracantha coccinea	Low

5.6 Good practice guides

The preparedness phase

WUI inhabitants need to improve their awareness through information and training to perceive that they are at risk and to be quickly informed on how to self-protect themselves and how to carry out preventive actions. Improving the preparedness of structures and people aims to increase the resilience of assets and facilitate emergency intervention. Housing vulnerability can be drastically reduced by observing the following points:

- Double entrance to the property;
- Fireproof construction materials;
- Fireproof doors and windows, roof and gutters;
- Pay attention to architectural details such as possessions, gazebos, balcony, fabric, sheds, garden furniture;
- Care for the garden and the property in general: in particular, it is important to avoid the most burnable species, to install an irrigation system, to limit the density of vegetation by thinning, to ensure the disjunction of the undergrowth with overlapping canopies by pruning and to clear the vegetation in the immediate vicinity of the house for at least 5-10 m, which must be completely devoid of fuels;
- Place firewood stockpiles, gas/oil storage, piled vegetation debris and other possible burnable materials away from the house and covered to protect them from ignition;
- Installation of active devices such as sprinklers;
- Avoid dangerous habits such as leaving windows open with the blinds down to let air into the house: in case of fire, plastic blinds do not offer adequate protection;
- Adopt safe behaviors and habits before and during a possible emergency.

Fire behavior in the space around the house is conditioned by the presence of fuel accumulations: fuels should not be kept in contact with the house, such as wooden construction planks, firewood reserves, old furniture, wooden or plastic garden furniture leaning against the perimeter walls, creeping plants.

The emergency phase

Sheltering or early evacuation should be actively prepared in advance to avoid:

- Risky escapes on foot or by car, with limited vision due to the presence of smoke, without knowing exactly where the fire is active or will burn, with exposure to possible intoxication and the worst consequences in case of fainting;
- To risk locking oneself in a house whose immediate surroundings have not been prepared and without having prepared the house itself to safely resist the passage of fire.

The option of actively sheltering indoors and defending the home until the flames are really close may be a good choice for those homeowners who are prepared to face the passage of fire as long as the building materials are fireproof and the maintenance and preparation of the home and its surroundings have been adequately done in advance. Vulnerable people should avoid shelter and it is much safer to evacuate early to a safe area. It is preferable to take shelter in the house when escape means crossing the flame front (or if there is a possibility of being trapped). Preparing the home is done through a series of preventive actions. Some of them have a lasting time horizon:

- Cleaning the roof of needles, leaves and other burnable materials that may accumulate;
- Remove any flammable materials near the house;
- Clearing of the surroundings of the house creating a buffer of at least 5-10 m completely devoid of fuels and thinning treatments to disarticulate the canopy;

- The Water Tank must be in the high position to ensure that it can supply water even if a power failure interrupts the electrical supply;
- The irrigated lawn is well mowed.
- Other actions will be carried out during the event:
- Use a long hose that reaches the entire perimeter of the house before the arrival of the flames to extinguish all fire sources and keep the most exposed parts of the house wet;
- Park the car in a safe place;
- Close all blinds, windows and fireplaces;
- Leave all entrance doors open for escape and fire department access;
- Wear suitable cotton clothing that fully covers arms and legs, boots, work gloves, long vest, protective mask or wet handkerchief/scarf, hood (or balaclava) to protect hair from possible ignition;
- Remove any fuel residue that may have been left near the house.

When the flames are too close, people should enter the house and stay together as a group. Also inside the house, some important actions should be taken before the flames arrive:

- Keep all interior doors closed to prevent air circulation;
- Keep a fire extinguisher and a bucket of water handy;
- Use wet towels to extinguish possible small fires and to reinforce the closing of doors and windows;
- Vacuum the lower air layers (smoke tends to occupy the higher layers) using a wet handkerchief to filter the air.

Early evacuation is also a good option, especially for vulnerable people or for inhabitants who have not prepared their homes in advance.

Evacuation by car may involve being prepared to meet other panicked drivers, suddenly appearing out of the smoke; it is important to turn on all lights, including fog lights and 4-turn lights, to recirculate the interior air. In case the road seems impassable or may involve too high a risk of entrapment, it is better to park the car on the side of the road opposite to the burned one.

When evacuating on foot:

- Search for safe places (already burned areas, paved squares devoid of fuels);
- Use walls, rocks and other solid objects to shelter from direct radiation, remembering that in case of wind they can be reached by flames if they are upwind and downwind;
- The respiratory tract should be protected from hot air and smoke;
- Move in the same direction as the fire avoiding going towards it or moving parallel to the front;
- If a forest fire is approaching, it is necessary to find a place devoid of fuels and cross the front or wait for the front to pass;

- Avoid uphill escape, characterized by slower and more exhausting running, often in a smoky atmosphere, and by a higher rate of spread and greater intensity of the wildfire.

Safety protocols

Lookouts, Awareness, Communications, Escape Routes and Safety Zones (LACES) is a protocol that is still considered an international reference for maintaining the safety of firefighting teams in wildland fire scenarios. LACES is an operational guide that can be used in any fire situation acting as a control method that, if followed, ensures the monitoring of fire dynamics, as well as the reduction of critical risks and the safety of firefighters. (LACES) should be established and maintained in all missions, including scouting, reconnaissance and patrol. Rapid and unexpected changes in fire behavior during all phases of firefighting operations can result in wildland firefighter entrapment. Therefore, always identify the worst-case scenario, keep SA focused and always check your LACES Protocol prior to any operation or action in the fire danger zone, establish realistic trigger points, and stand down when prudent.

This protocol and other key message for firefighters have been developed in the Deliverable 2.6, "Handbook with guidelines for fire fighters to face to extreme fires, fires in WUI and fires in high latitudes/ altitudes"
Below is a focus on the LACES protocol adapted for fires in the WUI.

LOOKOUTS (L)

A fire lookout or analyst during a wildfire must be far enough away to be able to understand the fire as a whole and to transmit to the firefighters the dangerous situations that may occur in their surroundings. Fire monitoring in WUI areas should cover both inhabited areas and the surrounding forest. This allows a better understanding of the integral framework of intervention in the whole territory affected by the wildfire.

ANCHOR POINTS/AWARENESS (A)

Firefighting maneuvers should always start and end in safe places. Therefore, it is necessary to identify the points where defense is possible and safe for firefighters, this will also serve as a limitation to firefighting maneuvers outside these safety zones.

Anchor points for interface zone defense are strategic non-flammable areas, such as perimeter roads or fuel-free perimeter strips. Therefore, protection and security measures at the mesoscale level should encourage their presence and continuous maintenance.

COMMUNICATIONS (C)

During a wildland fire emergency, where sudden changes in fire behavior may occur, it is necessary to establish an effective communication system. Since close monitoring and effective communication with personnel is often difficult in a fire emergency, portable and hand-held radio systems should be prioritized and made widely available at fire locations.

In turn, all necessary measures should be implemented and encouraged to ensure that communication promotes social behavior that avoids further endangering the lives of people in interface zones.

ESCAPE ROUTES (E)

Evacuation routes and emergency exits must be identified and properly marked in advance, and more than one alternative route must also be available. In addition, the planning and management of a fire operation must always consider the worst-case scenario. Finally, the protocol insists on keeping all teams involved in the emergency informed at all times of the available evacuation routes.

The complexity of WUI areas has led to situations where inhabitants or firefighting teams have been trapped inside dwellings with no escape routes. For this reason, it is of utmost importance to act before the fire reaches the inhabited area by identifying escape routes and managing the inhabitants in a coordinated and safe manner.

SAFETY ZONES (S)

Firefighter safety zones should be identified prior to the start of any activity and teams should be aware of their status and location at all times. If new fire outbreaks start, the teams must find new safety zones or seek refuge in areas that have already been burned. In short, it is a matter of knowing the operational environment at all times to base any decision made by the firefighters on safety.
In WUI areas, the identification of safety zones is also essential to implement other safety measures that may affect the population in the area, such as evacuation, moving away from exposed areas or, if necessary, shelter-in-place:

Evacuation consists of moving people in danger to safe locations. This option should be maintained as long as there is sufficient time to do so and the direction in which the fires are moving does not compromise the evacuation. Those in charge of the evacuation must be trained in the procedures necessary to carry it out (brigades, police, fire department, etc.). All accesses to housing developments must be closed to prevent looting inside them. This measure requires the availability of adequate infrastructures to safely accommodate the evacuated population. The evacuation routes available in the urban area condition the actual functioning of this measure.

The sheltering of the population in their own homes should be carried out when there is no possibility of evacuation or the evacuation routes are compromised and there are no risks for the confined persons. Otherwise, the option may be to provide these people with the necessary health care to ensure their safety. In this case, the construction materials used to build the dwellings must resist the passage of fire. This measure requires greater provisions for the protection and safety of the people inside their homes.

Finally, there is a third alternative, the displacement of the population further away. The population should be moved away from the interface zones and confined to areas free of risk. This measure is applied whenever there are safe areas inside or not exposed to flames and when there is not enough time or escape routes to implement adequate evacuation measures.

5.7 Risk self-assessment application

The following is an application scheme for self-assessment in wildland-urban interface environments. The objective is to facilitate users to assess the fire risk in their urban-forest environment, providing practical and personalized recommendations to reduce this risk.

Application components

Visualization module

Displays general information about the user's plot and house on a map for its location.

- Base map and layers
    - A map with different layers will be offered to locate and provide basic information about the properties.
- Location of the plot
    - Position of the property using geolocation or manual entry.

Information gathering module

Collects relevant data from the user about his property and the environment. The main features are:

- Relevant questions and pre-established answers for the most part.
- The tool will adapt the flow of questions according to the initial answers, it will not be necessary to ask all the questions if the final number of questions is high.
- Open-ended or free-text answers are totally avoided.

The following flow is proposed as an example for the collection of information:

- Basic data
    - What is the size of your land or property (indicate number)?
    - Do you have a swimming pool on your property (yes or no)?
    - Are there people with reduced mobility on your property?
- Vegetation characteristics:
    - What type of vegetation surrounds your property (e.g., forest, scrub, pasture)?

- How far away is the nearest vegetation (indicate number)?
- Do you perform regular maintenance of green areas (pruning, removal of dry material)?
- Housing infrastructure and materials:
  - What materials predominate in your home (wood, brick, cement)?
  - Do you have active fire protection systems (hoses, sprinklers, fire extinguishers)?
  - Are the roof and windows protected against incandescent particles (yes or no)?
- Safety practices:
  - Do you have an evacuation plan (yes or no)?

  Have you participated in prevention campaigns or drills (yes or no)?

Results analysis module

Provides risk assessment, recommendations and prioritization of actions. Includes resources to deepen prevention and mitigation.

- Personalized risk map:
  - It offers a map with an easy and intuitive color-coded classification:
- Low risk (yellow or green) : Optimal conditions, adequate preventive practices.
- Moderate risk (orange): Need for improvements in some critical areas.
- High risk (red) : Urgency to take specific measures to mitigate the risk.
- Detailed analysis:
  - Identification of critical factors (e.g., flammable accumulations, vulnerable infrastructure).
  - Risk score (0-10) based on the answers provided by the user.
- Recommendations for actions to be taken:
  - Priority actions: actions to be taken immediately to reduce the potential risk as much as possible.
  - Complementary actions: other actions that serve to avoid increased risk in the medium or long term.
  - Actions in case of emergency: actions to be carried out in the event of a forest fire emergency in a clear and specific manner.
- Downloads and resources:
  - Detailed report with the above points.
  - General visual guides and brochures: How to create defense zones and maintain vegetation. Good practices in the WUI.
  - Useful links: Connection to local authorities and emergency resource centers.

User Interface (UI)

It must be simple, visual and accessible to all audiences. The main key points are:

- Visual and graphical interface: Use of interactive maps, images and diagrams to facilitate understanding.

- Intuitive navigation: Progress in clear steps (e.g., "Basic data", "Results", "Recommendations").
- Drop-down modules: Access to more detailed information only if requested by the user.
- Multiplatform: Available as a web and mobile application. It must also be multilingual.

6 Conclusions

This document provides critical insights into the necessary strategies for addressing escalating wildfire risks across European territories over several scales in future risk scenarios. The following conclusions have been drawn:

- **Holistic Risk Management**: A comprehensive wildfire management strategy is imperative. This approach must integrate prevention, suppression, and restoration practices, emphasizing collaboration among stakeholders to ensure the protection of citizens, ecosystems, and economic assets.
- **Policy and Legislative Support**: Implementing adaptation strategies requires alignment with national and regional legislation. Policymakers must address regulatory barriers to facilitate fuel management, urban planning, and community engagement in fire-prone areas.
- **Fire Adaptation and Ecosystem Services**: Effective fire adaptation measures, such as targeted fuel management, can significantly mitigate risks to vital ecosystem services, including water quality, carbon retention, and nutrient cycling. The removal of fine fuels (1-hour dead fuels) was identified as a particularly effective strategy in high-risk regions like Southern Europe.
- **Technology-Driven Insights**: The application of predictive tools such as WEPPcloud-EU-WATAR highlights the importance of modelling future fire impacts. These tools enable informed decision-making by simulating scenarios of soil erosion, ash deposition, and nutrient losses, helping prioritize intervention strategies.
- **Municipal Wildfire Action Plans (MWAPs)**: MWAPs provide a structured framework for coordinating public and private responses to wildfires. These plans include zoning for risk assessment, resource cataloguing, and establishing self-protection measures in WUI areas.
- **Preparedness and Community Engagement**: Effective wildfire preparedness hinges on educating communities about prevention and self-protection. Public awareness campaigns, drills, and tailored risk assessment tools are essential for fostering a culture of shared responsibility in WUI areas.
- **Future Considerations**: While current models provide valuable insights, they may not fully capture the extreme events projected under harsher climate scenarios. Ongoing refinement of these models and local-level assessments are necessary to adapt to evolving risks.

These findings underscore the need for integrated and scalable fire preparedness strategies to enhance resilience against future wildfires, safeguarding both ecosystems and human communities within a trans-scalar approach.

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