*Working Document*

# An Integrated Wildfire Risk Management Strategy for the EU: developing resilient landscapes and safer communities


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## 1 Executive Summary

**Problem statement:** Fire is a natural element in many ecosystems. However, wildfires are changing worldwide in different aspects, including frequency, intensity and behaviour, making them more damaging than previously observed. The time and locations of wildfires are changing, resulting in prolonged fire seasons in many parts of the world, especially so in Europe, as well as in new wildfire realities in places that were traditionally not fire prone[1]. The frequency and intensity of extreme events is increasing with climate change[2] and research shows that an increased frequency of fires (reduced interval between fires) may hamper the health of ecosystems.[3] This development is particularly concerning since these new realities both in traditional and increasingly fire-prone countries are overwhelming suppression capacities and hence jeopardising the protection of citizens, the environment, and infrastructure. Recent models to predict climatic and socio-economic conditions, indicate a worsening of the risk in most of Europe over the next five decades, including some areas of Central and Northern Europe.[4]

While anthropogenic climate change is an important driver of increasing wildfire risk, other human-related factors also play a key role in shaping growing impacts and losses. Together with increasing ignitions and thus the risk of simultaneous wildfires, several factors have contributed to changes especially in Mediterranean-type landscapes. These factors include the abandonment of rural areas and the consequent accumulation of fuel, the focus on fire suppression as a risk management intervention, or the continuous expansion of wildland-urban interfaces, even in high-risk areas. These are just some examples of a systemic problem with many causes and processes that require an integrated response from society, a response that needs to involve all relevant stakeholders to effectively mitigate these problems.

A new approach and concerted action are thus required to apply existing knowledge, and to unleash the potential of recent investments in wildfire risk-related research and innovation. However, respective approaches remain scattered across Europe, hindering synergy, the potential for knowledge sharing and joint action to exploit innovation and technology.

**Joint vision to address wildfire risk in an integrated manner:** This paper proposes that the European Union should adopt a strategy and framework to manage wildfire risk jointly and in an integrated manner. This strategy could build upon the Landscape Fire Governance Framework (LFGF)[5] which was developed in 2023. Its core elements comprise of risk assessment and evaluation, risk and adaptive management, stakeholder engagement, systemic and public communication and education, facilitated by governance structures and bodies and promoting international collaboration. It received expressions of support from several countries, namely the United States of America, Germany, Brazil, Canada, Cyprus, Portugal, Spain, Australia and New Zealand as well as from some international agencies such as the OSCE, OCDE, the Council of Europe, the United Nations Organization through the UNEP, FAO, UNDRR, and the UNFF. The European Commission (DG ECHO) has used the LFGF as a reference for its Wildfire Peer Review Framework.[6] This paper builds on the respective structure to propose a Strategy for Europe, building on

[1] Galizia et al. (2023): Global Warming Reshapes European Pyroregions, in: Earth's Future, https://doi.org/10.1029/2022EF003182.

[2] Cunningham et al. refer to events ≥99.99th percentile: Cunningham et al. (2024): Increasing frequency and intensity of the most extreme wildfires on Earth. In: Nature Ecology & Evolution 8 (8), S. 1420–1425, doi: 10.1038/s41559-024-02452-2; Duane, A., Castellnou, M. & Brotons, L. (2021): Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change* **165**, 43, https://doi.org/10.1007/s10584-021-03066-4; Pausas, J. G., & Keeley, J. E. (2021): Wildfires and global change. *Frontiers in Ecology and the Environment*, *19*(7), 387-395; Di Virgilio, G., Evans, J. P., Blake, S. A., Armstrong, M., Dowdy, A. J., Sharples, J., & McRae, R. (2019): Climate change increases the potential for extreme wildfires, *Geophysical research letters*, *46*(14), 8517-8526.

[3] Turner, M. et al. (2019), "Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests", Proceedings of the National Academy of Sciences, Vol. 116/23, pp. 11319-11328, https://doi.org/10.1073/pnas.1902841116 (04.04.2025).

[4] Billing et al. (2023): Simulated fire and vegetation dynamics at three spatial scales, FirEUrisk D3.4, available via: https://fireurisk.eu/wp-content/uploads/2024/05/FirEUrisk_D3.4-v1.0.pdf (02.04.2025).

[5] AGIF (2023): Landscape Fire Governance Framework. Unter Mitarbeit von J. Verde, M. Monteiro, P. Moore und C. et al. Gamper. Online verfügbar unter https://www.wildfire2023.pt/conference/framework (12.12.2024).

[6] We acknowledge that guidelines have been developed for example by the Food and Agricultural Organisation (FAO) (2024): Integrated fire management voluntary guidelines: Principles and strategic actions, Second Edition, Forestry Working Paper, No. 41. Rome,

recent research. It is intended to open a wider conversation with policy makers and relevant stakeholders to advance the discourse and identify how to enhance and integrate strategic action addressing wildfire risks in Europe.

**Unleashing the potential of research and innovation:** The European Union has invested over 70 million Euros in wildfire risk management related research and innovation activities[7], mainly under its Green Deal Program aiming to transform the EU into a modern, resource-efficient and competitive economy, with a reduced impact of wildfires, ensuring no net emissions of greenhouse gases by 2050. All projects covered prevention, preparedness, response and recovery as well adaptation aspects. Collectively, these projects bring forward innovative scientific research, complemented with the use of new technologies. These research outcomes have been validated across several European pilot sites. The development of new scientific research and technologies relies on the use of new data sources (such as Copernicus satellites, drones, robots, and data-driven algorithms) that have been developed, and feed this proposal for a European Strategy.

This proposal was developed jointly by the researchers and practitioners of four large research and innovation actions, namely FirEUrisk[8], FIRE-RES[9], SILVANUS[10] and TREEADS[11] which brought together about 120 different organisations, many of which encompass several decades of experience in investigating and managing wildfire risk inside and outside the European Union. These partner organisations represent a very large share of the European Fire Community. Additionally, the several projects were consulted for this strategy proposal including FireADAPT, EWED, PyroLife, NERO, FireLinks or SAFERS.

**Aim & Audience:** This strategy proposal addresses all stakeholders involved in the management of wildfire risk across Europe. Specifically, it aims to propose a range of innovations that may be applied for reducing the wildfire risk across multiple geographic and time scales by integrating stakeholders such as forest and land managers, civil protection organisations, local, regional and national authorities, fire management agencies, the private sector, financial institutions and the wider public. It explains how recent research findings, governance approaches, innovative measures, data sets, modelling techniques and technologies may facilitate the implementation of Integrated Wildfire Risk Management approaches across Europe and details the structural support that will be needed to realise its full potential.

This document will be complemented by a policy brief, proposing policy action and next steps at the European scale, but also applicable at national, regional and specifically cross-border levels, to promote a seamless management of wildfire risk across Europe.

https://doi.org/10.4060/cd1090en (31.03.2025) and recent research on Integrated Fire Management proposes a roadmap to implement Integrated Fire Management (IFM) at national or regional scales (Oliveras Menor,et al. (2025): Integrated fire management as an adaptation and mitigation strategy to altered fire regimes. Commun Earth Environ 6, 202, https://doi.org/10.1038/s43247-025-02165-9). Given the level of acceptance of the LFGF as a conceptual ground, we propose its selection as a basis for European Strategy.

[7] The funded projects included FirEUrisk, FIRE-RES, SILVANUS and TREEADS. They received funding under the following Grant Agreements: 101003890 (FirEUrisk), 101037419 (FIRE-RES), 101037247 (SILVANUS), 101036926 (TREEADS), 101036534 (Firelogue).

[8] Dissecting risk to prevent extreme wildfires - FirEUrisk (31.03.2025)

[9] FIRE-RES - Innovative solutions for fire resilient territories in Europe - FIRE RES (31.03.2025).

[10] SILVANUS | Integrated Technological and Information Platform for Wildfire Management (31.03.2025).

[11] Homepage - TREEADS Project (31.03.2025).

**Key suggestions for a strategy:**

- The development of a European Strategy and its respective implementation should be led by an **inter-agency working group** at European level, bringing together DG ECHO, DG ENV, DG AGRI, DG CLIMA, DG GROW, DG REFORM, DG BUDG, DG CINEA, DG ERCEA, DG RTD, DG REGIO, REA and JRC among others and being mandated to coordinate efforts between these bodies and to exploit existing synergies. A respective group should also supervise the exploitation and update of solutions, with a specific focus on the European vegetation data sets developed which will lose value quickly if not updated regularly.
- **Integrated fire risk assessment systems** should be developed, which shall include the relevant variables related to fire ignition and propagation, but also exposure and vulnerability, going beyond current systems that are mostly restricted to weather variables.
- **Guidance** is needed for the implementation of Integrated Wildfire Risk Management approaches across Europe, considering the specific national and regional contexts in terms of wildfire experience, or socio-economic and climatic conditions. Harmonised approaches, building on lessons learnt and research insights, will allow for a better comparison of activities as well as for a more effective knowledge sharing between all stakeholders. A **European Wildfire Directive**, complemented by **guidelines**, e.g. for the use of modelling and decision support tools, interaction with citizens, or the integration of machine learning is recommended.
- Guidance should also include the development of **IWRM targets** at multiple temporal and spatial scales and the development of **Key Performance Indicators (KPIs)** and related data sets that can facilitate the assessment and monitoring of IWRM measures.
- To exploit the recent developments including Decision-Support Systems (DSSs) and data sets as well as to enable the implementation of regenerative landscape solutions, **new forms of funding** are needed. This includes for example new structures for knowledge sharing between all stakeholders including land-use planners, farmers, or infrastructure operators. In addition, public-private partnerships to accelerate funding for the tailoring of solutions to local contexts and their wider testing and application are needed.
- A **European Technical Working Group** on the use of data-driven decision support systems dedicated to wildfire risk management, and specifically the use of **Artificial Intelligence (AI) and machine learning** will be needed to adopt and scale the most recent developments and drafting suggestions for data curation and harmonisation.
- Specific focus for the strategic use of **adaptation** and **rehabilitation strategies** as windows of opportunity for transformative change should play a critical role to ensure the landscape resilience against climatic and socio-economic changes.

# 2 Introduction | Key challenges

## 2.1 Worsening wildfire extension and severity

In recent years, the growing wildfire challenge is becoming evident globally.[12] While fire is a natural part of many ecosystems worldwide and a powerful ecological and evolutionary force, the frequency, timing, and locations of wildfires are shifting, leading to longer fire seasons in many regions[13] and introducing new wildfire challenges in areas that were considered less prone to fires. Climate change is creating longer periods of fire-conducive weather and more frequent extreme events[14]. Drought effects on the vegetation are increasing their propensity to burn, affecting ecosystem resilience and biodiversity[15] while raising concerns about the carbon feedback loop from wildfires. In Europe, wildfires have historically been concentrated in Southern Europe and are now affecting regions from Scandinavia to Central Europe. This seasonal and geographical expansion of fire-affected areas together with an increasing number of extreme events affected by climate change[16], signals a fundamental shift in European wildfire patterns and thus requires a concerted response from Europe. Overall, in recent years, catastrophic wildfires have been common in the European Union with 'megafires' challenging traditional firefighting means. For example, a fire near the Greek city of Alexandroupolis was the largest single wildfire recorded in the EU since the European Forest Fire Information System (EFFIS) started tracking them in 2000.[17]

## 2.2 Drivers of increasing wildfire risk and current governance challenges

The drivers of increasing wildfire risk in Europe are complex and interconnected and climate change is compounded by significant socio-economic shifts, including rural abandonment, leading to unmanaged landscapes with higher fuel loads, poorly maintained or abandoned croplands, plantations and houses, aging rural populations, with reduced economic and land management capacity, and declining traditional agricultural practices.[18] Several sectoral policies are hence impacting wildfire risk and need to be coherent to contribute to its reduction.[19] At the European level these include for example the EU Forest Strategy for 2030, the EU Bioeconomy Strategy, the EU Strategy on Adaptation to Climate Change, the Nature Restoration Law or the Farm to Fork Strategy.

These environmental and socio-economic factors intersect with governance challenges across Europe. The growing urban-rural interface, the loss of traditional fire management knowledge, the limitation of its application by legal restrictions, and changing tourism patterns create new exposures and vulnerabilities. Risk management is further complicated by fragmented approaches across regions and a lack of effective policies that may address these differences, limited cross-border cooperation, and insufficient coordination between stakeholders. The varying capacities and resources across European regions, combined with the need to

[12] Cunningham et al. 2024 show that the frequency of extreme events (≥99.99th percentile) increased by 2.2-fold from 2003 to 2023.

[13] Pausas, J.G. and J. E. Keeley (2021): Wildfires and global change, Frontiers in Ecology and Environment, 19(7): 387–395, doi:10.1002/fee.2359 (31.03.2025).

[14] Hetzer, J.; Forrest, M.; Ribalaygua, J.; Prado-López, C.; and Hickler, T. (2024): The fire weather in Europe: large-scale trends towards higher danger, Environmental Research Letters 19: https://doi.org/10.1088/1748-9326/ad5b09 as well as Moghli, A., Karali, A., Varotsos, K.V., Giannakopoulos, C., Brotons, L., Duane, A. (2023). Adapted long-term climate change projections and seasonal forecasts. Deliverable 1.5 FIRE-RES project. 90 page, https://doi.org/10.5281/zenodo.10211204.

[15] Grau-Andrés, R.; Moreira, B. and J. G. Pausas J.G. (2024): Global plant responses to intensified fire regimes. Global Ecology & Biogeography 33(8): e13858, https://doi.org/10.1111/geb.13858 (02.04.2025).

[16] Galizia et al. (2023): Global Warming Reshapes European Pyroregions, in: Earth's Future, https://doi.org/10.1029/2022EF003182; Cunningham et al. refer to events ≥99.99th percentile: Cunningham et al. (2024): Increasing frequency and intensity of the most extreme wildfires on Earth. In: Nature Ecology & Evolution 8 (8), S. 1420–1425, doi: 10.1038/s41559-024-02452-2.

[17] 2023 among the 5 worst years for wildfires in Europe, Commission report shows - European Commission (31.03.2025).

[18] Moreira et al. (2020): Wildfire management in Mediterranean-type regions: paradigm change needed, in: Environmental Research Letters, 15 011001, https://doi.org/0.1088/1748-9326/ab541e (02.04.2025).

[19] Plana E, Serra M, Smeenk A, Regos A, Berchtold C, Huertas M, Fuentes L, Trasobares A, Vinders JN, Colaço C, et al. Framing Coherence Across EU Policies Towards Integrated Wildfire Risk Management and Nature-Based Solutions. Fire. 2024; 7(11):415. https://doi.org/10.3390/fire7110415.

balance conservation with the sustainable use of forest products, specifically considering strengthening bio-economies alongside to face the demographic challenge (aging population of rural areas), underscore the complexity of developing effective wildfire risk management strategies.

The risk of wildfires is hence essentially a societal problem which can be extensively modified, mitigated or reduced by individual and collective actions, if there is a common Strategy to reach that goal.

## 2.3 Growing wildfire impacts

Depending on the future climate change pathway, future landscape design will have to recognise the increasing fire danger. Fires will occur more often and burn larger areas from Mediterranean-type ecosystems to temperate and boreal forests. Mountainous and forested regions in Central and Eastern Europe will likely experience an increase in fire danger exposing managed and natural forests alike to be affected by an increase in the area burned, thereby increasing their vulnerability due to increased potential losses[20]. Fire seasons will last longer, extend into the autumn and be more variable in their extremeness in the later summer months[21]. These climate-induced changes will have an effect where demand for forest products remain high, land continues to be abandoned and WUI continue to exist.

In line with an increasing occurrence of extreme events, there is also a larger negative impact on all aspects of life, from citizens' safety and health to climate and environmental protection, socio-economic activities, and infrastructure and ecological systems. This is shown as an example, (Figure 1) in the case of Portugal and Spain, in which the average area of the five largest fires that occurred in each year since 1980, is increasing gradually, despite all the efforts made, and the improved efficiency in fire suppression. Those negative effects may manifest across multiple dimensions, particularly when compound or cascading effects occur, throughout society, economies, and the environment. The economic consequences are substantial[22], including direct costs of fire suppression, reconstruction of damaged housing and infrastructure, biodiversity loss, and recovery from impacts on local economies and tourism, while the growing strain on national budgets and insurance systems reflects the increasing scale of the challenge. These economic impacts are coupled with severe environmental effects, including biodiversity loss, soil degradation, and deteriorating air and water quality, which can persist long after fires have been extinguished.[23]

[20] Billing, M. et al. (2023): FirEUrisk D3.4 – Simulated fire and vegetation dynamics at three spatial scales, available via: FirEUrisk_D3.4-v1.0.pdf.

[21] Hetzer, J., Forrest, M., Ribalaygua, J., Prado-López, C., and Hickler, T. (2024): The fire weather in Europe: large-scale trends towards higher danger, Environmental Research Letters, 19, https://doi.org/10.1088/1748-9326/ad5b09.

[22] Meier et al. (2023): The regional economic impact of wildfires: Evidence from Southern Europe https://www.sciencedirect.com/science/article/pii/S0095069623000050?via%3Dihub.

[23] Kalapodis, N., Sakkas, N., & Demestichas, K. (n.d.). Final policy recommendation framework. SILVANUS project report (D7.3).

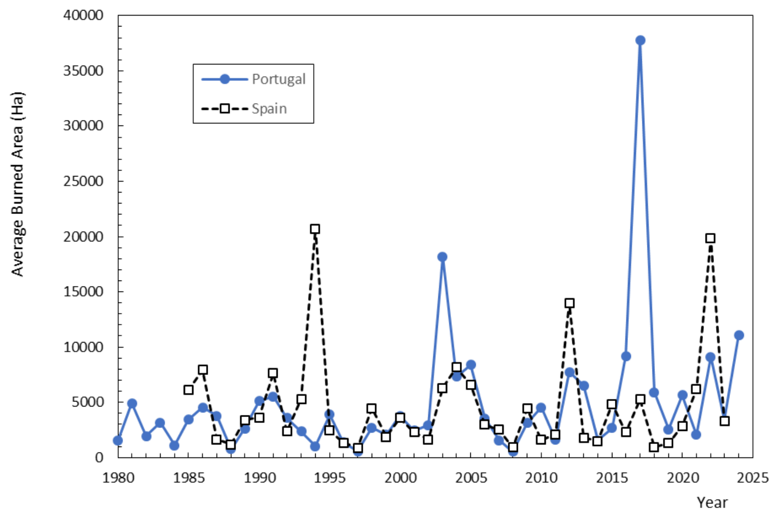


*Figure 1: Average area (hectares) of the five largest fires in each year in Portugal and Spain, between 1980 and 2024.*
Source: FirEUrisk; Source of data: ICNF; Landsat.

The social implications of wildfires penetrate deep into communities, with immediate public health impacts, from fire and smoke exposure, compounded by longer-term effects, such as community displacement, loss of livelihoods, and psychological trauma. These impacts are particularly significant in rural areas, where they can accelerate existing trends of rural abandonment and loss of traditional land management practices such as the use of prescribed burns, creating a feedback loop that further increases wildfire vulnerability[24]. Likewise, large and intense wildfires can contribute to the deterioration of carbon sinks, like forests and peatlands, diminishing their ability to store carbon and thereby accelerating climate change.[25] Health impacts of wildfires are a growing concern especially for vulnerable groups, like firefighters, and old or very young citizens and those already affected by some respiratory or cardiologic problems. These persons can be subject to intense and acute or long-term episodes of smoke exposure that can impair seriously their health and quality of life. In the fires of Pedrógão Grande, on the 17th of June of 2017 and in those on the 15th of October, in Portugal, more than one hundred persons lost their lives by direct action of the fire and smoke, but more than three hundred were affected by burns and respiratory infections and had a premature death.[26] Similar processes occurred in the Mati fire, July 2018, in Greece, in which more than one hundred persons perished caught by rapidly spreading fire or while attempting to escape from it, and many more were affected by the smoke. With Europe as the second strongest warming continent, it is expected that such extreme fire conditions will get worse. Simulations, considering plausible future climate and socioeconomic evolution scenarios, indicate clearly a tendency to an increase of the probability of having high fire danger days and an increased burned area, mostly in Southern Europe, but also in Central and Northern Europe, as it is shown in Figure 2.

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[24] Uyttewaal, K., Prat-Guitart, N., Ludwig, F., Kroeze, F., Langer, E.R. (Lisa). (2023). Territories in Transition: how social contexts influence wildland fire adaptive capacity in rural Northwestern European Mediterranean areas. Fire Ecology. 19, 13.

[25] OECD (2023): Taming Wildfires in the Contetxt of Climate Change, Paris.

[26] See for example Viegas et al. (2019): Análise dos Incêndios Florestais Ocorridos a 15 de outubro de 2017. Centro de Estudos sobre Incêndios Florestais (CEIF/ADAI/LAETA). Coimbra, Portugal. Análise dos incêndios florestais ocorridos a 15 de outubro de 2017 - XXI Governo - República Portuguesa or Viegas et al. (2017): O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017 (Vol. 2017). Centro de Estudos sobre Incêndios Florestais (CEIF/ADAI/LAETA). Coimbra, Portugal. https://www.portugal.gov.pt/pt/gc21/comunicacao/documento?i=o-complexo-de-incendios-de-pedrogao-grande-e-concelhos-limitrofes-iniciado-a-17-de-junho-de-2017.

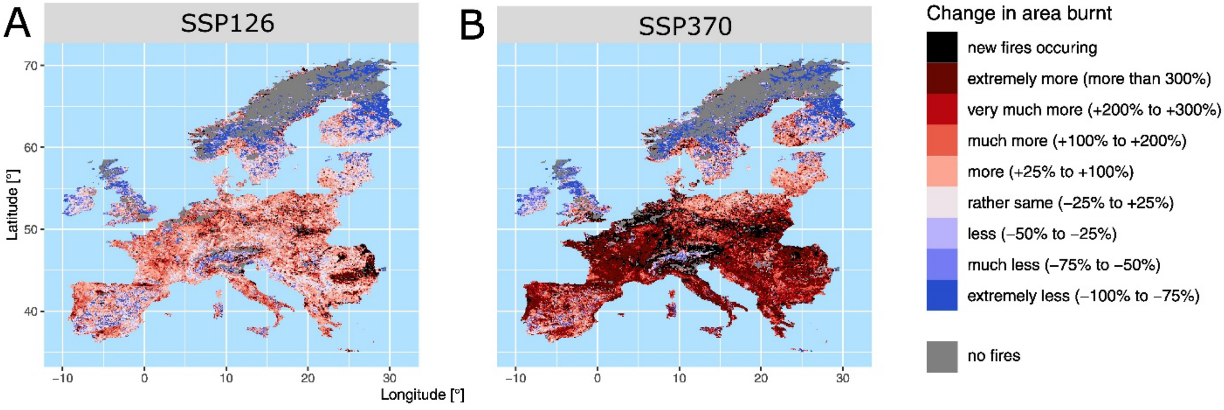


*Figure 2:* Projected increase in burned area in Europe for two climatic and socio-economic evolution scenarios, from present to the period of 2070-2100: A) Better land management and 2 to 3ºC temperature increase; B) Fractured land management and 4 to 5ºC temperature increase.
Source: Billing et al. (2023): Simulated fire and vegetation dynamics at three spatial scales, FirEUrisk D3.4 (02.04.2025)..

## 2.4 Why a European IWRM strategy is needed

This new context of wildfire risk in Europe is challenging existing wildfire risk management programmes and strategies and has shown the limitations of our ability to effectively prevent and respond to extreme events such as megafires. Until now, countries and regions have addressed the problem in different ways, and for a long time the main wildfire risk approach in many countries focused on response efforts (Southern Europe) while in other regions like Northern Europe, whereas the risk was not prevalent, any risk management efforts have been hardly considered. Adapting to more damaging fires, longer fire seasons and more fire-prone areas not only requires shifting the focus from suppression to prevention but calls for European member states to rethink wildfire risk in a more holistic way. Unlike other regions or countries of the world that are affected by the increasing risk of wildfires, Europe does not have a common strategy or system to manage it in an integrated form. Such integrated wildfire risk management strategy implies addressing the wildfire risk as a long term and prevailing problem, transversal to the entire society and requiring multi-lateral and multi-party responses, looking at the issue from multiple angles to ensure that wildfire risks are reduced in a way that people and housing safety, economic growth, well-being, carbon sinks, biodiversity and ecosystem services are maintained or increased. The current lack of an integrated approach manifests in the following aspects:

- A fragmented landscape of risk reduction approaches and a scattered application of strategic goals that involve creating trade-offs and conflicting objectives such as the implementation of prescribed burning vs. securing air quality, the application of nature-based solutions vs. increasing wildfire risk, the development of advanced landscape planning approaches by the integration of recent technologies and available data, to name just a few.
- Limited experience in the management of high-intensity fires in some EU countries and regions.
- Insufficient coordination between policy initiatives such as EU climate and biodiversity ambitions and lacking integration of decision makers, scientists, operational agents, the private sector and citizens at multiple scales and subsequent synergy development of urban planning, biodiversity, energy, agricultural policies contributing to wildfire risk reduction.
- Inadequately sustained pan-European cooperation mechanisms including all phases of managing wildfire risk involving the multitude of stakeholders such as landscape planners, foresters, farmers and community groups.
- Fragmented research programs, with overlaps, lack of follow up, concertation and integrated exploitation of results.

- Lack of coordinated effort in the uptake of new technologies for implementing risk mitigation strategies and promote preparedness and response coordination strategies for fire incidents, also considering the intensifying change in climate.

A joint strategical approach is therefore essential. This approach should focus on the latest research and technological advances, established good practices and tested exchange and training formats. Following the example of Portugal, we propose that the creation of a strategy should include some key elements such as the creation of an **Inter-agency at the EU level**, to work transversally with the various agencies and European Commission Directorates (DGs) to operationalise the implementation of inter-agency articulation and coordination, to avoid overlaps and gaps. Also, several of the measures proposed in this document concern the activities of some of these agencies including, for example DG ENV, DG CLIMA, DG ECHO, DG AGRI, DG REFORM. In line with this, we also advocate the implementation of a **European Wildfire Management Directive** as a regulatory framework to guide wildfire risk management activities.

The harmonisation and concertation of approaches across the EU would facilitate the exchange of good practices and expertise while creating potential uptake of new solutions and links for future research and dedicated training programmes. Furthermore, a better alignment of approaches would facilitate the development of **Key Performance Indicators (KPIs)** and subsequent impact assessments, benefitting a better evaluation of risk reduction measures, and finally a more efficient use of resources.

In addition to these structural needs for IWRM efforts to be enforced and guided, a strategy should also **propose activities** and **initiate guidance** at the EU, national, regional and local levels with respect to the different IWRM building blocks. In the subsequent chapters we propose several approaches that have been developed and tested in the mentioned projects, that could be supported by a strategy and may qualify for broader application across Europe.

# 3 Integrated Wildfire Risk Management (IWRM) for resilient landscapes and safer communities

We consider that the crucial elements of a strategy reducing wildfire risk (Figure 3), namely the risk assessment and evaluation (Section 2.1), the subsequent informed design of risk management and adaptative planning strategies to mitigate the risk (Section 2.2) stakeholder engagement formats and systemic communication approaches (Section 2.3) need to be developed and implemented at multiple scales, namely the EU, national, regional and local levels, at the service of our entire society, involving all stakeholders including citizens not normally involved in wildfire risk management. All these aspects need to be embedded into concerted governance approaches (Section 2.4).

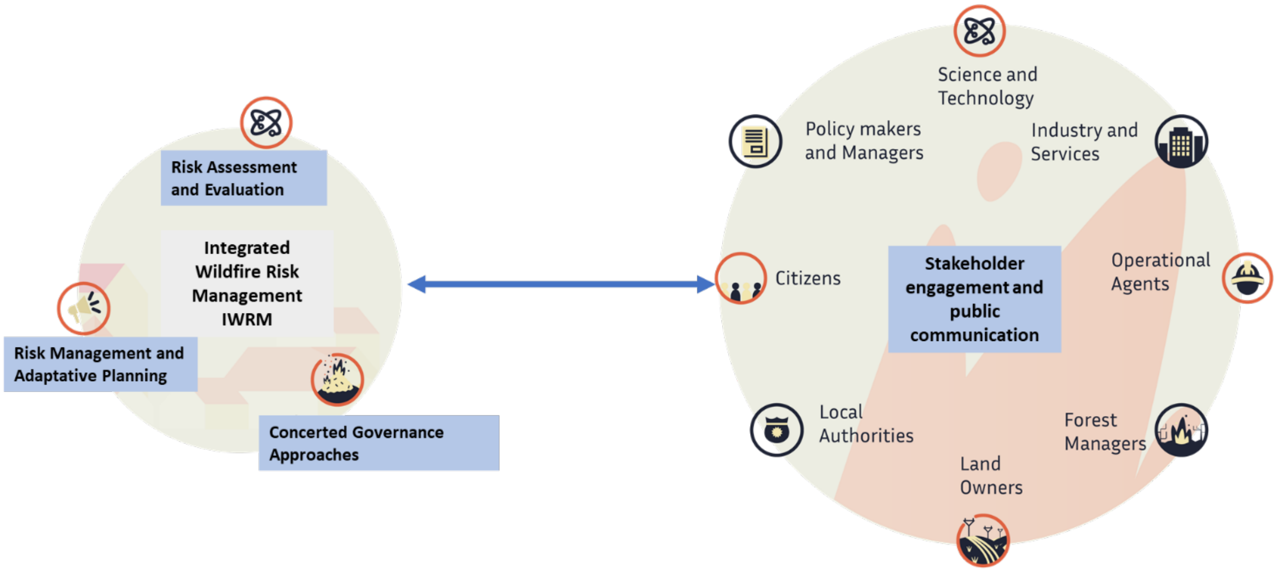


*Figure 3: Proposed components of a strategy, building on the LFGF.*

## 3.1 Risk Assessment and Evaluation

The assessment and evaluation of wildfire risk is a crucial step towards reducing risk and to adapt landscapes and communities to future conditions. Wildfire risk involves three main interrelated components[27]: Danger, Exposure and Vulnerability, and each is the result of complex processes that depend on many physical, biological and socio-economic parameters.

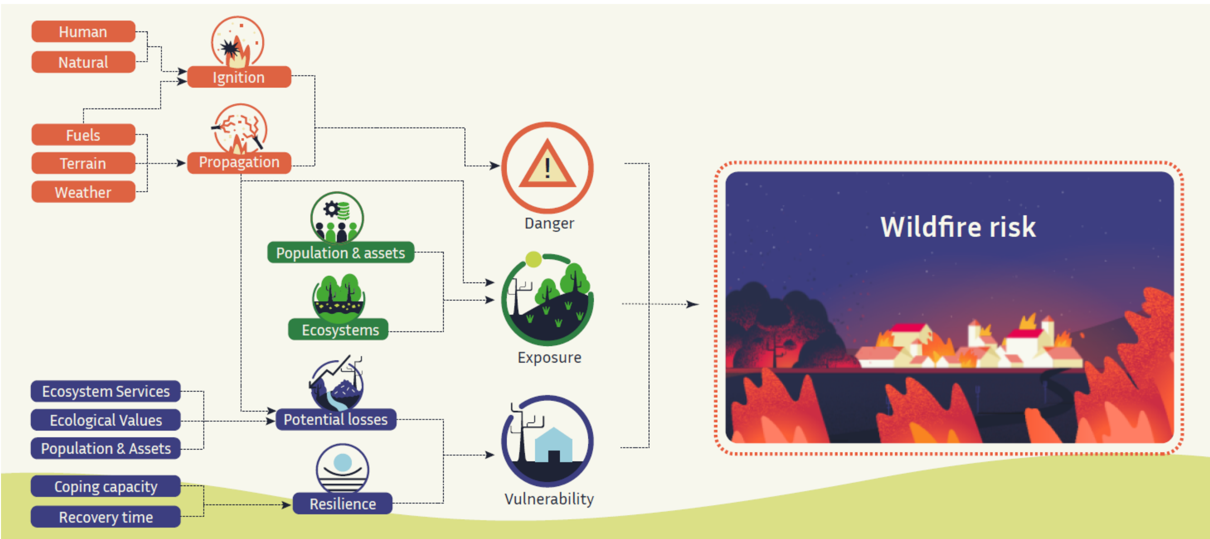


*Figure 4: Conceptual integration of wildfire risk assessment components*
Source: Chuvieco et al. (2023).

To assess wildfire risk in all its components, an approach as proposed by FirEUrisk (Figure 4) or the Joint Research Centre[28], should be adopted to consider all the processes and their driving parameters that can be monitored or managed to reduce risk and to prepare Europe to face the challenge of future conditions. Practical experience and scientific research have identified, measured and mapped the variables and the

[27] Chuvieco et al- (2023). Towards an Integrated Approach to Wildfire Risk Assessment: When, Where, What and How May the Landscapes Burn, in: Fire, *6*(5), 215. https://doi.org/10.3390/fire6050215 (02.04.2025).

[28] Oom et al. (2022): Pan-European wildfire risk assessment, Publications Office of the European Union, Luxembourg, doi:10.2760/437309 (02.04.2025).

parameters that affect the various processes involved in the initiation and spread of wildfires and in the assessment of their impact on human and natural environment, at various spatial and temporal scales.

This approach considers the exposure of population, assets and ecosystems to the impact of wildfire[29], as well as the fire vulnerability of society and ecosystems, based on potential losses and resilience. Wildfire danger, that derives from the wildfire ignition and propagation, associated with natural factors and human activities, is a key component of wildfire risk, but it is closely related to exposure and vulnerability and should be managed in an integrated form with those components. In other words, fire risk reduction and adaptation strategies should include methods that consider all components, e.g. policies to reduce human ignitions, to improve fuel management and firefighting to reduce potential losses, increase societal and ecological resilience and reduce exposure to fire. A methodology to classify vegetation cover as fuel types for fire risk assessment was developed[30], along with crown quantitative parameters for fire propagation potential[31]. Both the fuel typology and the crown parameters were generated for the European territory, but they could be adapted to different spatial scales. A similar procedure was followed for all other components of fire risk identified, as is exemplified in Figure 5. The suggested framework can also be adapted more accurately to regional or local study areas, provided that more detailed input parameters are available.

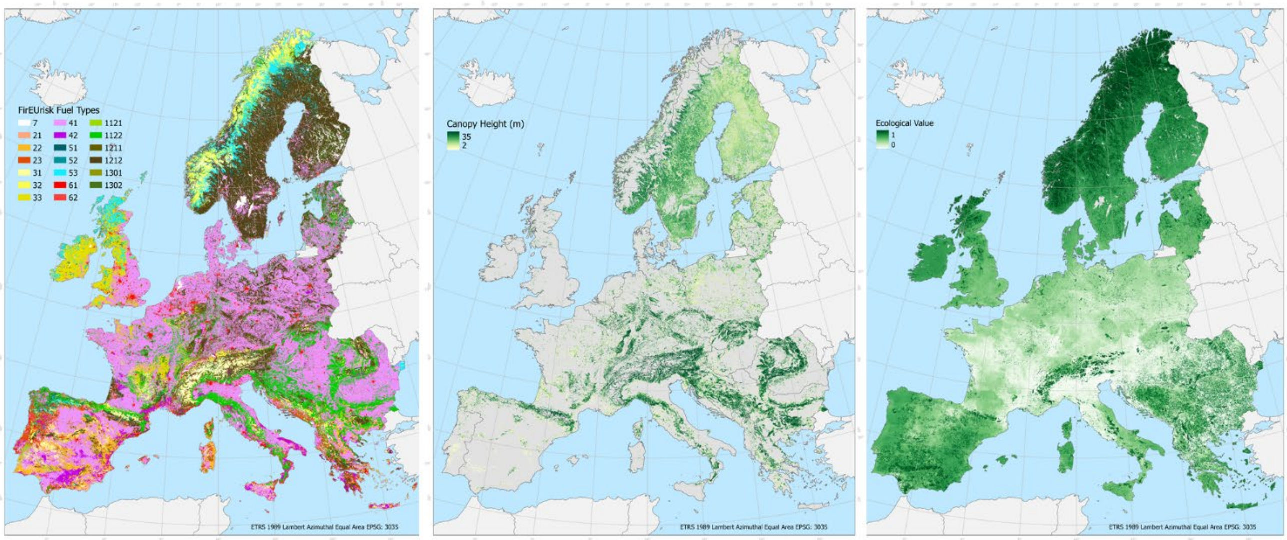


*Figure 5: Risk variables generated for the European pilot site: fuel types, canopy height and ecological values. Source FirEUrisk project, based on Aragoneses et al., 2023 and 2024, and Arrogantes-Funes et al., 2024*
Source FirEUrisk.

It is important to acknowledge that wildfire risk assessments can be used for predictive analysis using future climate, socio-economic, and environmental scenarios. Socio-economic and environmental scenarios up to 2050 have a strong anthropogenic component based on landscape management decisions (see Section 3.2). Instead, climate projections depend on global socio-economic pathway scenarios and therefore add uncertainty at medium term (until 2050). Increments in average temperatures and changes in precipitation patterns must be considered for long term risk assessment for the development of resilient landscapes and

[29] We use wildfire hazard and danger interchangeably as a description of the combination of constant and variable factors that affect the initiation, spread, and ease of controlling a wildfire on an area.
[30] Aragoneses, E., García, M., Salis, M., Ribeiro, L.M., & Chuvieco, E. (2023). Classification and mapping of European fuels using a hierarchical-multipurpose fuel classification system. *Earth System Science Data, 15*, 1287–1315.
[31] Aragoneses, E., García, M., Ruiz-Benito, P., & Chuvieco, E. (2024). Mapping forest canopy fuel parameters at European scale using spaceborne LiDAR and satellite data. Remote Sensing of Environment, 303, 114005 and Aragoneses, E., García, M., Tang, H., & Chuvieco, E. (2025). A multi-sensor approach allows confident mapping of forest canopy fuel load and canopy bulk density to assess wildfire risk at the European scale. Remote Sensing of Environment, 318, 114578.

safer communities of those areas with higher future wildfire risk. Fire adaptation methods must be robust under such future climatic, environmental and socio-economic changes.

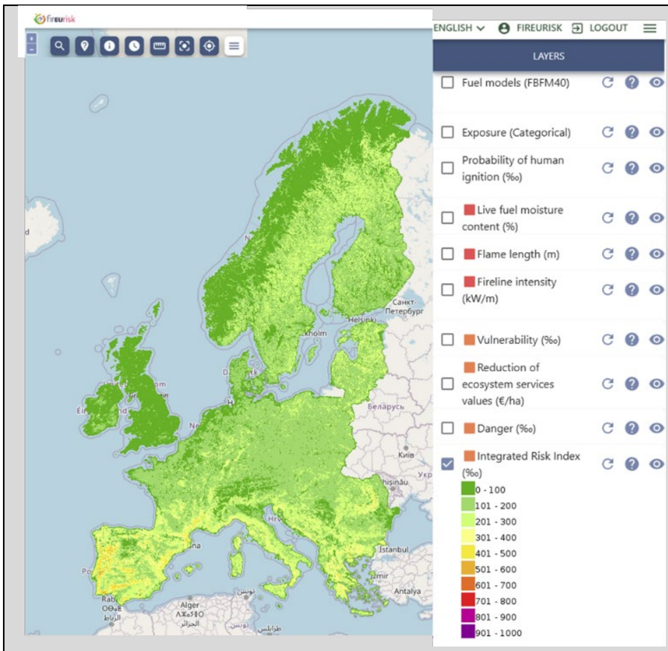


*Figure 6: FirEUrisk Viewer*

The FirEUrisk project has developed an encompassing data hub where European data sets for respective assessments are available: in the figure the Integrated Risk Index for the 11th of April 2025, is shown[32].

FIRE-RES has developed a Pan-European Fuel Map Server. This web-GIS server delivers a comprehensive suite of geospatial datasets, essential for wildfire simulation and risk assessment

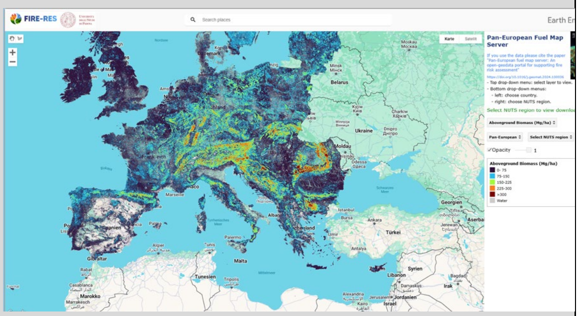

*Figure 7: FIRE-RES Pan European Fuel Server[33]*

*Box 1: New data sets for assessing wildfire risk in Europe.*

Thus, a European strategy should incorporate the development of **guidelines for risk assessment including the use of projections and scenarios for fire adaptation purposes** based on a standardised data collection of environmental, social and economic indicators. Overall, indicators could be monitored by taking advantage of advances in 1) high resolution fuel models, 2) vegetation characterisation using Earth Observation data (e.g., Sentinel-2 and other Copernicus missions, plus Lidar data) combined with Artificial Intelligence, 3) vertical atmospheric structure data based on satellite observations [34], 4) coupled fire-atmosphere models based on

[32] FirEUrisk DataHub (01.04.2025).
[33] Pan-European Fuel Map Server (01.04.2025). The related scientific article is Kutchartt et al. (2024): Pan-European fuel map server: An open-geodata portal for supporting fire risk assessment, Geomatica, 76(2), https://doi.org/10.1016/j.geomat.2024.100036 (01.04.2025).
[34] van der Grijn, G., Ferràndiz Ensesa, A., (2024). FIRE-RES Earth Observation Data Collection to Support Decision-Making. Deliverable 5.6 FIRE-RES project. 44 pages. DOI: 10.5281/zenodo.14188148

high resolution weather data[35], 5) High Altitude Pseudo Satellites[36], or 6) real-time smoke propagation simulations[37]. Guidelines for risk assessment should also provide **standardised indexes for early warning and related communication campaigns**[38].

The adoption of these guidelines will allow the European Member States to better assess their wildfire risk in a unified and consistent form, and to monitor and evaluate the effectiveness of risk reduction activities, or indeed, the lack of them. Moreover, it is important that in a joint effort between the scientific community and the national and European agencies, the technical and scientific advances in gathering and updating data are made available and incorporated into the decision-making process and maintained for their operational use. While regional approaches will be tailored to local specificities and context, European data sets need to be tailored to their application at EU level. For example, a **Central Data Hub** maintaining and updating risk information including fuel maps that may feed into the European Forest Fire Information System (EFFIS) providing centralised data and risk assessment support to the EU Civil Protection Mechanism coordinating cross-border response efforts should be enforced. It should be paired with guidelines and good practice documents, for example on stakeholder engagement and the application of technological innovation.

Wildfire risk **tolerance** differs among societies depending on how different populations and cultures perceive and accept impacts. Upon a thorough assessment, acceptable (and to some extent unavoidable) wildfire impacts will have to be negotiated with all stakeholders (see also Section 3.3 below). Fire education platforms proposing materials and activities addressed to broad audiences (e.g., policymakers, schools, families, etc.) to disseminate fire ecology and related behavioural and management recommendations, and a citizen-science mobile app to gather or disseminate wildfire risk information to the public, have been developed by the projects and may serve as a blueprint[39]. Platforms in local languages will contribute to improving the knowledge about the impacts and benefits of fire. Another recommendation is to implement Fire Forums[40], i.e. multi-stakeholder fora on those areas of high wildfire risk. These forums are decision-making participatory processes where local stakeholders have face-to-face meetings and field visits to discuss future fire scenarios, prioritisation of values and definition of responsibilities to reduce social vulnerability[41]. Agreed results of these forums contribute to better fire knowledge and faster decision-making in case of fire.

In addition, it is important to increase the general acceptance of the population to the use of fire and the presence of smoke, at tolerable levels.[42] This is required to promote the implementation of prescribed fire programs and even a policy of letting some wildfires spread and perform the role of reducing biomass and therefore reduce the risk of (future) wildfires.

## 3.2 Risk management and adaptive planning

The Landscape Fire Governance Framework (LFGF) highlights the integration of Planning, Preparation, Prevention, Pre-suppression, Suppression and Post-fire activities within risk management. Each segment

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[35] See for example, Baggio, R. Filippi J.B. (2024). Modelling the EWE and smoke spread based on coupled fire-atmosphere approaches. DOI: 10.5281/zenodo.14187388

[36] See for example, Souto-Lorenzo, O. et al. (2024) Results and recommendations from a HAPS fleet simulation confronted to real risk and fire events data at South European level. Deliverable 5.7 FIRE-RES project. 10.5281/zenodo.1418154

[37] See for example, Baggio, R. Filippi J.B. (2024). Modelling the EWE and smoke spread based on coupled fire-atmosphere approaches. DOI: 10.5281/zenodo.14187388

[38] See for example, Ruffault, J. Pimont, F., Opitz, T., Dupuy J-L. (2025). Piloting early-warning indicators of Extreme wildfire events incorporating fire-weather and vegetation conditions. FIRE-RES project. 57 pages. DOI: 10.5281/zenodo.15040271

[39] For example, FIRE-RES develops an educative platform (see https://youtu.be/MLaMb5a6NZU, 01.04.2025); the SILVANUS Citizen Engagement App can be downloaded from respective online stores, e.g. SILVANUS on the App Store (01.04.2025), the FirEUrisk project developed a citizen-science mobile app to disseminate fire risk, which can be downloaded also from online stores. SILVANUS developed a citizen engagement reference framework (Citizen Engagement in Wildfire Management: Needs, Challenges, Methods and Framework) and course (Citizen Engagement Course | SILVANUS)

[40] See for example IA 4.1 Fire forums - FIRE RES (01.04.2025).

[41] FirEUrisk - D2.8-Guidelines-to-reduce-communities-vulnerability-METEOGRID-v1.pdf

[42] FirEUrisk D4.5 on the Roadmap for an integrated wildfire risk management strategy for Europe (https://fireurisk.eu/deliverables/).

should be managed by competent and accountable actors moving away from a siloed mindset. In this section, a set of transversal risk management measures building on recent research are depicted with the aim to develop and manage forested and rural areas, recognizing the role of fire, assessing its risk, and promoting safer conditions for citizens in Europe.

### 3.2.1 Landscape design

Landscapes play a central role in risk management as wildfires take place there. The design of pre- and post-fire landscape mosaics that are less prone to the occurrence of wildfires, that can facilitate detection and suppression in case a wildfire does occur and that may contribute to adaptation and restoration after a wildfire, involves the development of landscape management strategies that recognises the landscapes multifunctionality. Moreover, the design of the Wildland Urban Interface requires building codes as well as specific vegetation management guidelines[42]. Specific measures such as the implementation of nature-based solutions, involvement of grazing methods and shepherds, the close exchange with farmers including the development of labels for local fire-smart products and the promotion of prescribed burns need to be part of this portfolio.

Landscape management strategies

The design of resilient landscapes requires an efficient and effective data-to-information-to-knowledge strategy. The latter must take advantage of recent scientific and technological advances to engage stakeholders in the development, assessment and discussion of proposals to lay out adequate management options over space and time[43]. This will be instrumental in meeting the relevant prerequisites of the Integrated Wildfire Risk Management value chain's planning, prevention, pre-suppression and post-fire stages. As landscapes are typically fragmented into several holdings and ownership and exploitation types, joint management planning processes should be developed that involve representatives from all stakeholders to define management scenarios and to monitor the implementation of management plans. An example from Portugal is shown in Box No. 2 below.

The processes should be supported by adequate participatory approaches that may forecast and monitor outcomes and risk management scenarios, specifically considering climate change scenarios. The resulting **landscape-level resource capability models** may provide stakeholders with information to co-develop cost-efficient vegetation management options such as fuel treatments or species conversion. This information may be encapsulated within advanced decision support tools to generate knowledge to select the most cost-efficient pathway to configure a resilient landscape mosaic and minimise expected losses from wildfires. The suggested approach will further support the design of strategic networks of managed areas to facilitate suppression efforts in case of wildfires. This design may build from criteria such as vegetation status (e.g., fuel type, arrangement, load), suppression drivers (e.g., accessibility, availability of suppression infrastructures), exposure to wildfires (e.g., areas that are particularly threatened by fire and that hold significant cultural, social, or environmental value), to be listed and assessed by relevant stakeholders including firefighters, civil protection, to **classify and monitor areas in the landscape** according to the fuel treatment priority. The classification of areas according to criteria such as vulnerability to wildfires, or erosion potential, considering the expected wildfire intensity, that are relevant for emergency, rehabilitation and restoration priorities may further benefit from collaborative processes. Figure 8 shows examples of such collaborative processes and of a priority map, co-created with all stakeholders.

[43] Baskent, E., J. G. Borges and J. Kaspar 2024. An Updated Review of Spatial Forest Planning: Approaches, Techniques, Challenges, and Future Directions. *Current Forestry Reports* https://doi.org/10.1007/s40725-024-00222-8 / or FirEUrisk - D2.8-Guidelines-to-reduce-communities-vulnerability-METEOGRID-v1.pdf.

The example below shows the process of designing networks of managed areas to facilitate suppression efforts in the Vale do Sousa landscape, FIRE-RES Living Lab in Portugal (FIRE-RES). Similar approaches have been implemented by all projects.

*Figure 8: Designing strategic networks of managed areas to improve suppression efforts against EWEs*
Source: González-Olabarria et al. (2024) , p. 56

*Box 2: Innovating stakeholder engagement-driven landscape design*

Fuel management activities to reduce biomass of fine fuels are mandatory in the whole territory of Europe affected by the risk of wildfires. In FirEUrisk that applicability and effectiveness of grazing, mechanical reduction or prescribed fire was analysed for the territory of Europe[44]. Prescribed fire (PF) has proven to be a valuable tool for wildfire prevention and landscape management in several Sardinian municipalities, particularly within agro-silvopastoral systems increasingly affected by land abandonment and fuel accumulation. As part of the FirEUrisk Project, pilot activities were carried out in the municipalities of Alghero, Suni, Isili, and Nuoro, showcasing different objectives and operational contexts. In Alghero, prescribed burning was implemented both for fuel reduction and as a training exercise for fire prevention personnel, under the coordination of the Sardinian Forest Service (CFVA). In Suni, collaboration between CFVA, local communities and stakeholders enabled the treatment of 100 hectares, marking an important step toward participatory land management. In Isili, PF was applied to reduce shrub biomass and vertical fuel continuity within a forested area located in a penitentiary colony, where ignition risks are particularly high near road infrastructure. Finally, in Nuoro, PF complemented silvicultural treatments in a wildland-urban interface area, aiming to enhance canopy base height while reducing understorey vegetation. Despite regulatory constraints limiting the optimal timing of interventions, these experiences illustrate the potential of prescribed fire as a strategic tool for integrated fuel and risk management in the diverse landscapes of Sardinia.

<u>Fuel management and building codes</u>

To have fire-resilient buildings in the Wildland Urban Interface (WUI), building codes should promote enhancements such as the installation of double-glazed windows or the addition of aluminium shutters for improved protection. Furthermore, gutters and roof overhangs should be constructed from non-combustible materials and maintained regularly. Additionally, fuel management measures need to be developed and implemented. For example, this should include recommendations on exclusion of vegetation and other combustible materials in the immediate vicinity of the houses and define the distances between trees and bushes while considering tree species and height. The box below depicts the application of the EXPLORII platform as a technological solution that helps to implement building codes.

[44] FirEUrisk - D2.3 - Guidelines for LMS: applicability, socio-economics and environmental concerns and D2.4 - Map of LMS options at European scale (https://fireurisk.eu/wp-content/uploads/2024/05/FirEUrisk_D2.3-LMS-Guidelines.pdf).

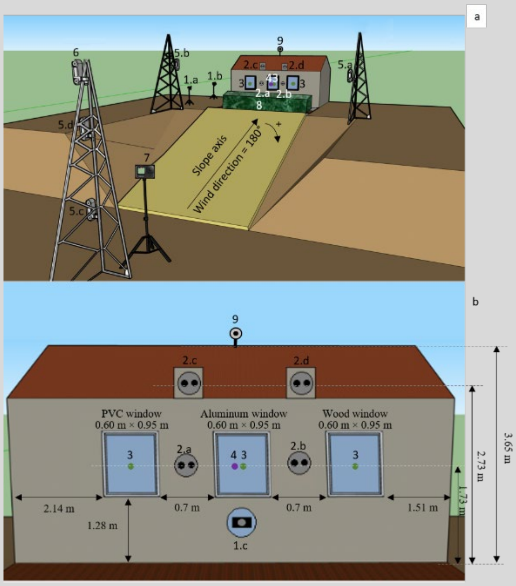



*Figure 9: Layout of the EXPLORII platform*

*Figure 10: Photograph of the EXPLORII platform*

a) General view b) View of the exposed facade - 1: Cameras. 2: Pairs of total and radiant heat flux gauges. 3: K-type surface thermocouple 4: Radiant heat flux gauge. 5: 2D sonic anemometer. 6: 3D anemometer. 7: Go Pro. 8: Load Cell under the hedge. 9: Sampling rod for the outdoor smoke analysis

The hedge is placed on a load cell to determine the heat release rate. The house facade is equipped with heat flux gauges and thermocouples to monitor the impact of the fire. Cameras placed around the fire allow the geometry of the flames to be monitored. Anemometers measure the wind speed and direction.

Source: Virginie Tihay-Felicelli et al. (2024).[45]

*Box 3: Technological support for developing building codes and landscaping in the WUI*

Moreover, vegetation management guidelines should include a reference to low-combustibility vegetation and to the monitoring of foliar moisture content and consider the topography of the site as fire spread and the management distances are quite different for upslope or downslope conditions.

Developing **cost-efficient fuel treatment networks** within rural WUI areas requires collaboration among stakeholders to identify values-at-risk and prioritize preferences, while utilising metrics and decision-making tools to strike a balance between protection and costs (Box 4). Nevertheless, successful implementation of building codes[45] and vegetation management strategies necessitates local context consideration, stakeholder engagement, and oversight by public administration, aligning these efforts with the Integrated Fire Management value chain's planning and prevention stages to foster resilient communities.

[45] Tihay Felicelli, V., A. Graziani, T. Barboni, Y. Perez-Ramirez and P.-A. Santoni (2024): FIRE RES D2.3 Quality standard for WUI architecture and landscape design, 90 p. https://doi.org/10.5281/zenodo.13941898 (11.04.2025).

Powered by Cell2Fire World, the QGIS Fire Analytics Toolbox is an open source tool developed by FIRE RES that allows the user to develop wildfire simulations (using Scott and Burgan, KITRAL or FBP fuel models), calculate different risk metrics and optimize landscape design by fuel treatment allocation to protect values at risk in the landscape.

An allocation of fuel breaks covering just 5% on the landscape can reduce the expected losses of the values at risk by more than 35% (Figure x).

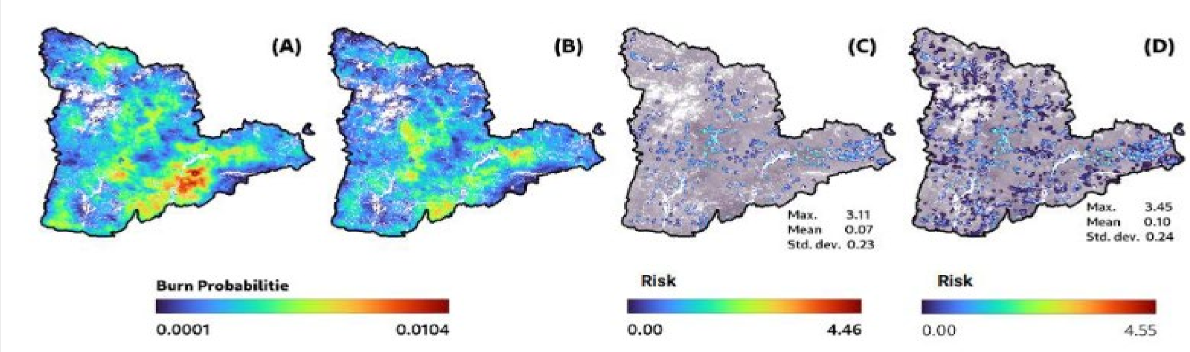



*Figure 11: Allocation of fuel treatments to 5% of the area of Catalonia by the Fire Analytics QGIS Toolbox. (A) shows the baseline burn probability in Catalonia, (B) shows the resultant burn probability, (C) shows the resultant urban risk and (D) shows the resultant multi criteria risk (this considers burned area, archaeological sites, protected areas, and population).*
Source: Badilla et al, 2024.[46]

*Box 4: QGIS Fire Analytics Toolbox for landscape design*

### 3.2.2 Fire-smart bio-economy landscapes

Risk Management requires the integration of spatial-temporal and sectoral perspectives, and the respective social, economic and ecological processes involved. Fire-smart landscapes encompass dynamic mosaics targeting the provision of ecosystem services and benefiting from cross-sectoral collaborations that may drive bio-economy value chains towards improving landscape fire resilience. In fragmented landscapes and value chains, transaction and coordination costs[47] complicate concerted planning and implementation. Hence, institutional frameworks for value chain[48] joint adaptive management planning and monitoring are needed. They should also address measures such as nudging and financial incentives (see Figure 12 for a portfolio) such as land consolidation or a group management bonus for spatial coordination. These incentives are typically linked to different markets for environmental services (subsidies and payments for environmental services), commodities (e.g., fire-resilience product labels), credit (landscape-targeted bonds), insurance (differentiated premiums) and taxes and liability fees for fire damages – the latter partially also working as disincentives.[49]

[46] Badilla, F.; Carrasco, J.; Espinoza, C.; González, J. R.; Palacios, D.; Mahaluf, R. Vilchez, M.; Weintraub, A. Recommendations for improving security on WUI at multiple scales. Deliverable D2.4 FIRE-RES project. DOI: 10.5281/zenodo.14206158

[47] These refer to the resources (e.g., time and effort) needed to develop negotiation (transaction costs for e.g. product sale) and agreements (coordination costs for e.g. joint management, collective action).

[48] "A value chain is a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via the feed forward flow of materials and the feedback flow of information", see: The European Innovation Partnership 'Agricultural Productivity and Sustainability' (EIP-AGRI) (2016): New value chains from multifunctional forests, available via: eip-agri_workshop_forest_value_chains_final_report_2017_en.pdf (11.04.2025), p. 11.

[49] Górriz-Mifsud et al. (2025): IA 3.2 brief: Development and implementation of incentive mechanisms at regional policy level to support resilient landscapes. FIRE-RES Deliverable 3.4. doi: 10.5281/zenodo.15120270 (02.04.2025).

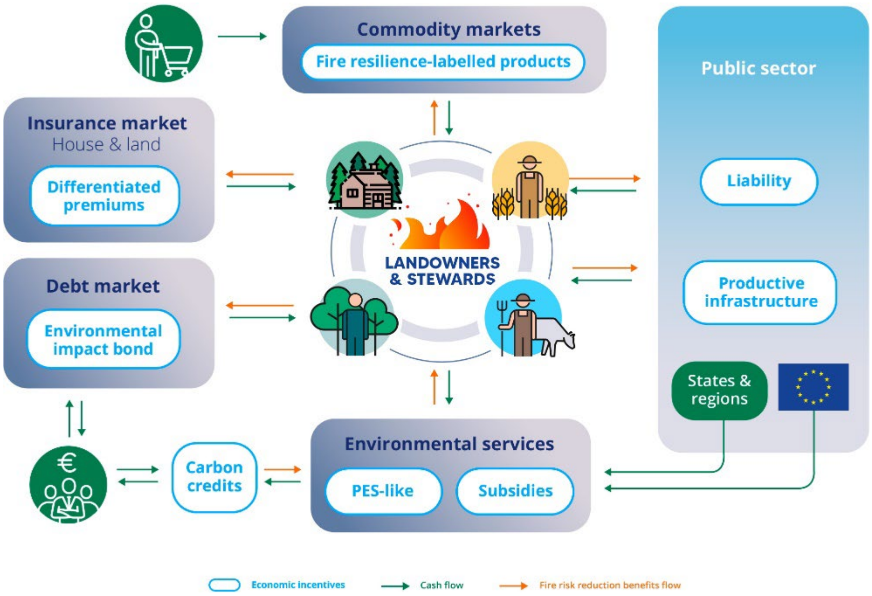



*Figure 12: Pool of economic instruments to incentivise wildfire risk mitigation*
Source: Wunder et al. (2023).[50]

Well-functioning forest-based value chains represent an indirect approach to maintain fire-smart landscapes[51]. The effectiveness of value chain management relies on adaptive participatory tactical planning and on the assessment of impacts of prevention and preparedness options (e.g., alternative fuel management schedules) and adaptation and restoration options (e.g., species conversion) on the provision of ecosystem services, as well as of the trade-offs between regulatory services (e.g., carbon sequestration and carbon storage, water supply and purification and other ecosystem services (e.g. timber supply, pest control and cultural services) [52]. Besides, optimisation in harvesting and transport operations can reduce the exposure to fire of marketable products within the forest, reducing potential short-term losses.[53]

The development and monitoring of adaptive management plans should take advantage of cross-sectoral synergies, e.g., through specific contracts with shepherds to reduce fuel by grazing in the buffer strips of the WUI[54], or by encouraging active maintenance of agricultural plots in the WUI as well as in strategic zones for fire spread by fire-smart product labelling, to guide consumers' choices and provide a price bonus to farmers[55]. Legislation should adapt to promote these synergies whenever pertinent. The insurance sector can also contribute to fire-smart territories through modulating housing, agriculture and forestry premiums according to the mitigation measures implemented. Likewise, a restructuring of insurance investments into nature-based solutions (or the divestment from nature-negative projects) need to be explored further. However, further policy actions for boosting the entrepreneurial context to incorporate innovative approaches to reduce silvicultural work costs (e.g., new mechanisation opportunities to combine fuel harvesting and forwarding

[50] Wunder et al. (2023): Can economic incentives help reducing wildfire risk? Reviewing economic tools to motivate more fire-resilient land management. FIRE-RES Policy Brief. https://doi.org/10.5281/zenodo.7994139 (02.04.2025).
[51] Wunder et al. (2021): Resilient landscapes to prevent catastrophic forest fires: Socioeconomic insights towards a new paradigm. Forest policy and economics, 128, 102458.
[52] FirEUrisk D1.4 - Report on methodological frameworks for Vulnerability assessment (D, S) in the FirEUrisk- Wiki (https://fireurisk.eu/wpcontent/uploads/2024/05/D1.4_FirEUrisk_ReportMethodologicalFrameworksVulnerability_V1.pdf )
[53] Marques et al (2024): Towards an innovative digital architecture for more resilient forest-based supply chains. IUFRO World Congress, Stockholm.
[54] Rovellada Ballesteros et al. (2025): Aspectos socioeconómicos clave para el pastoreo en Interfaz Urbano-Forestal como Solución Basada en la Naturaleza para la mitigación del riesgo de incendios. *9º Congr For Español*.
[55] Górriz-Mifsud et al. 2025. Bridging wine and forestry sectors to reduce wildfires: Wine actors' perceptions, their role in risk reduction and externality labelling. *Trees, For People* 20:100835.

functionalities to increase the effectiveness of fuel treatment while contributing to biomass supply along the value chain)[56], and to facilitate the demand of novel marketable forest-based products (e.g., public procurement) are needed.

### 3.2.3 Emergency management and response operations

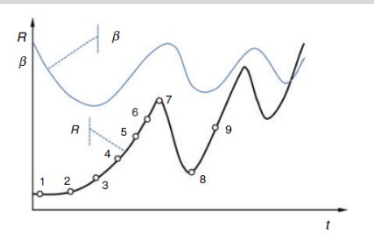
For aspects of emergency management and response, two aspects must be considered: science-based solutions and analytical support to response operations and emergency planning as well as direct advances in response operations including aspects of interoperability.

Analytical support to emergency planning and response operations

Wildfire behaviour models have demonstrated their ability to capture extreme fire dynamics in wind-driven events and thus support emergency management. Yet the intricate interactions between wildfires and the atmosphere can lead to inaccuracies in estimating the rate of spread due to a lack of consideration for fire-induced local meteorology. To mitigate these challenges, **coupled atmosphere-fire models** need to be developed and applied to deepen the understanding of fire spread across diverse landscapes. These models should address the uncertainties inherent in pyro-convection related phenomena so that information is provided to stakeholders, particularly in anticipating extreme wildfire behaviour. Examples of such models are depicted in the box below.

Wildfire behaviour models coupled with atmospheric models simulate the fire line progress, smoke concentration at the ground and development of pyro-convection materialized as high-altitude smoke (yellow).

Vie Source: Jean-Baptiste Filippi


The interaction between the fire and its surrounding flow induces oscillations in the rate of spread of the head fire, that are associated to large accelerations and decelerations of the fire.

Source: Viegas et al. (2021)[57]

*Box 5: Emergency Management and Response Operations: Innovations and insights from FIRE-RES and FirEUrisk*

While there has been leaps and bounds of progress being made in the use of Artificial Intelligence (AI) for wildfire behaviour models, processes driving to pyro-convective behaviour is not yet modelled and the representation of such behaviour should transition from 2D maps to 3D **digital elevation models (DEMs)** including atmospheric layers to model relevant processes (e.g., changing conditions of the Atmospheric Boundary Layer) and parameters (e.g., atmospheric vertical profile)[58]. The DEMs provide critical topographic data that enhances analytical support for emergency planning and response. DEMs can accurately represent

[56] Busquets, E. et al. (2024): FIRE RES D2.2 Scheduling and implementing novel management practices, 189 p. https://doi.org/10.5281/zenodo.14245905.

[57] Viegas et al. (2021): On the non-monotonic behaviour of fire spread, *International Journal of Wildland Fire* 30(9) 702-719 https://doi.org/10.1071/WF21016 (01.04.2025)

[58] Castellnou et al. (2024): Testing key inputs for atmospheric data analysis using new knowledge and expertise on EWE. Deliverable D1.4 FIRE-RES project. 66 pages. DOI: 10.5281/zenodo.11385129 or Castellnou et al. (2022): Pyroconvection classification based on atmospheric vertical profiling correlation with extreme fire spread observations. Journal of Geophysical Research: Atmospheres, 127(22), e2022JD036920.

terrain elevations and enable detailed risk assessments for wildfire spread forecasting[59]. In emergency scenarios, DEMs support the identification of safe evacuation routes, optimal placement of emergency infrastructure, and prediction of hazard impact zones. Their integration with GIS and real-time sensor data improves situational awareness, decision-making, and the coordination of rapid response operations.

The representation of fire behaviour on 3D maps will further enhance the quality of the **firefighter training using immersive technologies** such as AR/VR, which has been developed and tested in FIRE-RES, SILVANUS and TREEADS projects. The training modules allow first responders, forest managers, and civil protection units to engage in geographically accurate simulations. These include terrain-informed fire propagation scenarios, optimized evacuation route planning, and deployment of ground and aerial firefighting resources. The use of remote sensing-collected data ensures up-to-date, site-specific modelling for pilot areas, enhancing both spatial awareness and the adaptability of emergency operations under realistic conditions. This approach supports improved preparedness, coordinated response, and more effective mitigation strategies in topographically complex and high-risk environments.

In the context of **smoke spread prediction** from forest fires, traditional methods often fall short due to their reliance on high-resolution weather models that inadequately account for active fire behaviour. This disconnect can lead to inaccurate forecasts, especially during critical fire events, when understanding smoke movement and concentration is vital for firefighters and public safety[60]. To address this, the integration of coupled fire-atmosphere models along with local weather forecasts, simulating both fire and smoke dynamics and a comprehensive range of atmospheric processes, should be prioritised. Recent improvements in weather forecasting techniques, characterized by enhanced spatial resolution and reduced computation times, facilitate the **routine application of these coupled models**, enabling real-time updates on atmospheric conditions and fire behaviour, thus enhancing the accuracy and reliability of smoke predictions. By incorporating these integrated approaches into forecasting systems, emergency management can be significantly improved and contribute to adaptive risk management, informed decision-making, and the development of effective mitigation strategies taking climate and socio-economic changes into account.

In addition to this, emergency responders require **training in decision-support tools a**nd advanced technologies to enhance their ability to manage complex emergencies. We thus recommend a unified application integrating real-time data to ensure informed and timely decision-making especially when facing extreme fires and fires at the WUI.[61]

Advancing response operations through mutual learning and enhancing interoperability

In terms of advancing response operations, **international training** should be designed to strengthen firefighters' capacity to apply beneficial fire strategies, such as backfires and managed burns, to reduce fuel availability during emergencies. Well-documented fire management experiences[62] are key for the scientific assessment of the medium- and long-term effects of Integrated Fire Management on ecosystem services. They

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[59] For example, Mangiameli, Mussumeci & Cappello (2021): Forest Fire Spreading Using Free and Open-Source GIS Technologies. Geomatics. 2021; 1(1):50-64. https://doi.org/10.3390/geomatics1010005.

[60] Lioliopoulos et al. (2024): Integrated Portable and Stationary Health Impact-Monitoring System for Firefighters, in: Sensors, 24(7):2273, https://doi.org/10.3390/s24072273; Lioliopoulos et al. (2024): "Real-Time Monitoring of Wildfire Pollutants for Health Impact Assessment," IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium, Athens, Greece, 2024, pp. 2373-2378, doi: 10.1109/IGARSS53475.2024.10641771; CSIC (2025): Improved evacuation/confinement protocols based on informative air pollution thresholds, air quality data and smoke propagation models. Deliverable 4.11, FIRE-RES, In preparation.

[61] Lahaye et al. (2024): Handbook with guidelines for fire fighters to face to extreme fires, fires in WUI and fires in high latitudes/ altitudes, Deliverable 2.6, FirEUrisk project, D2.6-Handbook-with-guidelines-Final-approved_EN.pdf (02.04.2025) and Reis, V. et al. (2024): IA 5.8 brief: Using innovative tools for training schools certificate EW ICS training programs. Deliverable 5.11 FIRE-RES project. 53 pages. https://doi.org/10.5281/zenodo.14193576.

[62] Such as described by Nebot, E. et al. (2024): Integrated fire management model: demonstration, training and piloting activities, including new-fire prone areas. FIRE-RES Deliverable D1.9. https://doi.org/10.5281/zenodo.11950636.

are influential too for the effectiveness of demonstration and training of appropriate Integrated Fire Management techniques and strategies.

By combining technology-driven analysis with fire management, training may enhance wildfire response efficiency across Europe, supporting more adaptive operational responses and helping to reduce risks for firefighters and communities, particularly in the case of fires at the wildland urban interface. Building from experience in the management of large wildfires is thereby an important source of knowledge exchange. The reports on the large wildfires that occurred in Europe in 2021 and 2022 that were produced by FirEUrisk and edited by JRC are good examples of such studies[63]. The documentation of large fires or accidents should be mandatory, following, for example, the guidelines proposed by FirEurisk[64].

Wildfire response frequently involves cooperation between responders and other stakeholders from numerous countries. It is important to improve the **interoperability** between the agencies involved as provided by the EU civil protection mechanism (UCPM). This may be achieved by **thematic workshops on operational practices** with a regional anchorage and yet also involving experts from different countries (e.g., fire-prone and "fire-emergent" countries). We recommend further homogenisation between bodies to facilitate cooperation including aspects such as operational, technical, communications, legal and policy, training and procedural, resource, and cultural interoperability. By sharing knowledge on host nation logistics, wildfires planning and operational practices at intermediary management level, cross-European exchanges may increase mutual trust and efficiency in operation. Box No. 5 shows the implementation of an Incident Commander Training Course with a range of representatives from different European countries and the training of fire Commanders on extreme fires at the Fire Research Laboratory, in Portugal.

Impression from an Incident Commander training course aiming to enhance interoperability in case of cross-country deployment. The picture shows an initial briefing from the Incident Commander.

Source: Escola Nacional de Bombeiros

Training session on extreme fire behaviour and fire safety for fire commanders and fire officers at the Forest Fire Research Laboratory, Lousã, Portugal.

Source: ADAI.

*Box 6: Innovative Incident Commander Training*

Finally, a legislative framework such as a Directive could have an impact on occupational safety, the status of volunteers, or aerial fight standards.

[63] Almeida et al. (2024): Report on the large wildfires of 2022 in Europe, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/19760, JRC138859.
Almeida et al. (2023): Analysis of 2021 critical wildfire events in the Mediterranean region, Publications Office of the European Union, Luxembourg, 2023, https://doi.org/10.2760/562495, JRC133972.

[64] FirEUrisk D2.7 - Report analysing destructive fires with a protocol to collect feedback from next fires and the reports on large fires "Analysis of 2021 critical wildfire events in the Mediterranean region" and " the large wildfires of 2022 in Europe".

## 3.3 Stakeholder engagement and public communication

In IWRM, **stakeholder engagement** refers to a two-way interaction between autonomous actors who collaborate in the performance of their functions. It is a practice grounded in negotiation and cooperation between organizations or individuals possessing varying levels of access to authority[65], responsibilities[66], values[67],information, services, or goods[68]. The definition of stakeholders[69] in IWRM encompasses a broad range of actors. In the private sector it includes forestry and land development companies, landowners, critical infrastructure operators, and business whose operations and assets are subjected, or contribute to, wildfire risk. In the public sector it refers to organisations with formal wildfire management responsibilities – such as fire brigades, civil protection agencies, and emergency rescue services – and those with indirect but significant connections to wildfire risk, such as infrastructure managers, service providers, and local or regional authorities. Stakeholders in civil society include, for example, volunteer groups, landowners, and community and hunters' associations. Citizens acting in their individual capacity, rather than through organizations, can also be recognised as stakeholders.

Stakeholder engagement contributes to all phases across the IWRM cycle. In risk assessment, it enables professionals and systems to anticipate changes by improving access to scientific, technical, and cultural knowledge and data sources and supports risk evaluation analysis aligned with local values and landscape management practices.[70] It improves coordination, policy coherence and the harmonisation of standards between actors operating in different jurisdictions, governance levels, sectors, and areas of expertise.[71] In response, it promotes risk awareness, leading to behavioural changes, ownership of solutions, proactive self-organisation, and efficient decision-making. The long-term results of these approaches support the creation of systems that manage risk more efficiently and are better prepared to interact and exchange data with response systems during emergencies[72].

**Systemic communication** refers to the strategies for sharing data, information, and knowledge that support stakeholder coordination in IWRM. Typically conducted through targeted campaigns, it fosters a shared understanding of hazards and responsibilities among key actors while increasing awareness of risks. It also enhances the response capacity of fire management systems by encouraging citizen engagement and promoting shared ownership of risk mitigation processes. Several projects have developed tools to communicate risk.[73] To ensure effectiveness, communication efforts should be systematically measured and

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[65] Provan, K. G., & Kenis, P. (2007). Modes of Network Governance: Structure, Management, and Effectiveness. *Journal of Public Administration Research and Theory*, *18*(2), 229–252. https://doi.org/10.1093/jopart/mum015

[66] Steelman, T., & Nowell, B. (2019). Evidence of effectiveness in the Cohesive Strategy: Measuring and improving wildfire response. *International Journal of Wildland Fire*, *28*(4), 267–274. https://doi.org/10.1071/WF18136

[67] Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press. https://doi.org/10.1017/CBO9780511807763.

[68] Sandström, A., & Carlsson, L. (2008). The Performance of Policy Networks: The Relation between Network Structure and Network Performance. *Policy Studies Journal*, *36*(4), 497–524. https://doi.org/10.1111/j.1541-0072.2008.00281.x.

[69] Stakeholders are defined as "a collection of people sharing a [...] relationship to the outcome of an environmental-management decision" Reed, J., Ickowitz, A., Chervier, C., Djoudi, H., Moombe, K., Ros-Tonen, M., Yanou, M., Yuliani, L., & Sunderland, T. (2020). Integrated landscape approaches in the tropics: A brief stock-take. *Land Use Policy*, *99*, 104822. https://doi.org/10.1016/j.landusepol.2020.104822.

[70] Clement, S., Garmestani, A., Beckwith, J. A., & Cannon, P. (2024). To burn or not to burn: Governance of wildfires in Australia. *Ecology and Society*, *29*(1), art8. https://doi.org/10.5751/ES-14801-290108.

[71] Kirschner, J., Clark, J., & Boustras, G. (2023). Governing wildfires: Toward a systematic analytical framework. *Ecology and Society*, *28*(2), art6. https://doi.org/10.5751/ES-13920-280206.

[72] Vallim, D., Giannakopoulou, A., Schmidt, A., Altsitsiadis, E., Froes, I., Drews, M., Siganos, M., Lekka, Z., Lucceri, D., & Zecca, G. (2024). *TREEADS Report on Organizational Structural and Sociotechnical factors V2* (2; p. 163). European Comission. https://treeads-project.eu/wp-content/uploads/2024/01/D3.2-v2.pdf.

[73] For example, FirEUrisk mobile app described in D1.3 https://fireurisk.eu/wp-content/uploads/2024/05/FirEUrisk_-D1.3-%E2%80%93-FirEUrisk-mobile-app_v1.pdf.

evaluated based on feedback from local actors and observed changes at the landscape level. A clear understanding of communication objectives is essential for guiding these evaluation efforts and maximising their impact.

The **recent findings** from EU-funded fire projects provide relevant references on how to improve IWRM through stakeholder engagement and public communication. In TREEADS, stakeholder engagement has guided the development of the TREEADS WebGIS described in Box 7 below. The engagement between universities, developers, and local and regional government led to the creation of two service modules. The first provides services for the fire season through forecasting and detection. The second module supports services performed outside of the fire season, such as in depth-risk analysis and detailed forest mapping. The projects also developed solutions to engage citizens and key partners into decision making in prevention and restoration through collective mapping exercises that tap into local knowledge about landscape dynamics.

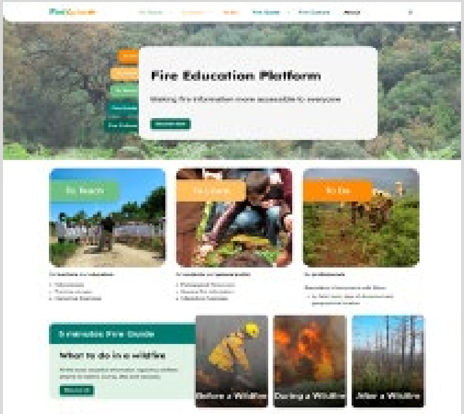


*Figure 13: FIRE-RES Fire Education Platform*

The FireExplorer information platform is organized into different sections according to the target public, making fire information accessible to everyone. The section "to teach" provides content to - educators; the section "to do" is aimed at professionals; the section "to learn" is aimed at students and people that want to learn more.

Engagement with local and regional governments has guided the development of the TREEADS WebGIS into two complementing modules. The first supports management during fire season through **fire daily forecasting, early warning system, fire simulation models, and social media analysis.** The second module provides off-season support, offering advanced risk analysis and detailed **forest mapping**. Grounding the interface design in local dynamics and processes enhanced the local governments' ability to manage wildfire risk by prioritizing areas and planning risk activities across different seasons.[74]

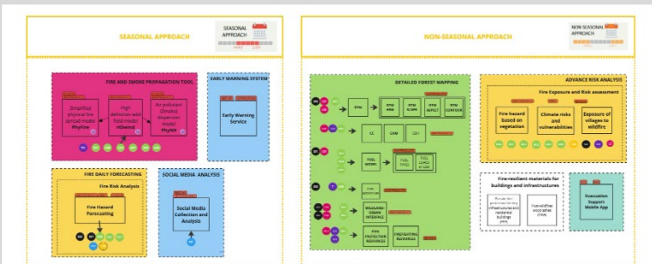

*Figure 14: TREEADS WebGIS*

*Figure 15 Stakeholder engagement in Sardinia.*

Stakeholder engagement on the use of prescribed fire in Suni, Sardinia (FirEUrisk)

*Box 7: Innovation in Stakeholder engagement from TREEADS and FIRE-RES projects*

[74] USAL et al, 2024

The FIRE-RES project developed FireExplorer, that addresses stakeholder engagement and citizen awareness by improving communication and make fire information easier to understand and accessible to everyone. The goal of the platform is that society is more educated about wildfires and becomes more prepared to face extreme wildfires by having more knowledge about how to create resilient landscapes and reconnect and recognize the fire's cultural heritage. In SILVANUS, a citizen engagement video course had been produced for raising awareness among the young people and audience. Similarly, social media campaigns were produced and launched to enhance citizen awareness on the impact of wildfire[75]. Likewise, applications for engaging citizens in all phases of IWRM, e.g. for biodiversity mapping[76] were developed. In FIRE-RES, training for journalists were organised in different regions to increase their awareness on wildfire issues and their acquaintance with available data and resources, boosting new quality reporting on the topic [77]. Also, in FIRE-RES, a campaign addressed to the wider public was launched to extend the wildfire risk awareness, perception and knowledge [78].

Overall, it needs to be stressed that the suite of developed tools for prevention, preparedness, response and recovery including decision support systems, digital forest twins, or applications bring together stakeholders and data and hence carry great potential to add value for stakeholder collaboration and communication beyond their intended direct impact.

## 3.4 Integrated Wildfire Risk Management Governance

Governance refers to the actions, processes, traditions and institutions by which authority is exercised, and decisions are taken and implemented. Risk governance applies the principles of good governance to the identification, assessment, management and communication of risks. It includes aspects such as the understanding of hazards and their consequences, the contribution of science to risk-related policymaking, or the understanding of societal, environmental and economic values at risk. [79] A European Strategy on Integrated Wildfire Risk Management should focus on the operationalisation of multi-stakeholder approaches, the development of monitoring frameworks as well as the scaling of science and technology. At European level, the creation of an inter-agency body and the establishment of a governance and respective legal framework (e.g. a Directive) is recommended.

### 3.4.1 Operationalising multi-stakeholder engagement and good governance mechanisms

Effective wildfire risk governance requires the involvement of the citizens, the collaboration among various stakeholders, including government agencies, local communities, non-profit organisations, and the private sector. Recent research has thereby detailed, that core aspects in integrating stakeholders and creating effective governance mechanisms, are the consideration of justice aspects along the risk management cycle as well as policy coherence across the different relevant policy fields. The dedicated **analyses of justice aspects** relate to the distribution of risk, the representation of stakeholders and risk management and the impacts of compensatory measures may help to develop an integrated understanding of the envisaged governance mechanism and the implications of strategies.[80] **Policy coherence** addresses the streamlining of IWRM

[75] https://www.youtube.com/@silvanusproject4671/videos
[76] Biodiversity Profile Mobile App | SILVANUS
[77] OBCT (2025). FIRE-RES Deliverable 7.4. Training package on EWE for journalists (in preparation)
[78] https://www.europeandatajournalism.eu/wildfires-in-europe/
[79] IRGC (2019): What do we mean by 'Risk Governance'? - IRGC (05.03.2025).
[80] Schinko, T., Berchtold, C., Handmer, J. et al. A framework for considering justice aspects in integrated wildfire risk management. Nat. Clim. Chang. 13, 788–795 (2023). https://doi.org/10.1038/s41558-023-01726-0

concerns in a range of policies towards an ‘all policies’ fire-smart governance framework [81]. These encompass for example[82]:

- Enhancing the wildfire protection function of land management
- Reinforcing fire ecology in biodiversity and ecosystem restoration
- Wildfire-proofing landscapes
- Embedding fire-smart benefits into the ‘one-health’ approach
- Reinforcing civil protection capabilities
- Anticipating environmental and liability conflicts

### 3.4.2 Developing and implementing monitoring frameworks

The use of **qualitative or quantitative targets** in governance processes is an established tool that is applied in a range of international mechanisms such as the Sustainable Development Goals or the Sendai Framework. Setting targets and monitoring frameworks in disaster risk management (DRM) helps guide policies, resource allocation, and community engagement. It is hence important that all IWRM activities are performed in a transparent and documented way, and that monitoring and evaluation mechanisms are in place at both national and EU levels. Such indicators would help measure the effectiveness of governance structures, coordination mechanisms, and stakeholder engagement efforts.

Potential **performance indicators** include the assessment of effectiveness of risk reduction measures, human caused ignitions and reduction in losses and burned area, response time, preparedness levels, cross-border collaboration, community resilience, and technological integration. Respective Key Performance Indicators (KPIs) can form a crucial part of a European Risk Governance Framework, providing a standardised means of assessing and comparing wildfire management effectiveness across different member states and at the EU level. This allows for the **identification of good practices** and areas needing improvement, fostering a culture of progressive and continuous enhancement in EU-wide wildfire risk governance. Starting points for the development of KPIs may be the impact assessment methodologies developed by the Green Deal projects which again have been synthesised and assessed with respect to their assumptions and advantages.[83] The Green Deal Wildfire Project call identified seven ambitious and relevant targets to be achieved by 2030 in the management of wildfires in Europe. Some of the targets have proven controversial while initial reflections about potential definitions and reference data to assess their implementation have been specified[84].

Overall, more robust methodologies to acquire and share data necessary to **evaluate the effectiveness of wildfire policies and governance structures** across different EU member states is needed, including comprehensive economic impact assessments of wildfires and cost-benefit analyses of various prevention and mitigation strategies to inform policy decisions. Such analyses can provide valuable insights into the most effective allocation of resources and the long-term economic benefits of investing in wildfire prevention and management. A major challenge that remains to be addressed is the **assessment** and **monitoring *avoided* losses** and the contribution of fire-smart land planning in risk reduction from burnt area to health aspects that could reason the funding of risk reduction measures at the present from an economic perspective. However, data to develop such methodologies is lacking, even though developments in economic evaluation of

[81] EFI (2025). FIRE-RES Deliverable 4.6 Report on Policy clinics (in preparation).

[82] Plana E, Serra M, Smeenk A, Regos A, Berchtold C, Huertas M, Fuentes L, Trasobares A, Vinders JN, Colaço C, et al. Framing Coherence Across EU Policies Towards Integrated Wildfire Risk Management and Nature-Based Solutions. Fire. 2024; 7(11):415. https://doi.org/10.3390/fire7110415.

[83] E.g. Pettinari et al. (2023): Firelogue D3.2 Baseline Assessment Report, available via: Firelogue D3.2 Baseline Assessment Report.pdf or Kaskara et al. (2024): Firelogue D3.4 Impact Assessment Methodology Harmonisation II, available via: Firelogue D3.4 Impact Assessment Methodology Harmonization II.pdf.

[84] Petersen et al. (2024): Green Deal Wildfire Risk Management Targets Contextualising the expected Green Deal call “Preventing and fighting extreme wildfires with the integration and demonstration of innovative means” targets and suggesting first steps for the way forward; Communication to the EC, Journal Article Submitted.

ecosystem services potentially affected by fires could facilitate a trade-off between investments and benefits[85]. Depending on each countries' fire management organisation, some data is less complete or not available. A common effort to gather and update data such as damage assessment, insurance coverage, health impact, operational costs, should be made in each country and at the EU level.

Finally, it needs to be stressed that targets must be well reflected upon to avoid conflicting effects between them or long-term counter effects. For example, an initial attack success may perceivably be understood as a measure of good performance but depends on long-term effects of climate change on vegetation growth to contribute to fuel build-up in seasonally dry climates, whereas vegetation changes keep being influenced by climate in temperate and boreal climates, even though burned area increases under climate change[86]. The consideration of different dimensions of justice is therefore crucial.

### 3.4.3 Leveraging Integrated Wildfire Risk Management using science and technology

IWRM governance approaches and the monitoring of KPIs can be facilitated by science and technology. Leveraging technology such as satellite monitoring and predictive modelling including advances in the understanding on the fire-atmosphere interaction along with the use of AI data services can improve early warning systems and inform resource allocation during wildfire events [87]. The use of air quality monitoring devices can measure the health of the firefighters and citizens while dynamic fire spread data and models can be used to identify safe evacuation zones for the safety of the citizens [88]. Overall, examples of **wildfire applications** include advances in remote sensing technologies (satellite imagery, as well as drone applications), predictive modelling, sensors monitoring environmental conditions and ignitions in real time, or virtual reality solutions, e.g. for training responders and public education. It is thereby important to acknowledge, that the adoption of **decision-support tools** can also facilitate the collaboration between stakeholders and enhance the sharing of data – despite the functional advances the offer.

Artificial intelligence is playing an increasing role and recent studies have shown promising results in the use of deep learning algorithms for wildfire detection and spread prediction. As tested and validated in the field, AI applications may enhance prevention and response efforts through various methods. Predictive analytics utilises historical data to forecast fire occurrences, while image recognition using remote sensing imagery and IoT devices aid in detecting early signs of wildfires [89]. Current operational systems, such as NASA-FIRMS[90] for detecting fires in real-time should be extended, improving temporal resolution. Meteosat Third Generation sensors could be a sound alternative soon. Risk assessment systems would help to prioritise high-risk areas for better resource allocation, and decision support systems help develop fire suppression strategies by simulating scenarios. The use of AI for fire and smoke spread could assist in the determination of the placement of resources (such as fire suppression tools) by creating a projected fire front. Automated reporting improves communication with emergency responders and the public. A systematic application of AI by the EU and its Member States could significantly enhance the EU's capacity to respond to wildfire threats proactively.

[85] FirEurisk D1.4 on socio-economic vulnerability assessment: https://fireurisk.eu/wp-content/uploads/2024/05/D1.4_FirEUrisk_ReportMethodologicalFrameworksVulnerability_V1.pdf

[86] Billing et al. (2023): Simulated fire and vegetation dynamics at three spatial scales, FirEUrisk D3.4, available via: https://fireurisk.eu/wp-content/uploads/2024/05/FirEUrisk_D3.4-v1.0.pdf (02.04.2025).

[87] Baggio, R. Filippi J.B. (2024). Modelling the EWE and smoke spread based on coupled fire-atmosphere approaches. Deliverable 5.3 FIRE-RES project. DOI: 10.5281/zenodo.14187388

[88] Gili, J.; Karanasiou, Angeliki; Viana, Mar. (2025). Improved evacuation/confinement protocols based on informative air pollution thresholds, air quality data and smoke propagation models. Deliverable 4.11 FIRE-RES project. 8 pages. DOI: 10.5281/zenodo.15096997

[89] Souto-Lorenzo, O. et al. (2024) Results and recommendations from a HAPS fleet simulation confronted to real risk and fire events data at South European level. Deliverable 5.7 FIRE-RES project. 10.5281/zenodo.1418154

[90] https://firms.modaps.eosdis.nasa.gov/map/#d:24hrs;@0.0,0.0,3.0z

### 3.4.4 Adaptive governance

IWRM approaches need to differentiate adaptation to climate change and different socio-economic futures as well as adaptive governance which we understand as those governance structures, that allow organisations to organise required changes with a specific focus on two ways, top-down and bottom-up initiatives. It is thereby important to stress that we use adaptive governance as a concept included in the LFGF. However, **transformative aspects** of governance and the need for more radical systems change as opposed to minor, marginal, or incremental change is likely needed and needs to be explored further.[91]

The **DG ECHO Peer Review process** and its regular assessments of national and EU-level governance performance may be applied to ensure that wildfire management systems evolve in response to emerging risks and technological advances. Given the significant impact of climate change on wildfire patterns, the framework emphasises the development of more sophisticated climate and socio-economic change scenario analyses to inform long-term wildfire risk governance strategies and adaptation measures. These analyses should incorporate the latest climate [92], vegetation and management models[93] as well as socio-economic indicators such as population density and land-use changes to provide actionable insights, considering multiple future scenarios to ensure adaptable governance frameworks[94].

To facilitate adaptive management across the EU, the availability of a sound data basis of current and future wildfire risk is crucial (see also section 2.1). The upgrade of the European Forest Fire Information System (**EFFIS**) or its complementation with a continuously maintained and **updated data hub** to integrate the respective data sets, solutions and technologies developed in the research projects will hence be an important step. This may include an improved capability to provide real-time data and predictive analytics. For instance, integrating high-resolution satellite imaging, advanced IoT sensors, and AI-driven analytics could significantly enhance data accuracy and timeliness. **Data interoperability** is thereby crucial for creating a unified European wildfire information system supporting real-time decision-making and resource allocation.

To support this **technological integration**, it is recommended developing standardised data formats and protocols to ensure seamless integration of various data sources (satellite, ground sensors, weather stations) across different EU member states. Drawing on existing standardisation efforts such as the INSPIRE Directive[95] could provide a model for achieving interoperability. However, challenges such as data quality issues, computational costs, and the need for skilled personnel must be addressed, to ensure effective implementation.

## 4 Research and knowledge needs and gaps

In the wildfire risk management community, several remaining gaps are recognised as being needed to be addressed to enhance wildfire risk management. One key area is the enhancement of guiding frameworks, which could take the form of **legal frameworks** such as a Wildfire Risk Directive or voluntary **guidelines** covering all aspects of wildfire risk management. Relevant topics that have been identified are, for example, the development of guidelines for the implementation of fuel treatment measures in protected areas, the

[91] Korhonen-Kurki et al. (2025), Transformative governance: Exploring theory of change and the role of the law, in: Earth System Governance, 23, https://doi.org/10.1016/j.esg.2024.100230 (07.04.2024).

[92] Moghli, A., Karali, A., Varotsos, K.V., Giannakopoulos, C., Brotons, L., Duane, A. (2023). Adapted long-term climate change projections and seasonal forecasts. Deliverable D1.5 FIRE-RES project. 90 pages. DOI: 10.5281/zenodo.10211205

[93] ISA (2025). Optimizing landscape configuration and fire management policies to minimize expected losses from EWE. Deliverable 2.5 FIRE-RES project (in preparation and FirEUrisk D3.2 On Continental Climate and Land Use Scenarios (https://fireurisk.eu/wp-content/uploads/2024/05/FIREURISK-D3.2_Continental-LUC-Scenarios_v1.0.pdf)

[94] Billing et al. (2023): Simulated fire and vegetation dynamics at three spatial scales, FirEUrisk D3.4, available via: https://fireurisk.eu/wp-content/uploads/2024/05/FirEUrisk_D3.4-v1.0.pdf (02.04.2025).

[95] Infrastructure for Spatial Information in the European Community (Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)).

application of decision support systems, or the use of AI and machine learning for continuously updated data on different components of disaster risk.

Many innovative solutions are available now. The next crucial step is their widespread application. To facilitate this process, **accelerator mechanisms** are necessary to support the implementation of these solutions, provide training, develop guidelines, and promote the exchange of knowledge. This includes the allocation of resources for adoption needs of developed solutions, financing for technology readiness levels (TRL) 7-9, and other readiness level types (e.g., legal, organisation, user, society etc.) depending on local and national contexts. Such efforts require the **establishment of dedicated funds and knowledge exchange initiatives among peers** from different countries and solution developers, as well as dedicated training formats that consider the application of innovations derived from scientific programs.

Additionally, the development of **Key Performance Indicators (KPIs) and impact assessment frameworks** is essential for determining the cost-effectiveness of various actions in wildfire risk management. Identifying leverage points for systemic change is another critical aspect; this includes **adapting the insurance landscape to better manage wildfire risks** and creating regulatory frameworks that promote greener and more sustainable investments.

Furthermore, there is a need for better **synchronisation of programs** such as Horizon Europe, including Research and Innovation Actions (RIAs), Innovation Actions (IAs), and Marie Skłodowska-Curie Actions (MSCA), with topical project funds from entities like DG ECHO and DG REFORM, as well as consultancy services. In parallel, Public-Private Partnerships (PPPs) should contribute to finance the transition towards resilient landscapes and safer communities. Pursuing this goal, a strategic approach to attract private sector investment while ensuring public interest and long-term sustainability is desired.

While it is not feasible to detail all existing knowledge gaps within the body of knowledge and technical resources needed to address wildfire risks effectively, some specific examples can be highlighted. These include the **management of extreme fires** and their interaction with the higher layers of the atmosphere, understanding fire propagation dynamics, frameworks for assessing landscape resiliency that may integrate relevant spatial and temporal scales, and the design and scaling of incentives for different stakeholder groups. The **pairing of** Geo-Information Systems **(GIS)** with remote sensing, ground sensors, climate or vegetation models, fire behaviour systems and the wider application of **digital elevation models** (DEMs) to map natural resources, resource allocation for response operations, evacuation routes, or air quality maps need to be explored further. Similarly, the **continuous and automated mapping of landscapes to monitor the effects of risk management measures** will require more research. Furthermore, the analysis of **fuel management practices for its climate resilience and safeguarding biodiversity** while reducing wildfire risk requires more interdisciplinary research.

**A strategic fire management plan** is required to expand prescribed burns to reduce fuel loads, enhance wildfire suppression through controlled burns, and invest in training programs to build expertise in fire use among emergency bodies and specialised forest management companies. Engaging communities, implementing supportive policies, and fostering knowledge-sharing among stakeholders will ensure responsible fire management. By continuously adapting strategies based on ecological monitoring and climate trends, fire can be effectively used as a tool to reduce wildfire risks, restore ecosystems, and build long-term resilience.

To test the robustness of such strategies, integrated climate and land-use projection systems in connection with fire-enabled dynamic vegetation models are needed to assess if the anticipated adaptation goal can be achieved under climate change conditions. The design of fire-safe and climate-resilient landscapes needs to be tested, because vegetation, land-use and fire change simultaneously and interact. Such modelling systems allows to assess the robustness of fuel management scenarios under climate change conditions by taking an ecosystem perspective. In a sustainable future scenario the anticipated wildfire risk reduction can be achieved, while nutrient, water and carbon cycling is maintained and forests and open woodlands continue to provide ecosystem services and continue to be a biodiverse habitat[96].

# 5 Conclusion

The mitigation of impacts associated to wildfires in Europe necessitates a collaborative and integrated approach to wildfire risk management that may also address the increasing frequency of extreme events. This proposal for an Integrated Wildfire Risk Management Strategy for Resilient Landscapes and Safer Communities emphasises the importance of stakeholder engagement, adaptive governance, and the application of innovative solutions and scientific research. Concrete measures and next steps that should be considered in a European Strategy are:

## 5.1 Risk Assessment and Evaluation

- **Develop (binding) guidelines for risk assessments** including the consideration of all factors relevant for fire ignition-propagation, but also for fire exposure and vulnerability. Model future fire risk conditions by coupling climate and socio-economic scenarios such as the ones proposed in the scope of FirEUrisk project. European vegetation maps along with fuel parameters have been developed by FirEUrisk and FIRE-RES as depicted in Section 2.1 and could be applied in such guidelines. This also needs to include guiding documents for the definition of risk tolerance levels together with all relevant stakeholders and the promotion of fuel treatment activities such as prescribed burning.
- **Promote the application of innovative data and technologies** at multiple scales, e.g. through extensive of the Copernicus services and other aerial and ground sensors, strengthening the connection with data hubs and AI systems. This effort needs to include the allocation of resources for maintaining and updating the developed data sets.
- **Enhancement of Data and Technology Integration**: Invest in upgrading EFFIS to include real-time data analytics and predictive modelling, integrating other risk variables such as exposure and vulnerability, facilitating more harmonised prospective risk assessments as well as enhanced decision-making during wildfire events.

## 5.2 Risk management and adaptive planning

- **Guideline Development**: Formulate and disseminate clear and actionable guidelines for wildfire risk management practices, including recommendations for land use planning, building codes, and community preparedness as proposed in Section 2.3. These guidelines should be informed by good practices and evidence-based research, ensuring their relevance across different regional contexts.
- **Development of financial mechanisms to support the development of resilient landscapes and safer communities:** Invest in approaches that may provide incentives to diversify landscape mosaics and attract payments for public goods provided by rural landscapes.
- **Strengthening of strategies to promote joint adaptive landscape-level management planning:** Invest in tools that may integrate ecological and socio-economic data, vegetation and fire dynamics under climate change scenarios, stakeholders' preferences and decision support while facilitating negotiation and consensus building.
- **Development and implementation of integrative systems to support decision-making by responders:** Invest on technologies able to integrate real time high-resolution data (e.g., fuel conditions, weather data, Digital Elevantion Models (DEMs)) to provide key parameters for an effective and in-time decision making of responders
- **Support international exchanges of responders:** It is important to improve the interoperability between the agencies involved as provided by the EU civil protection mechanism (UCPM). This may be achieved by thematic workshops on operational practices.

[96] Neidermeier et al. (2024). Identification of effective adaptation measures. FirEUrisk Deliverable D3.7 (08.05.2025).

- **Invest in peer learning and training programmes for all stakeholders**: facilitate the exchange for all stakeholders including land-use planners, landscape managers, and community organisations to name just a few.

## 5.3 Stakeholder Engagement

- **Establishment of comprehensive stakeholder engagement capacity development programme across Member States**: The programme should harmonise stakeholder engagement approaches and prioritise local and regional authorities in developing competencies for collaboration and leadership across governance levels. Special attention should be given to local organisations including municipal governments, fire brigades, local NGOs, volunteer, hunter and citizen organisations groups, as their contextual knowledge enhances the objectives of the Union Civil Protection Mechanism.
- **Development of continuous, region-specific, audience-specific communication campaigns to enhance IWRM awareness:** The campaigns should leverage different media channels to deliver clear messages on IWRM roles, warning mechanisms, and good practices for managing wildfire risk in high-risk activities such as tourism with a very high amount of individuals not familiar with language and local geographies and risks. When possible, they should be designed, implemented and evaluated in close collaboration with target groups' representatives and complement risk and environmental education on IWRM and be complemented with the suite of technologies such as applications for engaging citizens and issuing warning.
- **Implementation of the European network on Wildfire risk and education**: This network would allow schools and educators to increase their knowledge and skills, promoting local activities like co-creation of educational programs. Co-creating the knowledge and the tools among with local actors generates ownership, contributing for them to be also part of the solution.
- **Development of Stakeholder Engagement Programs**: Initiate comprehensive capacity-building programmes for local and regional authorities to enhance their skills with a particular focus on stakeholder engagement and wildfire risk management and to facilitate peer learning. Following the learnings of the EU fire projects, it is also recommended to integrate the different local and regional dynamics into an EU level stakeholder pool.
- **Conceptualise and operationalise** decision support systems (DSS) as a strategy to integrate stakeholder inputs and data. Design DSS architectures to support collective use and ensure compatibility with legacy systems across all stages of the Disaster Risk Management (DRM) process.

## 5.4 Governance

- **Establishment of an Interagency Coordination Body**: Create an EU-level interagency to facilitate collaboration among various government agencies and stakeholders, ensuring cohesive wildfire management efforts.[97]
- **Implementation of a European Wildfire Management Directive**: Develop a European Wildfire Directive that requires the implementation of wildfire risk reduction measures, similar to the Flood Directive.
- **Monitoring and Evaluation Framework**: Establish Key Performance Indicators (KPIs) to assess the effectiveness of wildfire risk management strategies, ensuring transparency and accountability across member states.
- **Promotion of Innovative Practices**: Encourage the adoption of fire-smart land management practices that enhance community resilience against wildfires and scale the application of new technologies and

[97] For response operations, very good collaboration is already achieved for example in the context of the Emergency Response Coordination Centre (ERCC), operated by DG ECHO.

data sets including the application of AI. Specifically, joint efforts on harmonising data sets and machine learning are needed to allow for interfacing and comparability of results.

- **Invest in Research for Evidence-Based Policy**: To ensure informed, effective, and future-proof policies, continued support for high-quality research at multiple scales is needed. Continued scientific support enables preparedness of today's decision-making systems by ensuring they are science-based and fit for a climate-resilient future. More data and analysis are needed to address knowledge gaps, specifically with respect to avoided losses and the cost-effectiveness of measures.
- **Mainstream justice aspects** into IWRM policies and ensure **coherence** across sectoral **policies** with wildfire risk implications.