TREEADS

A Holistic Fire Management Ecosystem for Prevention, Detection and Restoration of Environmental Disasters

TREEADS D2.7 Restoration and Adaptation Understanding and Technical Requirement Report

Work package	WP2: Understanding the Lifecycle of Wildfires
Task	Task 2.5: Detection and Response Understanding and Technical Requirement
Authors	Universitat de Girona (UdG): Elena Puigdemasa Martí, Marina Palmero Iniesta and Pere Pons
Dissemination level	Confidential (CO)
Status	Final
Due date	24/11/2023
Document date	22/11/2023
Version number	2.0
	TREEADS project has received funding from the European Union's Horizon 2020 research & innovation programme under grant agreement No 101036926.

Revision and history chart

Version	Date	Main author	Summary of changes
0.1	05/05/2022	UdG	Draft outline
0.2	16/05/2022	UdG	Draft with synthesis from TL inputs
0.3	30/05/2022	UdG	Final draft with synthesis from TL inputs
1.1	09/05/2022	UdG	Revisions after submission (if required)
1.2	23/05/2022	UdG	Revisions after submission (if required)
1.3	26/05/2022	UdG	Revised submitted version
2.0	22/11/2023	UdG	Final version with corrections incorporated from external reviewers.

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GLOSSARY OF TERMS

Term	Description
Adaptation	Adaptation in ecosystem management involves strategies and processes that enhance the resilience of ecosystems, allowing them to persist and function effectively in the face of changing conditions.
Adaptative management	Adaptive management is an ongoing and flexible decision-making approach that acknowledges uncertainty and complexity. It involves iterative processes, regular monitoring, and stakeholder engagement to continuously learn from experience and adjust strategies (Rist et al., 2013).
Biodiversity refugia	An area in which a population of organisms can survive through a period of unfavourable conditions (Selwood 2020).
Ecosystem	A biotic complex or assemblage of species, an associated abiotic environment or complex, the interactions within and between those complexes, and a physical space in which they operate (IUCN, Bland et al., 2017).
Fire intensity	Fire intensity describes the physical combustion process of energy release from organic matter (Keeley 2009).
Fire severity	Fire severity defines the quantity of fuel and organic matter consumed aboveground (vegetation) and belowground (soil) during a fire (Keeley 2009).
Reforestation	Reforestation is the artificial or natural re-establishment of forest in an area that was previously under forest cover (OECD, 2001).
Rehabilitation	Rehabilitation in ecosystem management refers to repair or mitigate the immediate impacts of a disturbance and stabilize the ecosystem to prevent further degradation (Riley et al. 2015).
Resilience	The capacity of a system to recover from stress and disturbance while retaining its essential functions, structure, feedbacks and identity (Jones 2018).
Resprouting (resprouters)	Resprouting is defined as the initiation of new shoots, usually from existing plant meristems, following fire or other disturbances that affect the whole plant (Pausas et al., 2014). Resprouters are able to activate dormant vegetative buds to produce regrowth.
Restoration	Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER, 2002).

Seedling recruitment (seeders)	Recruitment of new plants from seeds surviving the fire, from resprout seed production, from surviving parent plants or from colonization (Keeley et al 2012).

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
FR	Functional requirements
ICT	Information and Communications Technology
LiDAR	Light Detection and Ranging
NFR	Non-functional requirements
RA	Restoration and Adaptation
RGB	Red, green, blue
VR	Virtual reality
WUI	Wildland-urban interface

EXECUTIVE SUMMARY

This document is the deliverable entitled "D2.7 Restoration and Adaptation Understanding and Technical Requirements Report" associated with *Task 2.5: Detection and Response Understanding and Technical Requirement* developed under the *WP2: Understanding the Lifecycle of Wildfires* of the TREEADS project.

This report provides valuable insights into fire ecology, post-fire management and its implications for ecosystems and society. Through an initial exploration of pilot technologies and their associated objectives, it pinpoints the functional and non-functional requirements necessary for the implementation of these technologies, both in the current context and the future scenarios. These insights will serve as a valuable resource for researchers, policymakers, and stakeholders involved in projects related to post-fire scenarios and environmental conservation.

INTRODUCTION

BACKGROUND

This document is centred in Task 2.5 Restoration and Adaptation Understanding and Technical Requirement. This task will try to understand and specify functional and not functional Requirements in the Restoration and Adaptation phase of wildfires.

PURPOSE AND SCOPE

The purpose of this task is to link environmental and technical partners to incorporate technological solutions in the current system and provide new techniques with the goal to assess, monitor, manage and restore burned wildland areas.

This document specifies functional and not functional requirements in the Restoration and Adaptation phase of wildfires. This document has been prepared with the inputs from each pilot coming via questionnaire prepared in WP2. It should be noted that this is a life document and, it is going to be updated as more information and data becomes available.

The current deliverable will focus on eight piloting countries: Norway, Italy, Romania, Spain, Austria, Germany, Greece and Taiwan. We provide, within this document, an analysis outlining the desired functional and non-functional end-user requirements focused on post-fire phase.

These requirements have been identified through the questionnaire and eight online workshops with the aforementioned countries, where feedback and ideas were collected and discussed. The feedback and the ideas generated here have been formulated as end-user requirements. These requirements will guide the technical partners in their efforts to develop the TREEADS holistic fire management platform for prevention, detection and restoration of environmental disasters.

Furthermore, this document aims to offer an easy-to-consult and basic knowledge to help managers and technicians to have an overview of post-fire assessment and management techniques and technologies can be used to adequately assess and manage burned areas.

THEORICAL FRAMEWORK

FIRE ECOLOGY

In an oxygen-rich atmosphere, accumulated organic biomass always has the potential to become fuel for a fire. So that, fire is an ancient and essential component of the Earth system and have shaped the evolution of plants, animals and biogeochemical processes in many terrestrial ecosystems as the coniferous forest in boreal and temperate regions, the deciduous temperate forests, the Mediterranean evergreen forests and shrublands, or the tropical savannahs (Lloret and Zedler 2009).

Aside from the negative impact of wildfires on human societies and the economic cost of prevention and extinction, from an environmental point of view, wildfires can be beneficial, detrimental, or neutral to the individual and communities depending on fire severity and the ecosystems' ability to cope with it (Cochrane and Ryan 2009). Fire may act as a selective force as many species have acquired adaptive mechanisms to persist and regenerate after recurrent fires (Lloret 2004). Fire can stimulate the germination of seeds because it promotes the breakdown of the external structures or because it acts as a signal to stimulate germination in new post-fire conditions. Fire may help to renew ecosystems and modulate the structure and configuration of our landscapes creating habitat diversity and heterogeneity. For example, without fire many forested communities become monocultures, shrublands become decadent or impenetrable thickets and grasslands become stagnant and are invaded by shrubs and trees (Wright and Bailey 1982). The ecosystems are adapted to the local and regional fire regimes which are closely related with primary productivity. Regions with intermediate levels of primary productivity, such as Mediterranean forests, burn at a high frequency (approximately 20-30 years) owing to abundant fuel, reliable dry seasons and ample natural and anthropogenic ignitions. In high-biomass boreal and temperate forests, the return time of fires varies between decade and century scales, and is largely controlled by extreme fire weather, ignitions and vegetation cycles (Bowman et al. 2020).

However, fire cannot be considered solely as a natural phenomenon and the current fire regime is largely determined by social factors. Firstly, the increase in anthropic ignitions has led to a general trend of increased numbers of fires and burned surfaces in Europe since the 60s (Pausas and Vallejo 1999). On the other hand, the high fire suppressing capacity in many countries has reduced wildfire frequency, causing an excessive accumulation of fuel in many areas now susceptible to burning with high intensity (Huston 2003). Additionally, the recovery of forest cover since the early 20th century due to farmland abandonment has favoured the forest continuity potentially increasing the propagation of large wildfires, especially in southern Europe (Brown 2007).

Simultaneously, current global warming (i.e. increase of periods with high temperatures and low relative humidity) is accelerating changes in wildfire regimes worldwide. These changes in the length of fire seasons and the frequency and/or intensity of wildfires and compromising the inherent resilience of ecosystems, especially those less adapted to new climatic conditions (Flannigan et al. 2009; Brotons et al. 2013; Williams et al. 2019). These trends on fire regime, together with global changes on the physical and biological environment, as well as management practices, will limit the resilience capacity and the regenerative response of ecosystems, which may cause dramatic changes in the structure and functioning of ecosystems. In the context of ongoing climatic warming, forest landscapes face increasing risk of conversion to non-forest vegetation through alteration of their fire regimes and their post-fire recovery dynamics. Therefore, it is fundamental to understand the vulnerability of land systems to fire in order to advise management and policy.

FIRE EFFECTS ON THE ECOSYSTEM

Wildfires constitute a natural ecological process that has shaped numerous ecosystems for millions of years, influencing the landscape and the composition and structure of plant and animal communities. Fire may have both positive and negative impacts, depending on the environmental characteristics when it happens and the regime of fire (Kotze 2013; Bowman et al. 2020; Jones and Tingley 2021).

On one hand, fire fosters ecological renewal by clearing dead vegetation, creating open spaces for new growth, and cycling nutrients (Cheng et al. 2005; Pausas and Keeley 2014). It rejuvenates ecosystems by facilitating the germination of certain plant species that rely on fire for reproduction and may be beneficial for many open habitat species (White 2020).

On the other hand, uncontrolled and severe fires can devastate habitats, resulting in the loss of both plant and animal species (Zabala et al. 2014). Moreover, these fires can degrade soil properties, increasing its susceptibility to erosion (Certini 2004). This erosion, in turn, leads to the runoff of sediment into nearby water bodies, with the potential to harm aquatic ecosystems.

To predict the effects of fire on individual organisms, it is crucial to integrate an individual's biological characteristics, the environment, and the heat transfer mechanisms that link the physical fire phenomenon to the biota.

Impact of fire on vegetation

Success in the plant community regeneration after fire will depend on structural and functional properties of individuals –age, height, cover, life cycle strategies, nutrient balance, etc– and by the characteristics of the environment, particularly in the post-fire period (Lloret 2004). Community resilience after fire is determined by species' ability to regenerate through two main mechanisms: the growth of new sprouts (resprouter species) and germination from surviving seed banks or from seeds arriving from neighbouring populations (seeder species). The occurrence of both types in a community depends on fire history and the bio-geographical history determining the available species pool.

Plant community regeneration after fire will depend also on wildfire characteristics, such as the fire intensity and exposition time that will determinate the individual survival and the affectation of adventitious buds that are capable to resist high temperatures (resprouting species) or the survival of seeds in soil or canopy banks (seeders species). The extension of the burning area will compromise the seed colonisation from nearby communities surviving the fire (Lawes et al. 2011; Lamont et al. 2011) and the interval between fires will compromise the rate of vegetation recovery (Díaz-Delgado et al. 2004). In addition, climatic warning could delay ecosystems' recovery by hindering plant seedling establishment and growth in some areas (Rother et al. 2015) having important implications for how landscapes respond to altered fire-regime drivers.

Impact of fire on soil

Generally, the effects of fires on the ground translate into an increase in resources immediately after the fire as a consequence of the deposition of nutrients in the ashes that were previously accumulated in the woody aerial part of plants. The ashes are particularly rich in nitrogen, phosphorus, calcium or magnesium and produce an alkalinizing effect (Lloret 2004). However, the increase in mineral nutrients will depend on the temperatures reached during the wildfire because when soil temperatures are as high as the volatilization temperatures it will cause substantial losses of mineral soil nutrients (Murphy et al 2006). Wildfires also may cause losses in the mulch and in the organic horizons of the ground by partial or total combustion of organic matter (Ferran and Vallejo 1992). An immediate effect of fire is a decrease in the stability of the aggregate structure, which together with the loss of vegetation protection, facilitates erosion and subsequent leaching, which will be potentially more important if heavy rains occur later of the fire.

It is therefore important to have an idea of the magnitude of these losses and their possible consequences for the ecosystem in the medium or long term. The post-fire soil losses are quite variable depending on vegetation, soil type, topography, post-fire weather conditions after fire and fire severity (Pausas et al. 2008). Fire intensity and severity are important factors determining erosion rates. For example, after low severity fires (i.e., low severity for trees), erosion is usually low due to the mulching effect generated both by the charcoal and by the dead leaves falling from the partially burned trees (Fernàndez and Vega 2016) but when the fire severity increases, the correlation between rainfall and erosion becomes stronger (Vieira et al. 2015).

Impact of fire on wildlife

Wildfires have important effects on fauna, either because their populations are directly affected by fire, or because they must adjust to a new scenario of availability of resources and predator activity. Fire influences composition, structure and landscape patterns of animal habitat because it alters the vegetation structure, which works as shelter and hiding cover for wild-animals and offers the resource needed to live and reproduce (Jhariya and Raj 2004). The ability of species to cope with change arising from disturbance as fire will depend on their ecological and life-history attributes. Species with low dispersal capabilities are less able to directly avoid rapid shocks and will be at increased risk of mortality unless they possess other adaptations that allow them to survive in situ (Whelan 1995).

In that context, ecological refuges can mitigate the impacts of fire by facilitating the survival or persistence of organisms in the face of disturbance events that would otherwise lead to their mortality, displacement or extinction. Refuges may have a critical influence on the successional trajectory and resilience of ecosystems after fire as they enhance immediate survival during a fire event, facilitate the persistence of individuals and populations after fire and assist in the re-establishment of populations in the longer term (Robinson et al. 2014).

The likelihood of immediate survival of an individual during a fire will be influenced by the severity of the fire, the individual's location in relation to potential refuges in the landscape and the physical or behavioural mechanisms the organism may use to avoid direct flames and radiant heat (Whelan 1995). After the fire event, patches of unburned vegetation, rocks and dead logs on the ground are essential habitat components for many invertebrates, amphibians, reptiles, birds or small mammals (Brotons et al. 2005; Jager et al. 2021). These refuges may facilitate colonisation by individuals arising from them or from outside the fire boundary, by providing resources in the short term (food, shelter) or longer term (resident habitat) (Turner et al. 1998).

FIRE EFFECTS ON SOCIETY

The impacts posed by wildfire involve also cultural and economic loss, social disruption, infrastructure damage, human injury and mortality, damage to natural resources, and deterioration in air quality (Neary and Leonard 2019). With larger human populations, larger urban encroachment of natural areas and a changing, drying climate, the impact of fire on humans and national economies will continue to increase. The twenty-first century societies will require higher levels of understanding, training, investments and improved planning to reduce fire impacts.

The hazards produced by wildfires affect both the biotic and abiotic components of ecosystems and occur during active fire as well as afterwards. After a wildfire is extinguished, hazards and risks arise from potential flooding, erosion, debris flows, and infrastructure damage (Neary and Leonard 2019). Water supplies and infrastructure, if not damaged during the active fire period, can be at risk during subsequent post-fire flood events. Economic losses accrue from declines in tourism, loss of timber and wood fiber resources, and declines in property values. Ecological impacts not assessed by traditional economic valuations include vegetation type conversion, aquatic species loss, decreased water quality, increased stream temperatures, and reduced soil quality. All of these changes are hazards in that they reduce the values and services of ecosystems or threaten human health and safety.

POST-FIRE MANAGEMENT

Management actions in burned areas must be planned taking into account the ecological impact caused by the fire, the possible hazards and the objectives of forest management (Moreira et al 2012). Managers need to have as much information as possible in the shortest possible time on the environment affected and the characteristics of the fire. The most suitable management alternatives must emerge from the analysis and interpretation of this information. Timely restoration actions should therefore be planned when a risk of environmental degradation is detected.

The formulation and selection of alternatives for the management of burned areas can emulate an adaptive management process. It allows the system to learn, as new information, especially coming from the assessment of management actions being performed, is available. This process focusses on the successive time phases, until achieving a global recovery of the affected area. The procedures or techniques to be implemented will consist of a diagnosis of the affected ecosystem, the selection of action alternatives in accordance with the diagnosis, a quality control, and the monitoring and evaluation of actions.

Fire impact assessment phase

The main objective of a fire impact assessment is to estimate the extent of damage caused by a fire. This assessment aims to determine two key aspects: the extent of the fire, usually measured as the perimeter of the fire, and the degree of fire severity, which encompasses the extent of organic matter consumption by the fire, involving both soil and vegetation (Keeley, 2009).

Environmental assessment phase

To assess the ecological vulnerability of an ecosystem following a fire, it is essential to determine the specific impact of the fire on that ecosystem. Two primary factors play a pivotal role in this assessment (Alloza et al., 2014). First, vegetation characteristics and environmental conditions significantly influence both short-term and long-term vegetation recovery rates. The recovery capacity of burned vegetation is primarily shaped by key characteristics of the vegetation, including its reproductive strategy, individual maturity, and overall structural integrity (Martin 2017). Second, abiotic factors, particularly those related to post-fire soil susceptibility, play a crucial role. Soil susceptibility to erosion is predominantly influenced by factors such as erodibility, terrain slope, and the severity of the fire's impact on both the ground and vegetation cover (Alloza et al., 2014).

Emergency stabilization phase

This phase begins right after the fire is contained and aims to address the most urgent post-fire issues. The primary objective is to prevent or mitigate the immediate consequences, such as soil erosion, landslides, and the loss of topsoil. During this phase, measures are taken to stabilize the burned area (Pereira et al., 2018). This can involve the installation of erosion control structures like silt fences, straw barriers, and mulching (Mauri and Pons 2019). Hazard assessments are also conducted to identify and address risks to public safety, infrastructure, and water quality.

Rehabilitation phase

The rehabilitation phase in post-fire management is a critical component of efforts to restore and recover ecosystems that have been affected by wildfires. The primary goal of rehabilitation is to repair or mitigate the immediate impacts of a disturbance, such as a wildfire, restoring the ecosystem's fundamental functionality and structure. Rehabilitation efforts include reseeding with native plant species, restoring riparian zones, removing invasive species, and replanting trees and shrubs as needed (Riley et al. 2015). Habitat restoration, the enhancement of wildlife corridors, and water quality improvement measures are also part of this phase. The rehabilitation phase requires a collaborative approach involving government agencies, scientists, local communities, and other stakeholders. It aims to promote the resilience of ecosystems, reduce the risk of secondary environmental impacts, and support the long-term recovery of natural systems after a wildfire.

Restoration phase

The restoration phase, which can extend over several years, focuses on complete ecosystem recovery, enhancing its resilience to future disturbances (Martin 2017). Restoration is a more comprehensive and long-term process aimed at returning an ecosystem to a condition that closely resembles its pre-disturbance state in terms of structure, function, and biodiversity (Burton et al., 2011). Restoration may involve extensive native species planting, ongoing ecosystem health monitoring, and long-term management to support natural processes (Mauri and Pons 2019). It often includes community engagement and partnerships to achieve broader conservation and restoration goals.

Adaptative management

It is necessary to monitor the results of actions taken throughout the process. Adaptive management is an ongoing and flexible decision-making approach that acknowledges uncertainty and complexity. It involves iterative processes, regular monitoring, and stakeholder engagement to continuously learn from experience and adjust strategies (Rist et al., 2013). This approach emphasizes the need for clear objectives, transparency, and feedback loops to enhance risk management and foster resilience in the face of changing conditions, ultimately striving for sustainable and effective long-term outcomes (Williams 2011).

FIRST APPROACH OF RESTORATION – PILOT CASES

QUESTIONNAIRE PILOT RESPONSES

To fully understand the needs of the restoration and adaptation phase, as well as how the technologies to be developed within the project could fit in, pilot sites were asked to answer a series of questions related to the restoration phase. These questions primarily focused on the current operational wildfire management processes, the existing equipment and ICT infrastructure (the "*as is situation*"), and what changes or solutions they desired within the framework of the TREEADS project (the "*to be situation"*).

The information was collected using a common questionnaire template[1] developed within WP2. Each pilot site received this questionnaire, which contained questions related to the three phases of wildfires management. They were asked about their current situation and the technologies they use for monitoring, studying and managing fires, as well as its pain points. Additionally, they were asked about their improvement and modification preferences, taking TREEADS' technologies into account. The surveys were completed by representatives who had a direct influence on the pilot site and possessed the highest level of knowledge about their specific needs. Subsequently, the information was clarified and refined through an individual pilot site workshop involving WP2 task leaders and pilot site leaders.

The following section is divided, as mentioned before, between *as is* and *to be situation*, with an additional section describing general aspects of the pilot site and previous wildfire events. Answers are grouped in similar responses; particular and interesting aspects are specifically pointed out.

GENERAL PILOT DESCRIPTION

TREEADS pilot campaigns across several European and global locations are addressing the escalating risk of wildfires in diverse landscapes.

Norway pilot, will concentrate, firstly, on forested, inland areas in the eastern part of the country and secondly, in the coastal landscapes in the western part of Norway, characterized by heather, grass, and scrub vegetation. These areas are grappling with more frequent extreme conditions like droughts and heavy rains that lead to floods. These conditions have become increasingly common, mainly due to climate change. Consequently, the occurrence of wildfires in Norway is expected to surge in the coming

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[1] The questionnaire is attached as an annex at the end of the report.

decades. While wildfires are most prevalent during the summer months, it has been also observed large winter wildfires, such as the ones in Flatanger, Frøya, and Lærdal in January 2014. The unexpected timing of these fires is projected to become more frequent.

Italy pilot, will be in the Campania Region, located in the southern part of the country, has seen a significant expansion in wooded areas, with over 30% of the region now covered by forests. These forests, comprising various tree species like chestnut, Neapolitan alder, and Mediterranean pine, often fall victim to wildfires typical of the Mediterranean profile. Despite periodic destruction, the area is consistently restored, primarily using Aleppo pine and maritime pine, alongside some stone pine individuals.

In Romania pilot, the Macin Mountains National Park is a haven for tourists interested in hiking, landscapes, flora, and local fauna. However, forest fires are a growing concern. On a national scale, Romania witnesses around 166 forest fires annually, affecting an average of 50,000 hectares over the past 60 years. The past decade has seen a 53% increase in the average surface area affected by forest fires, and their frequency has doubled. A significant proportion of these fires, about 61%, results from human negligence, while 35% have unknown causes, likely also originating from human error.

Spanish pilot, in the southern area of Ávila province faces a high risk of forest fires, with a substantial presence of pine species and mixed forests. This region, along with its municipalities, is classified as a "High-Risk Zone." Forest fires have become a pressing environmental issue due to their increasing frequency and intensity in recent decades. The Mediterranean climate, marked by prolonged droughts exacerbated by climate change, along with the abandonment of rural activities, has led to an increase in flammable vegetation and elevated risk.

Moving to Austria pilot, the district of Floridsdorf is an agricultural and mountainous tourist area. However, the region has experienced severe droughts since 2012, with traditional snowfall during winter months now becoming increasingly rare. This diminishing water supply has led to dried-out vegetation and the impact of parasitic species on tree health. Despite the forests' apparent health, the risk of wildfires is on the rise.

In German pilot, Saxony-Anhalt and Brandenburg are among the regions facing a high risk of forest fires, primarily affecting the common pine (*Pinus sylvestris*), making up 75% of forest fire incidents across the country.

Turning to Greece, the Samaria Gorge, situated in the southwest of Crete, is a National Park and belongs to NATURA protected regions. It is a popular tourist destination attracting thousands of visitors daily during the summer season. Unfortunately, the Gorge is considered a high-risk area for wildfires due to its challenging terrain, limited fire detection capabilities, high summer visitor numbers, and favourable fire conditions typical of the South Mediterranean.

Finally, in Taiwan pilot, forest wildfires are most common between January and April and are primarily caused by human activities. The tropical climate and drier conditions in spring contribute to these incidents, with an average of 50 fire alarms and 30 wildfire incidents each year, affecting around 650 hectares. Monetary damages are estimated at approximately 3 million euros. Human-caused fires often result from agricultural burning, discarded lit cigarette butts, building fires for warmth and light during camping activities, and the burning of joss paper.

Most of the pilot cases are focused on wildfires happening between forest/shrubland and urban areas, what is known as WUI areas (wildland-urban interface). The interaction between human populated areas and inflammable ecosystems means that both ignition risk and population vulnerability can increase.

Two pilot sites -Romania and Greece- focus their attention on wildfires in a purely wildland area, which is in its turn, a protected national park with limited infrastructure and permitted actions, depending on the country. However, both areas are highly frequented by people, and it may show a similar fire risk to WUI areas.

Thanks to the questionnaire, every pilot site has reported at least a fire event that occurred at the same study site or nearby. Mediterranean countries -Italy, Spain, Greece- offered more than two events with a considerable burned area primarily due to their climate and vegetation characteristics. Central and Northern Europe -Norway, Romania, Austria, Germany- typically experience fewer and smaller wildfires. However, past summer seasons have shown that climate change, characterized by increasing temperatures and longer drought waves, can facilitate larger and more intense fires in these regions.

Wildfire events reported included from crown to ground fires and affected a variety of ecosystems and vegetation. Those pilots that estimated severity show that it mainly depended on vegetation cover and duration of the fire. However, not all pilot sites offered a full understanding and correct measure of severity.

AS IS SITUATION

Some of the pilot sites are used to a regular fire regime due to their particular climate: with long hot summers and scarce rainfall (sometimes almost none), the Mediterranean countries have developed in response to this disturbance situation, specific guidelines and national or regional legislation regarding the response to wildfires. These guidelines, developed to varying detailed degrees, are mainly focused on prevention actions and direct interventions and responses to actively fight fire. Some countries also have specific bodies and institutions that are in charge of creating and applying restoration plans and managing post-fire restoration actions.

Central and Northern European countries do not have specific post-fire management or restoration guidelines because fire extent and frequency are much less than in Southern Europe. They merely have policies regarding prevention and response to fire. The main actors involved in firefighting just contemplate prevention and attacking phases.

Related to post-fire management, most pilot sites apply conventional restoration techniques focused on cutting burned trees and posterior reforestation. If there are any, restoration plans may be promoted by administration or by private initiatives depending on the ownership of land. Countries like Spain or Greece go beyond just basic reforestation and may apply techniques of restoration that imply taking into account other ecosystem levels: they contemplate the protection of the soil or a non-intervention perspective.

Germany has a particular policy about post-fire reforestation. One of the actions of what they call *Forest reconstruction programme* implies planting species that may create a stable and resilient forest structure to fire risk. This is an interesting approach taking into account climate change.

In most countries, monitoring burned areas normally contemplates visual surveillance during a few days after the fire to detect if there are any active spots left. In some cases, drones are used to do this visual surveillance with RGB, thermal or IR cameras. Only the Spanish pilot mentioned that they may do a post-fire assessment and data collection.

Some pilot sites foresee the mapping of burned areas or already have available burned area maps. These maps have free access just in some cases.

TO BE SITUATION

All pilots focus their attention on the solutions that will improve aspects from prevention and detection and response phases. None of them has a particular interest in the restoration and adaptation of specific processes or techniques.

Some mentioned they would be interested in monitoring certain parameters after fire: soil, vegetation and biodiversity are the main characteristics willing to control. Spain is prone to test new monitoring techniques using different levels of coverage. Greece expects to develop a personalised handbook of good practices in post-fire management techniques for its unique case.

SUMMARY OF AS IS AND TO BE SITUATION

Table 1. Pilot synthesis of as-is/to-be situation regarding restoration and adaptation phase under the TREEADS project. Information provided by the project.

PILOT	AS-IS SITUATION	TO-BE SITUATION	Contribution to TREEADS objectives
Norway	Fire perimeter Active surveillance for re-ignition	Not contemplated	No specific contribution to RA phase
Italy	Regional laws for restoration Recommendations for environmentally friendly actions for reforestation Fire perimeter	Development of insurance models and risk transfer solutions for restoration	O1: contributing to major challenges O4: validation and testing
Romania	Guidelines on afforestation	Not contemplated	No specific contribution to RA phase
Spain	Fire perimeter Post-fire assessment and data collection Post-fire management guidelines, national and regional level	Data collection and monitoring	O1: contributing to major challenges O4: validation and testing solutions O5: protecting human lives, environment and property
Austria	Fire perimeter Thermal cameras for embed beds No post-fire assessment/ management processes	Not contemplated	No specific contribution to RA phase
Germany	Fire severity maps Policies on forest conversion Drone observation of ember bed Post-fire monitoring depends on damage degree	Not contemplated	No specific contribution to RA phase

Greece	Fire perimeter Specific laws for reforestation (protected areas) Post-fire assessment (to determine the need for soil erosion control and reforestation)	Development of a handbook with good practices in post-wildfire management specialized for Samaria Gorge	No specific contribution to RA phase
Taiwan	Visual cameras of landscape	Weather data collection Vegetation monitoring	O4: validation and testing solutions

FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS

Next section summarises functional and non-functional requirements of the restoration and adaptation phase, taking into account different features: pilot's site nature, current objectives, available technology, existing management, post-fire interest, and the feasibility of the application for a potential post-fire assessment and application of restoration techniques for each pilot case.

Identifying both the functional and non-functional requirements in the restoration phase is crucial for converting the expressed needs of the pilots into comprehensive, user-centered requirements for the TREEADS holistic platform.

FUNCTIONAL REQUIREMENTS

For the description of the functional requirements, the most common requirements have been grouped by categories according to the next table.

Table 2. Functional requirements categories.

FUNCTIONAL REQUIREMENT CATEGORY	CATEGORY ABREVIATION (CAT)
INPUT	IN
DATA	DAT
PROCESSING	PROC
CONFIG	CONF
OUTPUT	OUT

The definition of the identifiers (**ID**) of these requirements uses the following nomenclature:

FR-CATN-M

FR = Functional requirements
CAT = Category abbreviation
N = index
M = subindex

NON-FUNCTIONAL REQUIREMENTS

For the description of the non-functional requirements, the most common requirements have been grouped by categories according to the next table.

Table 3. Non-functional requirement categories.

NON-FUNCTIONAL REQUIREMENT CATEGORY	SUBCATEGORY (With…)	CATEGORY ABREVIATION (CAT)
AVAILABILITY		AV
ACCESIBILITY		ACC
INTEROPERABILITY		IOP
	DEVICES	IOP-DEV
	SYSTEMS	IOP-SYS
	PHYSICAL RESOURCES	IOP-PR
	CONNECTIVITY	IOP-CON
COMPATIBILITY		COMP

The definition of the identifiers (**ID**) of these requirements uses the following nomenclature:

NFR-CATN-M

NFR = Non-functional requirements
CAT = Category abbreviation
N = index
M = subindex

The system refers to all post-fire key actors, processes, data, resources, management, techniques and actions performed.

PILOTS' FUNCTIONAL REQUIREMENTS SUMMARY

The following table includes a complete functional requirement aggregation of pilot cases. The table is based on pilots' responses on questionnaires and some of them are extrapolated taking into account technology, devices and means used for other phases (prevention or detection and response) which can be applied to restoration phase.

As-is	It refers to as-is situation, what pilots sites currently have and may dispose.
To-be	It refers to to-be situation, what pilots mentioned would likely apply in the future.
As-poss	It refers to what pilots could do with their current technologies and means but they do not do.
To-poss	Future things they could do with future technologies developed within TREEADS.

Table 4: Functional Requirements Aggregation Table

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
1	**FR-IN1**	The system must be able to retrieve, store and manage the information generated by all the sensors used for restoration								
1.1	**FR-IN1-1**	From cameras/optical sensors	as-is		as-is		as-is	as-is	as-poss	as-is
1.2	**FR-IN1-2**	From infrared cameras/optical sensors	as-is				as-is	as-is		
1.3	**FR-IN1-3**	From multispectral cameras								
1.4	**FR-IN1-4**	From thermal cameras					as-is		to-be	
1.5	**FR-IN1-5**	From LiDAR								
1.6	**FR-IN1-6**	From soil humidity sensors				to-be			to-be	
1.7	**FR-IN1-7**	From ambient temperature sensors	to-be			to-be			to-be	to-be
1.8	**FR-IN1-8**	From ambient soil temperature sensors				to-be			to-be	
1.9	**FR-IN1-9**	From weather stations							as-is	to-be
2	**FR-IN2**	The system must be able to retrieve, store and manage information from other systems								
2.1	**FR-IN2-1**	Relative to historic rainfall in the area	as-is							
2.2	**FR-IN2-2**	From external databases			as-is					

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
2.3	**FR-IN2-3**	From external GIS Sources		as-is		to-poss		to-poss		
2.4	**FR-IN2-4**	From external WEB Sources		as-is						
2.5	**FR-IN2-5**	From Copernicus Services - satellite data		as-is	as-is	to-be			as-is	
2.6	**FR-IN2-6**	From weather information services								
3	**FR-IN3**	The system must be able to allow the input, storage and management of information								
3.1	**FR-IN3-1**	Relative to characterized soil samples	to-be				to-be	as-is		
3.2	**FR-IN3-2**	Relative to characterized vegetation samples			to-be		to-be	as-is		
3.3	**FR-IN3-3**	Relative to topography information							as-is	
3.4	**FR-IN3-4**	Relative to forecast parameters			ass-poss	as-poss		as-poss	as-poss	
3.5	**FR-IN3-5**	Relative to historical data from the region - past wildfires								
3.6	**FR-IN3-6**	Relative to historical data from the region - land use/land cover			as-is	ass-poss				
3.7	**FR-IN3-7**	Relative to fire suppression strategies - prescribed burning	as-poss		as-is					
3.8	**FR-IN3-8**	Relative to use of general equipment - machinery								

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
3.9	**FR-IN3-9**	Relative to use of post-fire recycled materials		to-be						to-be
3.10	**FR-IN3-10**	Relative to custom parameters/other resources				as-is		as-is		
4	**FR-DAT1**	The system should be able to manage information concerning sectors/teams involved on restoration								
4.1	**FR-DAT1-1**	Environmental agents/technicians				as-is	as-is			
4.2	**FR-DAT1-2**	Forest rangers					as-poss		as-is	
4.3	**FR-DAT1-3**	Civil protection					as-poss			
4.4	**FR-DAT1-4**	Regional emergency services			as-is		as-poss		as-is	
4.5	**FR-DAT1-5**	Fire brigade					as-poss			
4.6	**FR-DAT1-6**	Land owners	as-poss			to-be	as-poss			
4.7	**FR-DAT1-7**	Volunteers					as-poss			
5	**FR-DAT2**	The system should be able to manage information concerning restoration guidelines or plans								
5.1	**FR-DAT2-1**	National legislation/restoration plans		as-is	as-is	as-is	as-is		as-is	
5.2	**FR-DAT2-2**	Regional restoration plans		as-is		as-is	as-is			

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
5.3	**FR-DAT2-3**	Local / Private restoration plans	as-is			as-is			to-be	
5.4	**FR-DAT2-4**	Policies regarding specific forest restoration aspects			as-is		as-is	as-is	to-be	
6	**FR-DAT3**	The system should be able to manage information concerning restoration resources								
6.1	**FR-DAT3-1**	Drones	as-poss		as-is	to-be	to-be	as-is	to-be	
6.2	**FR-DAT3-2**	Vegetation regeneration aid (seeds, seedling…)		to-be		to-be				
6.3	**FR-DAT3-3**	Heavy machinery								
6.4	**FR-DAT3-4**	Light machinery								
6.5	**FR-DAT3-5**	Third party provided resources								
7	**FR-DAT4**	Post-fire resources information should include dynamic information regarding monitorization								
7.1	**FR-DAT4-1**	Quantitative measurements					to-be		to-be	to-be
7.2	**FR-DAT4-2**	Drone flights					to-be			
8	**FR-DAT5**	The system should manage environmental information								
8.1	**FR-DAT5-1**	Data on characterized habitats	to-poss		as-is	to-be			to-be	

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
8.2	**FR-DAT5-2**	Data on characterized land use and cover	to-poss		as-is	to-be				
8.3	**FR-DAT5-3**	Data on characterized soil				to-be		as-is	to-be	
8.4	**FR-DAT5-4**	Data on characterized fuel models			as-is	to-be				
8.5	**FR-DAT5-5**	Data on characterized fuel models				to-poss				
8.6	**FR-DAT5-6**	Data on the terrain's orography			as-poss	as-is	to-be			
8.7	**FR-DAT5-7**	Terrain should include data on the terrain's dryness				as-is	to-be			
8.8	**FR-DAT5-8**	Terrain information should include data on the area access paths (roads, paths)			as-is	as-is				
9	**FR-DAT6**	The system should be able to store post-fire management actions, monitoring information and evaluation in a database of historical events							to-be	as-poss
10	**FR-PROC1**	The system must have the ability to operate with different data managed by it, store and provide results								
10.1	**FR-PROC1-1**	To obtain fire severity	as-poss	as-poss	as-poss	as-is	as-poss	as-poss	as-poss	as-poss
10.2	**FR-PROC1-2**	To determinate vulnerable areas			as-poss	as-is	to-be		to-be	
10.3	**FR-PROC1-3**	To obtain vegetation potential regeneration			as-poss	to-be	to-be		to-be	as-poss

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
10.4	**FR-PROC1-4**	To estimate potential soil erosion				to-be	as-poss		to-be	
10.5	**FR-PROC1-5**	To locate biodiversity refuges			as-poss	to-be	as-poss		as-poss	
10.6	**FR-PROC1-6**	To estimate other vegetation parameters			as-poss	as-is	as-poss	as-poss	to-be	
10.7	**FR-PROC1-7**	To obtain soil and vegetation terrain information	to-poss		as-is	as-is			to-be	
10.8	**FR-PROC1-8**	To enhance sensors retrieved information using information from other sources				to-be	as-poss	as-poss		
10.9	**FR-PROC1-9**	To optimize post-fire restoration strategies			as-poss	to-be			as-poss	
10.10	**FR-PROC1-10**	To design a decision support system				to-be			to-be	
10.11	**FR-PROC1-11**	To generate cartographic information				to-poss				
10.12	**FR-PROC1-12**	For meteorology in real-time monitoring			as-poss				to-be	to-be
10.13	**FR-PROC1-13**	For real time tree ecophysiology observation							to-be	as-is
10.14	**FR-PROC1-14**	To data analytics								
11	**FR-CONF1**	The systems should allow the creation, combination and parameters' configuration using all indexes managed								
11.1	**FR-CONF1-1**	To set up custom metrics and KPI's				to-be				

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
11.2	**FR-CONF1-2**	To enhance sensors retrieved information								
11.3	**FR-CONF1-3**	To generate data sources to feed models				to-be				
12	**FR-CONF2**	The system must allow to set delimited territory areas in terms of vulnerability								
12.1	**FR-CONF2-1**	Areas should include information about possible post-fire management requirements			as-poss	as-is			as-is	
12.2	**FR-CONF2-2**	Information prioritization and classification				as-is				
13	**FR-OUT1**	The system should have a central support access point/dashboard capable of receiving requests related to the information managed by the system								
14	**FR-OUT2**	The system must be able to manage and display information								
14.1	**FR-OUT2-1**	A decision support system to help on defining optimal restoration strategies/techniques				to-poss				
14.2	**FR-OUT2-2**	First assessment severity maps	as-poss	as-poss	as-poss	as-is	as-poss	as-poss	as-poss	as-poss
14.3	**FR-OUT2-3**	First assessment vulnerability maps			as-poss	as-is			as-poss	
14.4	**FR-OUT2-4**	On demand maps' catalogue - specific maps			as-poss					

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
14.5	**FR-OUT2-5**	Support for the exchange of information between sectors involved in post-fire restoration					as-poss			
14.6	**FR-OUT2-6**	Data Analytics								

PILOTS' NON-FUNCTIONAL REQUIREMENTS SUMMARY

The following table include a complete non-functional requirement aggregation of pilot cases. The table is based on pilots' responses on questionnaires and some of them are extrapolated taking into account technology, devices and means used for other phases (prevention or detection and response) which can be applied to restoration phase.

As-is	It refers to as-is situation, what pilots sites currently have and may dispose.
To-be	It refers to to-be situation, what pilots mentioned would likely apply in the future.
As-poss	It refers to what pilots could do with their current technologies and means but they do not do.
To-poss	Future things they could do with future technologies developed within TREEADS.

Table 5: Non-Functional Requirements Aggregation Table

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
1	**NFR-AV1**	System must be available to field actors during restoration and adaptation phase								
1.1	**NFR-AV1-1**	Maps and information must be downloadable								
1.2	**NFR-AV1-2**	Maps and information must be editable								
2	**NFR-ACC1**	System must be accessible to field actors using a personal device								
2.1	**NFR-ACC1-1**	From a web browser								
3	**NFR-IOP-DEV1**	The system should have installed sensors and devices to capture all the parameters considered in the restoration and adaptation phase			to-be	to-be				
4	**NFR-IOP-CON1**	The system could have connectivity with all involved sensors and devices in the measure of parameters related to the restoration phase	to-poss		to-be	to-be		to-be	to-be	to-be
5	**NFR-IOP-CON2**	Communication should always be ensured between system partners (users, devices, platforms, connected resources, TREEADS services as decision support system) using telematic means								

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
5.1	**FR-IOP-CON2-1**	4G/5G mobile connectivity			as-is					
5.2	**FR-IOP-CON2-2**	WLAN based connectivity using radiofrequency networks			as-is					
5.3	**FR-IOP-CON2-3**	Internet			as-is				as-is	
6	**NFR-IOP-PR1**	The system should have access to aerial means capable of transporting sensors and/or cameras								
6.1	**NFR-IOP-PR1-1**	Unmanned aerial means as drones	as-poss		as-is	to-poss	as-is	as-is	to-be	
7	**NFR-IOP-PR2**	All aerial assets used by the system should be geo-referenced and always plotted			as-is		to-be			
8	**NFR-IOP-SYS1**	The system should be integrated with external data sources/services								
8.1	**NFR-IOP-SYS1-1**	With regional database		as-poss		as-poss		as-poss		
8.2	**NFR-IOP-SYS1-2**	With centralized database								
8.3	**NFR-IOP-SYS1-3**	With Copernicus services								
9	**NFR-IOP-SYS2**	The system should be integrated with external Systems								
9.1	**NFR-IOP-SYS2-1**	GIS based systems								

NUM	ID	Description	Norway	Italy	Romania	Spain	Austria	Germany	Greece	Taiwan
10	**NFR-COMP1**	The information should be retrieved using Open-Source Framework								
11	**NFR-COMP2**	The information managed by the system should be stored in a repository based/standardized database on open standards								
11.1	**NFR-COMP2-1**	The information should be stored in a repository based on open standards (ISO 10303) in STEP data format.	as-poss							
11.2	**NFR-COMP2-2**	Standardized database								

RESTORATION SHORTCOMINGS

Through a general analysis of the responses offered by the pilot managers and the functional and non-functional requirements table, some shortcomings are detected. They are mainly gaps in fire cycle knowledge and a low interest in the post-fire phase and restoration processes and techniques.

- Gaps in understanding specific post-fire assessment concepts: fire severity, fire intensity.
- A potential misunderstanding of the role of fire on most ecosystems.
- Misunderstanding of the concept of restoration as a synonym to reforestation.
- Lack of knowledge that the best solution from an environmental point of view is often no intervention (*to do nothing).*
- Classical and conservative framework of restoration intervention – not totally aware of sustainable and innovative approaches to restoration.
- Non-Mediterranean countries normally do not have any public bodies/institution specifically dedicated to restoration processes and post-fire management.
- Most pilots are focused on prevention and detection and response phases and seemed unaware that post-fire phase will become the pre-fire phase in the future -the management done after a fire may increase or decrease the wildfire risk.
- Most pilots have available technology and means used in other phases that could be used in a preliminary assessment of a burned area (remote sensing, drones)

POST-FIRE FIRST ASSESSMENT

FIRE SEVERITY ASSESSMENT

Fire severity represents the degree of fire-induced environmental changes. It can be defined as the quantity of fuel and organic matter consumed aboveground (vegetation) and belowground (soil) during a fire. Fire severity is about physical and chemical changes to the soil, conversion of vegetation and fuels to inorganic carbon, and structural or composition transformation that bring about new microclimates and species assemblages.

Fire severity shouldn't be confused with fire intensity, although both terms have been used indistinctly in scientific literature. Fire intensity mainly describes the physical combustion process of energy release from organic matter. It is accepted to use burn severity as a synonym of fire severity, but burn severity also includes the effects of fire on the environment (Jain et al., 2004; Keeley, 2009).

Fire, as a complex disturbance, affects a large list of natural processes (erosion, vegetation regeneration, fauna recolonization, etc.) but not all of them have been directly related to fire severity. The ecological effects of fire are often considered a combination of the fire regime and the ecosystem’s vulnerability (Vega et al., 2013).

There is no specific consensus on the metrics used to evaluate fire severity, which may vary depending on management needs and objectives. Despite this, general indicators and qualitative variables are most used to establish a quantification of fire severity. They are based on the total quantity of fuel consumed in different strata: tree canopies, understory vegetation and soil’s organic matter (Keeley, 2009). Generally, the assessment requires ground observations, inspections and measurements, but for large wildfires (hundreds of hectares) this task can be simplified by using remote sensing. Remote sensing, however, has practical limitations, including the difficulty to measure strata concealed by the canopy and the inability of working at fine spatial resolution.

The evaluation and assessment of fire severity is a critical stage for the posterior application of restoration techniques. From a practical point of view, it is easier to separate severity assessment in two main components, soil and vegetation, as both react differently to fire severity.

FIRE SEVERITY ON SOIL

Fire severity effects on the soil depend on fire behaviour, fire intensity at the soil, combustion duration, and soil characteristics. These factors affect temperature transmission in the soil during combustion, consumption of fine organic matter, and consumption of coarse woody debris (Vega et al. 2013).

Burned soil suffer from biological, physical and chemical alterations because of elevated temperatures, and indirect effects due mainly to ash deposition, degree of vegetation recovery, post-fire weather patterns, topography and also post-fire management (Montorio 2014; Pereira et al. 2018). Changes in pH induced by ash deposition, modification of soil's aggregates stability due to loss of organic matter, nutrient availability, porosity alteration, modification of water retention capacity or water repellence that alters hydrological and erosive soil's dynamics, are some of the soil's parameters that may change after a wildfire. These changes are evaluated by soil ground sampling and visual assessment.

Differences between Mediterranean, Atlantic and Central European climates may be considered because of their variability in precipitation –and its associated erosion capacity– and soil's structure and composition.

Table 6. First idea of soil's fire severity assessment at sampling ground points. Adapted from Mauri & Pons (2019).

	Low	Medium	High
Effects on leaf litter	Intact	Partially burned	Generalised burned
Presence of white ash	Absent	Isolated patches	White ashes generalised

FIRE SEVERITY ON VEGETATION

Fire severity on vegetation is mainly assessed by quantifying the degree of consumption or/and suffocation of foliage and wood. Considering its direct relationship with biomass consumed, the evaluation and assessing of severity is a fundamental variable that provides essential information for prioritising restoration measures and techniques.

Two main techniques are used to assess fire severity on vegetation: field assessment and/or remote sensing. The first one uses specific ground measures that combine different metrics to estimate fire effects on each vegetation strata. Remote sensing is based on the optical spectrum and relies on reflectivity changes of the cover.

Both techniques could be combined depending on the robustness willed to acquire and the availability of economic and physical means. No automated procedure currently exists for this task.

During the last decade, other techniques have been used to assess fire effects. Active sensors such as LiDAR or radar, or even digital aerial photogrammetry, have demonstrated potential for characterizing fire-induced changes in vegetation structure (Kane et al. 2013; Reilly et al. 2021), quantify tree regeneration (Debouk et al. 2013) and estimate post-fire tree height (Magnussen and Wulder 2012).

Assessment based on field sampling

Field sampling needs to be done just few days after fire extinction to collect data for a short-term severity, to assess disorder fire effects. Measures to evaluate severity include the amount of surface fuel consumed, percentage mortality in both overstorey trees and understorey plants, percentage tree or shrub volume and cover affected, average diameter of the smallest branch remaining (Morgan et al. 2014), to cite some of them.

Field sampling must be evaluated in a systematic way, using randomly located points that will cover the heterogenic response of the ecosystem to fire. This response is known to be diverse as it depends on ecological vulnerability and on fire severity different combinations. The number of sampling points is subjected to fire extent. Based on the sampling data, homogenous zones can be mapped out where severity is similar (Mauri & Pons, 2019).

Table 7. First idea of vegetation's fire severity assessment at sampling points. Adapted from Mauri & Pons (2019).

	Low	Medium	High
Trees	>50% green canopy	> 50% dry leaves	Consumed canopies
Scrub	Some green leaves	Thin branches consumed	Thick branches consumed
Herbaceous plants	Green remains	Partially burned	Consumed

Assessment based on remote sensing

Using remote sensing to establish fire severity is much less time-consuming than assessments entirely based on field sampling. The wide range of available sensors, from multi-spectral to hyperspectral, with different spatial and temporal resolutions, can provide an essential source of data to map and assess burned areas.

Each spectral band responds differently due to the superficial characteristics of the earth cover such as water content, vegetation structure, productivity or mineral composition. When they are combined in mathematical equations, information about targeted features can be enhanced, isolated and analysed (Key & Benson, 2006).

Several existing indices may provide a first assessment of fire severity. The indices are normally based on the following spectral bands:

r	Red
NIR	Near Infrared
SWIR	Shortwave Infrared
MIR	Midwave Infrared

Most of them use the comparison between the previous and posterior state of a fire. Using pre- and post-fire images enables to detect the changes occurred between these two periods. Depending on the bands used, the changes detected rely on the vegetation response or the reaction to water content, both are critical parameters that suffer from modifications during a wildfire.

Table 8. Most common spectral indices used on fire severity assessment. R means reflectance. Adapted and updated from Montorio et al., 2014.

Index	Equation	Description
Normalized Difference Vegetation Index (Rouse et al., 1973)	$NDVI = \frac{R_{NIR} - R_R}{R_{NIR} + R_R}$	Detects photosythetically active biomass. Chlorophyll absorbs red and reflect NIR.
Delta Normalized Burn Ratio (López & Caselles, 1991; Key & Benson, 2006)	$dNBR = NBR_{pre} - NBR_{post}$ $NBR = \frac{R_{NIR} - R_{SWIR}}{R_{NIR} + R_{SWIR}}$	Like NDVI, NBR implies two bands that respond most, but in opposite ways to burning. SWIR detects changes in moisture content, where reflectance is low in healthy vegetation. dNBR measures the change caused by fire, as it relates fire effects on previously existing vegetative communities.
Relative delta Normalized Burn Ratio (Miller & Thode, 2007)	$RdNBR = \frac{NBR_{pre} - NBR_{post}}{\sqrt{\left(ABS\left({NBR_{pre}}/{1000}\right)\right)}}$	Relative metric, non-absolute. Inclusion of pre-fire information for neutralizing the effect of the amount of previous vegetation cover in stand-replacing fires. Suitable for heterogenous landscapes.
SWIR-MIR Index (Veraverbeke et al., 2012)	$SMI = \frac{R_{SWIR} - R_{MIR}}{R_{SWIR} + R_{MIR}}$	To avoid dependence on NIR, which is affected by smoke. This allows to map active fires. MIR is more sensitive to the char factional cover.
Relativized Burn Ratio (Parks et al., 2014)	$RBR = \left(\frac{dNBR}{NBR_{pre} + 1{,}001}\right)$	Simply adjustment to the pre-fire NBR. 1,001 is a coefficient to ensure that denominator is different from zero.

The dNBR index has been the most widely used to assess fire severity. Is an index that allows a greater spectral contrast and makes possible to analyse fire effects using pre-and post-fire information. This index is generally calculated using the first available cloud-free pre- and post-fire images. Even though it may show some problems in differentiation low severity and unburned areas, this index is considered a standard for fire severity assessments.

Table 9. Ordinal severity levels obtained calculating dNBR scaled by 10^3. Values are flexible, they are scene-pair dependent (pre/post images). Shifts in thresholds +/- 100 are possible and adapted depending on the bioclimatic region evaluated. Source: Key & Benson 2006.

Severity levels	dNBR range	Severity levels	dNBR range
Enhanced regrowth, high	-550 to –251	**Moderate-low severity**	+270 to + 439

Enhanced regrowth, low	-250 to -101	**Moderate-high severity**	+440 to +659
Unburned	-100 to +99	**High severity**	+660 to +1300
Low severity	+100 to +269		

RdNBR has also been used, but it is uncertain whether it outperforms dNBR for assessing fire severity. Other versions and indices provide brand new methods to evaluate severity, using recently installed sensors on satellites that could perform better in detecting changes or reflect little differences. However, these newly developed indices show similar performances as dNBR.

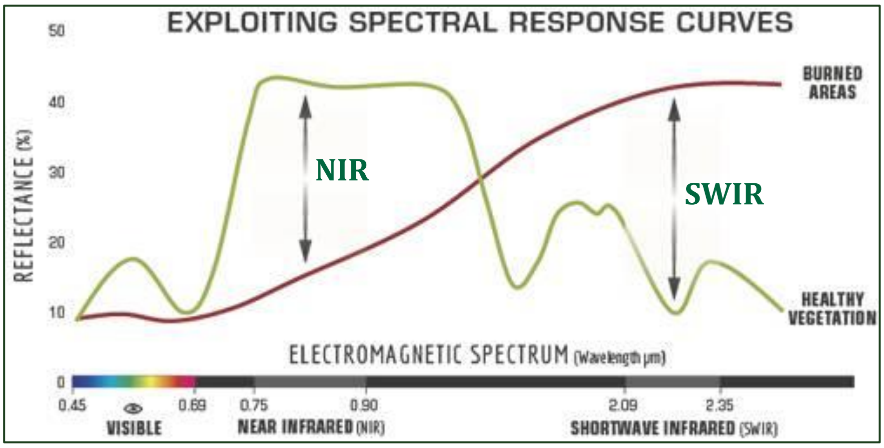

Figure 1. Comparison of the spectral responses of healthy vegetation and burned areas. The difference between the spectral responses reaches its peak in the NIR and the SWIR regions of the spectrum (UN). Source: U.S. Forest Service.

Combination of field and remote sensing assessment

Fire severity indices coming from remote sensing data have some limitations, such as misclassification among fire severity category pixels –due to sparse vegetation cover for example-, which need to be tested with ground sampling.

One of the most famous methods is the Composite Burn Index (CBI) developed in 2006 by Key and Benson from USGS (United States Geological Survey). This index summarises general fire effects within an area, which means the average burn condition of a plot. Field data is relatively quick to collect, and they mostly rely on ocular estimation and judgement. This allows sampling a large number of plots, as the main objective is to encompass the wide range of variation found within burns, covering as many fire effects and biophysical settings as possible (Key & Benson, 2006).

CBI assesses fire effects on both vegetation and soil. It uses 30x30 m plots that rate burn severity for 1) substrate, 2) herbs, low shrubs and small trees, 3) tall shrubs and sapling trees, 4) intermediate trees and 5) big trees. Each stratum is rated on a continuous scale from 0 (unburned) to 3 (high severity). Values are averaged together to calculate a value for each stratum and for each plot. Overall CBI values can be subsequently compared with satellite-derived data to develop linear regression equations for each wildfire event.

Many assessment methods have been inspired from CBI, like the modified version of CBI, GeoCBI (DeSantis & Chuvieco, 2009) or other methods with non-linear relationships (as in Parks et al. 2014).

Differences in perceptions and interpretations among observers with varying levels of experience can confound consistent CBI visual evaluations of severity attributes across different ecosystems (Morgan et al. 2014), although not all methods are suitable for all ecosystems.

SUMMARY TABLE

Table 10. Simplified guidelines for assessing fire severity for vegetation and soil using field sampling and remote sensing. Adapted from Morgan et al 2014.

	Soil severity	Vegetation severity
What imagery?	• Landsat/Sentinel-2 – most common • Quickbird or other high spatial resolution imagery – elevated costs • MODIS sensor for large extent – low resolution	
What index?	NBR, dNBR, RdNBR or RBR Adjust based on field assessments	dNBR, RdNBR, RBR, dNDVI
Timing of imagery	Immediately post-fire	Forest: • Immediately post-fire • Extended evaluation: 1 year for same phenology Non-forest: immediately post-fire
Field measures	Direct measures: e.g. soil colour, exposure, water repellence, ash amount	Depend on purpose of assessment CBI or GeoCBI common, but quantitative measures: e.g. tree mortality, fuel consumption, proportion of foliar biomass burned, reduction of canopy cover, etc.

VULNERABILITY ASSESSMENT

Vulnerability is the compound outcome of exposure, impacts on ecosystem services, and adaptability of natural and human systems (Turner et al. 2003). The analysis of an ecosystem's vulnerability provides information on its weaknesses as well as on its capacity to recover after suffering an impact.

The effect of fire on soil and vegetation increases the risk of water erosion and soil degradation, therefore, during the years immediately after the fire, processes of degradation can be triggered in the most vulnerable zones. The vulnerability will depend on the assessment of a combination of factors relaying on both soil and vegetation levels, as the soil's susceptibility, the slope, the vegetation's protection capacity, the vegetation's recovery speed, or the meteorological conditions after the fire.

Short-term ecological vulnerability

The vulnerability of the burned area is estimated from the susceptibility of the soil and the response capacity of the vegetation.

SOIL VULNERABILITY

The susceptibility of the soil to erosion depends mainly on its topography, its erodibility, the presence of protective covers, the weather after fire and the fire history (Alloza et al. 2014).

Topography

Soil is more vulnerable to degradation on steep slopes, especially after high-severity fires. Steep slopes are the most vulnerable to the effects of flames, especially if the fire line heads upslope, since convection of heat from the fire has the capacity to pre-heat the fuel, reducing moisture content before combustion. These effects are especially important on dry south facing slopes that are also the most vulnerable to soil erosion, which can be aggravated by slow vegetation recovery.

Lithology

The physicochemical characteristics of the soil describe the inherent resistance of geologic materials (soils and rocks) to erosion. Highly erodible geologic materials are readily displaced and transported by water. The intensity and type of deterioration caused by fires is closely related to physical and chemical properties of the burned soil, mainly texture, size and composition of the structural aggregates.

Protective cover

The percentage of soil that remains covered by vegetation, litter or stones (ash is not considered soil protection at all) after the fire determines the degree of rainfall interception and is inversely related to the degree of potential erosion. The lower the protection cover, the greater the risk of soil loss.

Weather after fire

Post-fire wind and rainfall intensity influence the degree of soil degradation in fire-affected areas. Ash, soil erosion and nutrient losses are high when intense rainfall (normally accompanied by strong winds) occurs in the period immediately after a fire. During this time, soils are very sensitive to any kind of disturbance, especially because vegetation has not yet started to recover.

Fire history

Previous wildfires have important implications on soil properties. Areas affected by high fire recurrences have lower quantity and quality of soil organic matter and store fewer nutrients such as nitrogen and carbon. It has also been reported that high fire recurrences decrease soil biota and increase total runoff, the amount of nutrients present in overland flow, organic matter losses and sediment transport.

Table 11. First idea of soil's environmental vulnerability assessment. Adapted from Mauri & Pons (2019).

Post-wildfire soil vulnerability		Low	Medium	High	Very high
Topography (slope)		<15%	15-30%	31-45%	>45%
Lithology		limes; dolomites; limes with dolomites or calcarenites; limes and sandstone	marly limestones; calcarenites; tophaceous limestones; conglomerates; conglomerates and clays; limestones and marls; flysch; calcarenites and marls; dolomites and marls; slates, schists and quartzites	granites, conglomerates with clays	sands; clays; clays with sands; gypsum; marls; clays with marls or silts
Previous signs of erosion	Degree of erosion	None / Minor	Moderate	High	Severe
	Terrace status	None or in good condition	Exceptional breakdowns	Widespread breakdowns	
	Degree of crusting	Minor	Moderate	Severe	
Soil protection	% Bare soil	<30%	30-60%	>60%	
	Leaf litter layer thickness	>3 cm	1-3 cm	<1 cm	

VEGETATION VULNERABILITY

The susceptibility of the vegetation is evaluated through the response capacity of the vegetation which, in turn, depends on the characteristics of each vegetation stratum (species composition, reproductive strategy, maturity stage, cover), their phytosanitary status, the recurrence of fires and the weather conditions after fire (Alloza et al. 2014).

Characteristics of the vegetation

The response of the vegetation to the fire depends mainly on the natural regeneration mechanisms of each species. Sprouting species regenerate and start covering the ground quicker than seeder plants. Among seeders, those with serotinus cones or with fire-induced germination seeds also have stronger regeneration capacities (Lloret 2004). For species without any of the above adaptations to fire, persistence may still be possible in post-fire environments via dispersal from nearby unburned stands or from fire refugia - locations that experience less severe and/or less frequent fire than the surrounding landscape-, although this is limited by the inherent dispersal capacity of the species as well as the spatial configuration of the fire refugia (Thomson et al. 2011). The slower response can be expected in habitats with little vegetation cover. In stands that have not reached reproductive maturity or produced viable seed in abundance, autosuccession (i.e. the recovery of the former plant community) will be compromised.

Recurrence of fires

High fire recurrences can decrease the capacity of vegetation to recover. Although many communities will remain resilient to changing fire regimes in the short-term, longer-term changes to vegetation structure, demography and species composition are likely, with a range of subsequent effects on ecosystem function (Neary and Leonard 2019). Resprouting species are likely to be most resilient to changing fire regimes but, even these species are susceptible if exposed to repeated short interval fire in combination with other stressors. Post-fire recruitment is highly vulnerable to increased fire frequency, particularly as climatic limitations on propagule availability intensify.

Weather conditions

In addition to its effects on fire regimes, climate change is affecting other abiotic and biotic disturbances, such as drought and heatwaves which may affect post-fire resprouting, recruitment, growth rates, and species-level adaptation capacity (Noaln et al. 2020). To understand post-fire resprouting and recruitment capacity of vegetation it is necessary to overlap climatic disturbance events and shifting fire regimes interaction.

Damage by pests

The risk of dead wood left in the forest becoming the focus of infestation for the neighbouring stands is minimal. Only trees weakened by the fire may be the focus of plagues of wood-boring insects that may affect individuals post-fire mortality.

Table 12. First idea of vegetation's environmental vulnerability assessment. Adapted from Mauri & Pons (2019).

Post-wildfire vegetation vulnerability		Low	Medium	High	Very high
Response capacity	Mature CCF* forest (serotinous or resprouting)	>60%		30-60%	<30%
	Resprouting shrub cover	>60%		30-60%	<30%
	Resprouting grass cover	>60%		30-60%	<30%
Fire recurrence in the last 20 years		0	1	2	>2
Damage by pests		Absent /light	Moderate	High	

*Canopy-cover fraction

DETECTION OF BIODIVERSITY REFUGIA

Detecting biodiversity refuges may be a key point to determine restoration objectives. On the one hand, refuge mapping is essential to avoid their destruction during forest operations and machinery movements. On the other hand, post-fire restoration actions near biodiversity refuges can improve and accelerate habitat recovery.

Unburned habitat patches (or low severity burned areas) provide essential resources to facilitate species survival until the surrounding landscape can be successfully recolonized (Berry et al. 2015). They usually act as source of seeds and as a shelter for remnant fauna, to cite some ecological functions (Robinson et al. 2013).

The following protocol uses severity assessment detected by satellites (see section Severity assessment) as a first filter of refuges detection. A second step, which comprises the use of drones, RGB cameras and LiDAR sensors, adds detailed information of vegetation structure and composition of refuges. The characterization of these refuges can facilitate the decision making of restoration actions.

POST-FIRE FAUNA OCCUPANCY

The objective of this section is to establish a wildlife detection protocol to help determine a first assessment of the impact of fire on the area. It can be a complement to the detection of biodiversity refuges.

The animals detected and their use of the burned area or the remaining habitat refuges can explain a variety of aspects: surviving individuals and species, colonizing species, use of resources after fire, behaviour... . Moreover, the mapping of animal movements will help to assess the spatial distribution of the ecosystem services that animals provide.

The protocol is designed to detect animals with a thermal camera, as this technology offers a greater detectability due mainly to the thermal contrast between the animal's body and the environment. Mammals are the main target group, due to their high body temperature and size, although reptiles and birds can also be targeted.

The protocol establishes the configuration parameters of the thermal camera, the flight characteristics –which mainly depends on the target species/s–, and the post-processing image analysis.

POST-FIRE MANAGEMENT TECHNIQUES

When forest managers have to determine the actions to be carried out in the burned area, they must consider the multiple uses of the land. Post-fire intervention must be defined according to the different objectives to be achieved, and often these goals may come into conflict with each other. This report focuses on interventions to restoring the integrity of the natural or semi-natural ecosystems, although it recognizes that land managers have many other objectives and, it will contemplate also the exploitation of the burned wood. Here we summarise some recommendations to address post-fire management actions, extracted from the Handbook of Good Practices in Post-wildfire Management (Mauri and Pons 2019).

As exposed in the Theoretical framework's section, wildfires are natural and essential forces that drive composition, structure, function, and geographic distribution of ecosystems (Keeley and Saffor 2016). Many plants and animals have strategies to naturally avoid or recover after a wildfire, showing a high resilience to fire disturbance. Following this statement, when there is no danger of ecosystem degradation a good strategy to manage a burned area is the non-intervention, which consists of letting the ecosystem regenerate itself with its own strategies. This can be an environmentally friendly and cost-free strategy, especially important when prioritizing possible interventions in a burned area. In those areas where a danger of ecosystem degradation is detected (e.g., soil erosion or lack of regeneration), restoration measures must be taken.

On the other hand, the increased consumption of forest biomass for energy purposes (in the form of wood, wood chips or pellets) is encouraging whole-tree harvesting in the burned areas, normally with few restoration measures and with logging beginning shortly after fire. Postfire logging can be a solution to get economic return from burned wood, but it can have negative effects on the environment and the ecosystem regeneration. This massive extraction of biomass from a newly disturbed ecosystem can create synergistic effects on the environment and its living organisms, which is why many uncertainties still surround this issue. Moreover, the use of heavy machinery may damage soil quality and plant recovery over short- and medium-terms (García-Orenes et al. 2017). In the following paragraphs we will propose mitigation actions to promote regeneration and the natural values of the ecosystem, and we will propose some precautions to be taken if wood extraction is planned in the burned area.

Soil and fertility losses

Soil erosion is the loss of solid materials from soil surface horizons by ablation caused by rainfall, gravity or the action of the wind. After a wildfire, the consumption of vegetation and litter reduces the protective cover of soil, decreasing rainfall interception and favouring erosion processes (Robichaud et al. 2000). Fire also may alter the soil structure by the destruction of organic matter and mineral bindings which may reduce the infiltration capacity of soils favoring the runoff generation and particle detachment

(Shakesby and Doerr 2006). The increased soil erosion after wildfires may also have off-site consequences such as the occurrence of destructive floods and debris flows downstream from the fire-affected area. Moreover, erosion may drag soil ashes which means a loss of nutrients that are particularly important to facilitate the regeneration of plants (Lloret 2004).

Soils provide numerous and crucial ecosystem services so their protection after wildfires is vital for maintaining the sustainability of fire-prone ecosystems. Post-fire erosion mitigation treatments mainly target the reduction of the kinetic energy of raindrops and runoff, favouring water infiltration and limiting the detachment and transport of soil particles and nutrients (Cerda and Robichaud, 2009).

The application of protective covers, mainly in the form of straw or wood-residue mulch, represent a widely used technique for post-fire soil erosion mitigation because of their cost-effectiveness (Robichaud et al., 2013). The most applied straw mulches are composed of agricultural residues from wheat, barley or rye; on the other hand, wood-residue mulches comprise a more heterogeneous set of materials, obtained from shredded or chopped tree barks, branches, and/or logs, produced in-situ or ex-situ and that may be applied in the shape of shreds, shavings, strands or chips (Girona-Garcia et al. 2021). On steeper slopes and/or in streams it is recommended the creation of erosion barriers along the contours to trap water and sediments to enhance the retention of runoff to reduce runoff velocity and increase infiltration and sediment retention by shortening the length of uninterrupted flow paths (Robichaud et al. 2008).

The use of on-site t wood debris from the burned vegetation represents a widely used technique because of their cost-effectiveness. Foresters may fell the trees, cut off the branches and chop them up to increase the surface area of the timber in contact with the soil with the aim of generating protective cover and accelerating the incorporation of the nutrients from the dead stems and branches. Manual logging i preferred to avoid the negative impact of heavy machinery on the soil and vegetation (i.e., soil compaction, damage of regeneration).

When wood is extracted from the burned area, it is recommended to leave a mosaic of logged and unlogged areas, which will regenerate naturally and may help adjacent logged areas to regenerate. Harvesting should usually begin several months after the fire because this delay allows the leaves and needles of the charred trees to fall, providing the soil with a protective layer. It is also recommended to log the burned forest after the rainy season, in climates with concentrated rainfall. If machinery is used, the use of lighter machinery should be prioritized. Machinery traffic should be restricted to clearing tracks, that should be as far apart as possible.

Finally, agrichemicals and flocculants such as polyacrylamides may also be used in burned areas with the aim of improving soil structure to increase the infiltration and the viscosity of overland flow and thereby decreasing its flow velocity and capacity to detach and transport soil particles (Inbar et al., 2015).

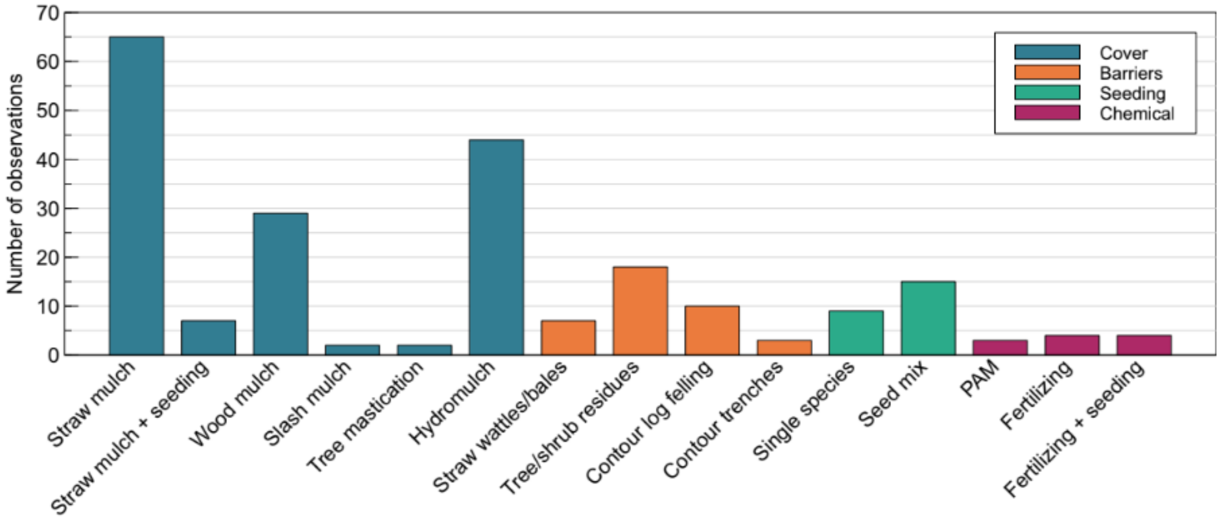

Figure 2. Treatment application frequency (number of observations) for the four major types of post-fire erosion mitigation treatments: cover treatments (n = 149; 67%), barriers (n = 38; 17%), seeding (n = 24; 11%) and chemical (n = 11; 5%). PAM: polyacrylamide. Figure drawn from Girona-García et al. 2021.

Plant regeneration

Plant community resilience after fire is determined by species' ability to regenerate through the growth of new sprouts or the germination from surviving seed banks or from seeds arriving from neighboring populations. In those areas where the plant cover has the capacity to regenerate adequately, non-intervention is advisable. If the aim is to protect this regeneration, grazing must be avoided in the burned area during at least the first years after fire because vegetation growth can be delayed due to the consumption of apical meristems, especially by sheep and goats.

If logging is planned in the burned area, precautions are needed r to avoid potential damage to the regeneration. All the logging operations should be performed before the saplings germinate or the stumps resprout so as not to damage plant regrowth. When harvesting, it is recommended to leave all the trees that show signs of life and those with dry leaves to protect the surviving seed banks in the crowns. During logging operations, the machinery traffic should be restricted to the clearing tracks to ensure that the least damage is done to plant regrowth (both trees and understorey). The burned understorey must be preserved avoiding driving machinery over it. The debris from the logging operation must not be burned in situ as this slows down the regeneration of the vegetative cover and the richness of the plant cover. Instead, logging debris should be left because it can help regenerate the vegetative cover by protecting seeds and seedlings from solar radiation, extreme temperatures and by promoting soil moisture retention.

On the other hand, when natural regeneration is not viable, tree planting should be carried out with as little ploughing as possible, ideally in places with a high risk of soil erosion. It is important to distinguish sites that won’t regenerate to forest because of changing climate from sites where trees could grow post fire if they had a seed source or were planted. When planting, small hollows should be made, and the plant inserted into it when manually intervention or use seed capsules to protect seeds and enhance germination.

Seeding treatments may also be done in burned areas, using seeds of grasses and leguminous, either from species native to the area or well-adapted to the specific environment of the study (Robichaud et al. 2013). In some cases, seeding has been complemented with the use of fertilizers (Robichaud et al., 2006).

Conservation of invertebrate and vertebrate fauna

Fire modifies vegetation structure and landscape patterns which influence the capacity of the fauna to find shelter and hiding cover and offers the resource needed to live and reproduce. To enhance the fauna colonization in the area it is necessary to perform actions to favour the conditions of its habitat.

It is important to conserve the unburned patches of vegetation and the leaf litter in order not to disturb the soil and litter fauna, and to protect its habitat role for invertebrates, amphibians, reptiles, birds and mammals. If some degree of harvesting is performed, it is recommended to leave the branches and other debris from the logging scattered on the site, creating heterogeneous habitat. Woody debris will protect animals from solar radiation and extremes of temperature and will maintain a higher degree of humidity. Also, woody debris of different diameters must be left on the logging strip, as stems with different diameters host different saproxylic communities.

It is recommended to let some standing live and dying trees as their roots can feed the underground fauna and may favour the visit of birds found in closed forest habitats that can still be present in the burned areas where no salvage logging has taken place until the burned trees fall. In these environments, these species continue to play a role in controlling insect populations and dispersing acorns.

When logging, tree branches should be left in piles or faggots to increase the number of frugivorous birds and mammals that are efficient seed dispersers (Rost et al. 2010, Puig-Gironpès et al. 2020). Seed-dispersing birds that select the lowest strata of vegetation use these piles and faggots and the seeds in their excrement find a more suitable microhabitat there to germinate (Rost et al 2009, 2012). To leave the branches on site and piled up may also provide benefits to reptiles, amphibians and mammals, such as rabbits and rodents (Rollan & Real 2011, Puig-Gironès et al. 2020) as it increases the amount of shelter, the availability of food and increase its mobility and breeding.

If the harvesting system is employed on a suitable scale (regional level) it can encourage the diversity of open-habitat animals that are threatened on a European scale due to loss of habitat caused by agricultural intensification and the abandonment of marginal agricultural and herding areas. Extensive grazing is the most effective, sustainable way to maintain plots of open habitats that will be used by birds that feed in these environments. Nonetheless, excluding domestic grazing during the first years after the fire is often recommended to reduce problems of soil erosion and to encourage the growth of a protective layer of vegetation cover over the soil.

It is recommended to avoid carrying out forestry work during the breeding season of sensitive species of large birds and mammals in areas designated by the environmental protection. Sensitive species are understood to be those considered as threatened and those negatively affected by noise and the presence of people and machinery near their breeding territory.

CONCLUSIONS AND IMPLICATIONS

Wildfires have become a common disturbance in the life of Europeans. Their occurrence is on the rise worldwide due to various factors, such as increased human-natural areas interaction, forest fuel accumulation, rising temperatures, altered precipitation patterns and prolonged drought driven by global climate change.

Society must adapt to this new scenario, and this goes by smartly managing burned areas. This management should include the results and data collected after an initial post-fire assessment, different perspectives of post-fire techniques and processes and adapting the objectives and intervention actions to each specific burned area.

The TREEADS consortium aims to provide technological solutions to facilitate managing these burned areas. As a preliminary step in task 2.5, an overview of current post-fire management in various European countries was gathered via a questionnaire to establish the baseline situation and identify the needs for successful technology development. The questionnaire focused on restoration and adaptation needs across pilot sites, examining operational wildfire management, existing technology, and desired changes within the TREEADS framework. Representatives from each site responded to the questionnaire, with their feedback further refined during individual workshops, resulting in two distinct sections: the current state and desired future situations, along with general pilot descriptions.

The pilots vary in focus, with most targeting wildfires in the WUI zones, while only two (Romania and Greece) concentrate solely on wildland areas. Climate change amplifies the frequency and intensity of fires, particularly in Mediterranean countries, with diverse impacts on ecosystems and severity measurement methods.

Each pilot site reflects unique management approaches; Mediterranean regions have specific guidelines and legislation addressing post-fire management, while Central and Northern European countries mainly focus on fire prevention and response. Post-fire restoration practices range from basic reforestation to more comprehensive soil protection and non-intervention approaches, with a shared emphasis on monitoring burned areas and improving post-fire techniques for assessment and data collection.

Thus, through this initial overview of the existing and desired situations, functional and non-functional requirements were identified, aimed at facilitating the implementation of these technologies on the TREEADS holistic platform, where solutions will be centralized and accessible to end-users. These requirements consider various aspects, including the specific nature of each pilot site, their current objectives in the Restoration and Adaptation phase, available technology, existing management practices, and interest in post-fire assessment and restoration techniques. Functional requirements focus on necessary system actions for restoration, while non-functional requirements concentrate on attributes like performance, security, and usability. Identifying these requirements is crucial as it aligns pilot needs with the user-centered requirements vital for the TREEADS holistic platform.

The holistic TREEADS platform will provide support for most Restoration and Adaptation solutions and tools, accessible to interested stakeholders. However, due to site-specific biogeographic and socio-economic characteristics, not all tools will universally apply to each pilot case, emphasizing the lack of a one-size-fits-all approach to managing burned areas.

In conclusion, the primary objective is to contribute to the development of more resilient ecosystems capable of coping with wildfires and the escalating challenges of global warming. The aim of utilizing these solutions is to mitigate the adverse impacts of fire on soil, flora, and fauna to a sustainable extent.

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ANNEX1: PILOT USE CASE QUESTIONNAIRE TEMPLATE

Please change the Pilot Use Case Number and Name below

Pilot Use Case {No}

{NAME}Pilot

1. OVERVIEW

1.1 Wildfire lifecycle and involved actors (in the scope of DRYADS)

1.1.1 *Overview of a characteristic wildfire lifecycle for your specific region*

An example of the overview for the Greek case study could look like the following:

The characteristics of wildfires in the Greek landscape typically fit the Mediterranean profile of wildfire development and proliferation. Mediterranean ecosystems are characterized by high biodiversity, with a flora consisting of a wide variety of tree, shrub and herbaceous species. Further, the Mediterranean climate is characterized by dry, and in the case of Greece, hot (35-40 ⁰C), summers with increasingly severe and long-lasting heatwaves, and mild winters. These conditions are highly favourable for the development of droughts that can last weeks and even in some occasions, months. As a result, in the Mediterranean basin wildfire incidents have been increasing at an alarming rate. Historically, wildfires in the Mediterranean are a result of two main factors: natural processes and human activity.

Wildfire prevention, detection and response usually relies on foresters, rangers and firefighters, and basic fire safety equipment such hoses, couplings, and nozzles based on a detailed firefighting plan suitable for the micro-climate conditions in the area. Local authorities contribute with regional medical emergency services and law enforcement units coordinated by a civil protection command and control center. Cross-organisational collaboration at a regional, national, and international level is required to tackle the difficulties encountered in prioritising the employment of resources available to different sub-scenarios (e.g., the allocation of available assets in handling heterogeneous causes.) In the event a fire often the only way to evacuate will be from the sea, as it can be difficult for the Fire Brigade to operate, and the road will likely be blocked. Often, wildfires occur in difficult to reach mountainous terrains, thus raging for days before they are put out. The lack of coordinated adequately funded and organised restoration and adaptation highlight the need for a holistic fire management ecosystem like DRYADS.

1.1.2 *Actors (roles) and contributions in the wildfire lifecycle*

Actors meaning external entities that interact with a system with the ability to make decisions. Please add as many rows as required in the table below.

Entity	Role	Contact Details

1.2 Major Stakeholders that need to be involved in project consultations

Stakeholders meaning entities who could be materially affected by the outcome of the project (actors are always stakeholders, but this relation is not bidirectional). Please add as many rows as required in the tables below.

1.2.1 *Forestry, Bio-economy, Communities, First Responders and Volunteers Experts/ Managers, (e.g. Union of forest owners, National civil protection)*

Entity	Role	Contact Details

1.2.2 *Other management personnel/ key partner companies and organisations (e.g police, insurance companies, whether forecast experts)*

Entity	Role	Contact Details

1.2.3 *Public Authority Personnel / Local Authority Officials*

Entity	Role	Contact Details

1.2.4 *Governmental Authority Representatives/ relevant Ministry Official*

Entity	Role	Contact Details

1.2.5 *Other key players/actors in the area/topi*

Entity	Role	Contact Details

1.3 Description of the wildfire incident/event(s) relevant for DRYADS

Please include as many incidents as you think are appropriate/important.

1.3.1 *Background – General description*

For each incident provide input on the points below, if applicable.

Incident 1

- Exact date (start/finish), location and area
- Type(s) of the event location (wildland, agricultural, wildland-urban interface, fully urban, artificial)
- Existing vegetation (before/after fire, if applicable)
- Type of land management (forest exploitation, stock breeding, prescribed burning, crops)
- Origin (natural causes/anthropogenic)
- Type of fire (crown, shrub layer, or ground fire)
- Fire severity (fire effects on vegetation and soil: degrees of combustion of plant and other organic material) (low-mid-high)
- Spatial heterogeneity in fire severity (low-mid-high)

Incident 2

1.3.2 How did the wildfire incidents escalate?

How did the fire start? What was the contribution of weather effects? For example, did the wind direction contribute to increase/decrease the wildfire (dry wind/moisture winds)

Incident 1

Incident 2

1.3.3 Describe meteorological conditions: wind, humidity, air temperature, etc. (pre-fire, active fire, post-fire)

Incident 1

Incident 2

1.4 Additional information

For example: wildfire perimeter map, fire severity map

2. AS-IS SITUATION (current scenario without DRYADS)

2.1 Description of current operational processes (tasks) relevant to DRYADS – add a flow diagram if available/required

2.1.1 If applicable, provide current wildfire national guidelines and policies

For example, legislative requirements for the prevention, the preparedness, and the evacuation planning, also legal and technical requirements of postfire management and restoration plans of recently burned areas

2.1.2 Provide current wildfire prevention measures

For example, you could provide information regarding prevention measures taken distinguishing according to type of fire (e.g. patrols, media applications)

2.1.3 Provide current wildfire detection and response-related operational processes

For example, you could provide information regarding the following:

- *Are there automated processes related to action protocols?*
- *How is the information regarding the start and spread of a fire distributed to the responders?*
- *What is the firefighting training regime?*

2.1.4 If applicable, provide current wildfire post-fire management processes/mechanisms

You could provide information regarding the management of the two main periods after a wildfire event:

- *Immediate response (max 2-3 years): soil erosion prevention, salvage logging (i.e. logging burnt trees for commercial purposes), restoration or reforestation plans, etc.*
- *Long-term response (2-30 years): forest and land management focused on regeneration: sapling or tree thinning, biomass management, etc.*
- *This long-term response eventually becomes the pre-fire phase. What is done in this period helps to prevent (or not) future fires.*

Additional points:

- *Is there any environmental evaluation (of soil erosion, plant regeneration, biodiversity…) of recently burned areas in the pilot region?*
- *Which is the main decision mechanism of land management after a wildfire? (public authorities decision, private plans, or a combination of both: public-private agreement)*

2.2 Existing pain points (Constrains/risks)

2.3 Information monitored at each phase (if any)

2.3.1 Pre-fire

2.3.2 Active fire

2.3.3 Post-fire

2.4 Key performance indicators (KPIs) and baseline assessments (depending on phase)

e.g. number of smoke detectors, number of firefighting vehicles, hectares monitored before and after fire, hectares managed before and after fire

KPI	Current Status

2.5 Existing equipment and/or ICT and technology infrastructure

You may provide information for the bullet points below that pertain to your case and if applicable clarify which phase(s) it refers to (prevention & preparedness, detection & response, restoration & adaptation)

2.5.1 Are there any sensor networks deployed to control the process?

- Which sensors are deployed and what data are they collecting?
- What is their purpose? What communication technologies are used?
- What are the control units (SCADA, PLC, etc.)?
- Is there any software-based alarm notification system? If yes, provide more details on what kind, architecture (from which data it is fed), workflows.
- For response actions, is there any software used? (from which data is fed)
- Geographical Information System (GIS) software used?
- In the case of aerial cameras what are the height/environmental correction techniques, and which license environmental correction software is used?
- Specific inventory of sensors with technical information
- What information sensors extract (format: data, image, etc)?
- Are the sensors connected to IoT devices?
- How can we collect information from sensors? (directly/centralized)
- Is the information collected by sensors georeflected or has enough information to be georeferenced (manually georeflected fixed objects, GPS, etc.)?

2.5.2 Are there any other technology elements, different from sensor networks, being used to control the process (e.g.: drones)? What is their purpose and condition? How the information they hold can contribute to the project?

- Which is your firefighting equipment? How is it maintained and used?
- Which devices are available to field actors (firefighters, volunteers, first response) (smartphone/app/web/tablet/dedicated devices)? How are these connected?
- Are there any existing fleet control systems? If yes, are those software based or manually operated?

- Geolocation data of the equipment and infrastructure (e.g. fire hydrant network)
- Technical data of devices (Multispectral camera with x bands, in which spectrum? maximum height of the drone, autonomy, energy consumed).
- On-board sensors: What information can be obtained?
- Privacy on data collected.
- Is there technology without human intervention that actively intervenes in extinguishing fires? (Example: water carrier drone).

2.6 Additional information

e.g. postfire management map

3. TO-BE SITUATION with DRYADS (Solutions to be investigated within DRYADS)

3.1 Description of new operational processes (tasks) within DRYADS based on the needs and areas of improvement for each relevant phase (prevention & preparedness, detection & response, restoration & adaptation)

Main parameter(s) to be improved within DRYADS; If there is a current management ecosystem and procedures, why do they need to be improved?

3.2 Information to be monitored before, during and after fire

Example: Soil, vegetation, biodiversity, ecosystem services, economic, social

3.3 New Key performance indicators (KPI) to be defined and monitored

KPI	Impact within the DRYADS project	Relative priority

3.4 Existing and new DRYADS ICT systems and technologies infrastructure to be integrated

3.5 Additional information

Example: severity maps, climate modelling future projection maps etc.

4. PERMITS & ETHIC REQUIREMENTS IN RELATION TO DRYADS PILOT STUDIES

4.1 Permits

4.1.1 General permits

Operational permit required with information on work, material and impact on site (if required).

4.1.2 Permits to enter the Pilot case site

4.2 Other legal Requirements

4.2.1 Insurance requirements

4.2.2 Environmental requirements

4.2.3 Ethics requirements

4.3 Additional information

TREEADS

A Holistic Fire Management Ecosystem for Prevention, Detection and Restoration of Environmental Disasters

The Members of the TREEADS Consortium:

Short Name	Country	Short Name	Country	Short Name	Country
FRN	NO	**INNOV**	CY	**DCNA**	AT
Jotne	NO	**FI**	EL	**IFR**	AT
BAM	DE	**GBD**	BE	**FGK**	AT
Capgemini Eng.	FR	**EFB**	EL	**BFG**	AT
DH	ES	**LAMMC**	LT	**STRESS**	IT
USAL	ES	**OneSeven**	DE	**ACaMIR**	IT
SQD	BE	**VIPO**	NO	**Sorrento**	IT
CARTIF	ES	**WAS**	NO	**PUI**	FR
UdG	ES	**CBS**	DK	**FAFCYLE**	ES
NCSRD	EL	**K3Y**	BG	**DdA**	ES
SIMAVI	RO	**MAGG**	IT	**TUC**	EL
OvGU	DE	**NOA**	EL	**MAICh**	EL
ADR	EL	**MEWF**	RO	**DAAC**	EL
CERTH	EL	**ASFOR**	RO	**NTUST**	TW
8bells	CY	**SMURD**	RO	**DTU**	DK
ACCELI	CY	**JOAFG**	AT		

Contact:

Project Coordinator: **Kemal S. Arsava** RISE Fire Research AS	kemal.sarp.arsava@risefr.no

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