FIRE-RES

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

D1.12 Innovative post-fire strategies and adaptation to the current context of increasing environmental uncertainties

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Abstract: This document is the first of two deliverables that focus on post-fire strategies and adaptation to increasing environmental uncertainties. Its goal is to identify high-priority areas for post-fire restoration across different forest types. The report draws on a literature review and survey of wildfire experts to identify key factors, metrics, and thresholds that determine post-fire recovery rates. Factors such as pre-fire vegetation, fire regime, topography, soil, and pre/post-fire climate were identified as the main drivers of post-fire vegetation recovery. The report provides a tabular summary of factors and associated thresholds to predict vulnerable areas at higher risk of erosion and runoff both before and in the short-term after the fire across different forest types.

Keywords: post-disturbance dynamics, resilience, fire adaptation, restoration, fire severity, plant strategies

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1 Introduction

The overall goal of this report is to enhance our comprehension of the variables influencing the ability of forests to respond to (and recover from) fires. This information holds significant importance in assessing the ecological resilience of the landscape. Ecological resilience is the ability of the ecological system to regain its previous functions and ecosystem services following a fire incident. Previous studies have shown that post-fire vegetation recovery is influenced by a number of factors related to pre-fire vegetation (e.g., forest composition and structure), fire regime (fire severity, fire frequency, fire season), soil properties (stoniness, lithology…), topography (slope, orientation), landscape structure (forest cover, diversity and distribution of land use) and climatic conditions before and after the fire event.

This report relies on the results derived from research conducted on wildfire and prescribed burning experiments of different intensities and severities. Emphasis was placed on studies conducted in new fire areas, since EWEs do not necessarily lead to ecological disasters (the inherent unpredictable behaviour of EWE can lead to a mosaic of different severities).

2 Deliverable aims

The primary objective of this document is to compile and integrate existing information concerning the main factors driving the recovery of vegetation in fire-prone and new fire areas. By utilizing this information, our aim is to facilitate the establishment of science-based criteria for identifying priority post-fire recovery areas, i.e. defining ecological units (e.g. species, communities…) that may be vulnerable to fire and might require management intervention if burned. The type of interventions required will be discussed later in *D. 12: Report on innovative post-fire strategies and adaptation to the current context of increasing environmental uncertainties*, scheduled for month 40 of the FIRE-RES project. Furthermore, this report provides the essential information for developing implementation guidelines for the *IA. 2.6 brief: Designing post-fire restoration strategies.* Consequently, the principal outcome is a summary table that outlines key factors, metrics, and thresholds for predicting vulnerable areas before and just after a fire occurrence.

This deliverable and D 1.11 (Ecological factors driving resistant and resilient landscapes to high-intensity and extreme wildfire events) are linked by a logical sequence of analyses, with D 1.11 establishing a basic understanding of resilience factors and D 1.12 building on this foundation by focusing on specific post-fire recovery and adaptation strategies. In D 1.11, the discussion focuses on the general role of species traits and two components of the fire regime (severity and frequency) contributing to ecosystem resilience. D 1.12 then takes this understanding to a more specific and applied level by addressing the practical aspects of predicting vulnerable areas based on various factors such as post-fire vegetation strategies, fire regime characteristics, soil properties, topography, climatic conditions and landscape structure. In addition, the information available in D 1.11, which addresses the identification of specific forest structural features that can generate high intensity fires and result in areas of high severity, could be helpful in identifying/mapping areas where high severity can be expected.

This document presents essential information for conducting the initial step of the framework developed by Moreira et al., (2012) to plan post-fire management and restoration in burned areas. The process entails the identification of priority areas for post-fire interventions both before and after a fire event (Figure 1). To accurately predict areas that are vulnerable to fire before it occurs, it is imperative to establish thresholds for various factors such as vegetation, soil characteristics, topography, landscape structure, and pre-fire climatic conditions. Conversely, to identify vulnerable areas shortly after a fire, pre-fire thresholds need to be combined with thresholds associated with factors such as the characteristics of the fire itself (i.e., the fire regime), post-fire conditions, competition with pioneer species, and pest outbreaks. This comprehensive approach facilitates a more effective and targeted intervention strategy.

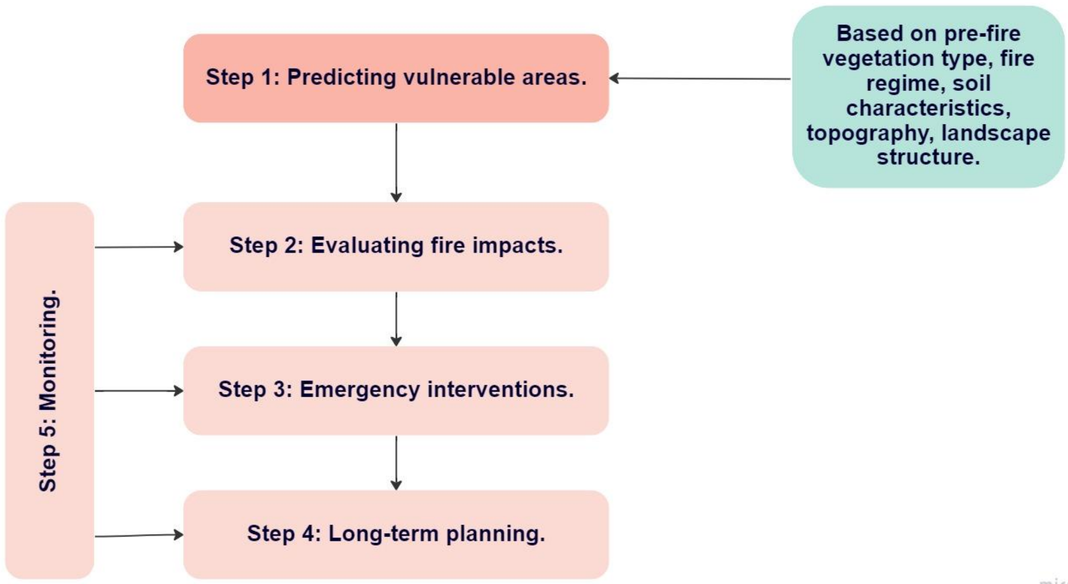

Figure 1. Framework to plan post-fire management and restoration in burned area (modified from Moreira et al., 2012). The focus of the current document is predicting vulnerable areas based on pre-fire vegetation type, fire regime, soil characteristics, topography, climatic conditions and landscape structure before and short-term after fire occurrence.

3 Methodology

The information presented in this deliverable was gathered by employing two methods: 1) a systematic literature review of the factors, metrics and associated thresholds affecting post-fire recovery for a range of forest types, and 2) a questionnaire distributed to FIRE-RES participants, foresters and forest scientists. The main output of this research is a tabular summary with a list of species (that are linked to the European Forest Types) classified in terms of their post-fire regeneration strategies and the identified factors and associated thresholds affecting their recovery. This summary may allow the identification of priority areas for establishing post-fire restoration actions for each forest type. More detailed information regarding the specific methodologies employed can be found in Appendix 8.1 (Literature review: search strategy) and 8.2 (Questionnaire).

3.1 Literature review

A preliminary selection of forest types from the European Forest Type Classification System (EFT) was carried out based on the work of Pividori et al., (2016), who classified overstory species for each European forest type (EFT) depending on their abundance and dominance. Only those species that exhibited significant abundance and dominance in a given EFT were selected to conduct the literature review on the factors influencing their recovery after fire (Appendices: Table 1). In addition to the overstory species, heathlands dominated by *Calluna vulgaris* were included because they are important habitats in northern Europe, and *Quercus coccifera* garrigues due to their importance in Mediterranean countries.

3.2 Questionnaire on factors affecting resistant and resilient stand and landscapes

The results of the literature review were used to formulate a questionnaire concerning the factors influencing post-fire dynamics for specific forest types. The aim of the questionnaire was as follows:

- To collect specialized knowledge regarding the various factors that impact the dynamics of some vegetation types from boreal, alpine and continental bioregions after fires, where information is currently lacking. This is important to make recommendations and set priorities for post-fire management in those particular forest types.

The questionnaire was distributed to experts in the field of forest fires in Europe and Chile. Section 5 presents the results of the questionnaire. The questionnaire also included questions on the factors and thresholds that determine the resilience and resistance of landscapes to EWE. These factors were discussed in *D 1.11 Ecological factors driving resistant and resilient landscapes to high intensity and extreme wildfire events* (Valor et al., 2023).

4 Review on factors modulating fire impacts and vegetation recover

Plants can be classified depending on their post-fire regeneration strategies as obligate resprouters, facultative seeders/resprouters, obligate seeders, and fire colonizers depending on their post-fire regeneration strategy (*Box 1*, see Pausas & Keeley, 2014).

Box 1. Post-fire regeneration strategies as defined in Pausas & Keeley (2014). As noted by the authors, the terms "seeders" and "resprouters" refer exclusively to post-fire conditions and cannot be used to plants that regenerate by seed or resprout under other conditions.

Obligate resprouters (R+S-): plants that rely on resprouting to regenerate after fire (resprouters without postfire seeding ability). These plants do not germinate after fire because they lack a fire-resistant seed bank.
Obligate seeders (R-S+): plants that do not resprout and rely on seeding to regenerate their population after fire (nonresprouters with postfire seeding ability).
Facultative seeders/resprouters (R+S+): plants that have both mechanisms for regenerating after fire, that is, they are able to resprout and to germinate after fire.
Post-fire colonizers (R-S-): plants that lack a mechanism for local postfire persistence, but they recruit after fire by seeds dispersed from unburned patches or from populations outside the fire perimeter (metapopulation dynamics).

Priority areas for post-fire restoration are generally those showing slow plant recovery and high risk of erosion and runoff after fire (Vallejo et al., 2012). The rate of vegetation recovery after a fire varies among forest types and depends on the presence and abundance of fire-adapted plant regeneration strategies in the system (Vallejo et al., 2012). Generally, a variety of fire-adapted plant characteristics coexist within a forest type, but the recovery of vegetation communities is often assessed based on the response of the most readily identifiable vegetation or the species dominating the overstory (Nolan et al., 2021). In this study, our focus is directed towards analyzing the factors driving the capacity of overstory species to recover or survive after a fire. To accomplish this, we utilized the BROT 2.0 database developed by Tavşanoğlu & Pausas (2018), fire-related traits (e.g., fire-stimulated flowering, ability to resprout after fire, heat-stimulated germination, seedling emergence after fire, fire-related chemical cues, thick bark, canopy seed bank) were compiled for the preliminary selected dominant species (Appendices: Table 3). However, for certain species, fire-related trait data was not available in the BROT 2.0 database. In such instances, we searched for their post-fire regeneration strategies in scientific articles using the species name and "post-fire regeneration" as keywords. A total of 22 species lacking data in both the BROT 2.0 database, and the ISI Web of Knowledge were removed from the list and not considered for the literature review. In the event that a post-fire strategy is needed in a particular LL, an expert panel should be established within the LL to assess its post-fire strategy.

Table 1. Post-fire strategies of selected dominant overstory species in a range of European forest types (see Appendices: Table 3). The assignment of post-fire regeneration strategy to each species was done using the database BROT 2.0. If the database BROT 2.0 did not contain data on fire-related traits for a given species, a literature search was

carried out to determine the post-fire regeneration strategy. In such cases, the reference is given as a note in the table.

Obligate resprouters	Obligate seeder		Post-fire colonizer	No fire-related traits
	Soil or canopy seed bank	No soil or canopy seed bank		
Pinus canariensis	*Pinus pinaster*	*Pinus pinea*	*Pinus pinea*	*Abies alba*[1]
Quercus suber	*Pinus halepensis*	*Pinus nigra*	*Pinus nigra*	*Picea abies*[1]
Quercus ilex	*Calluna vulgaris*[3]	*Pinus sylvestris*	*Pinus sylvestris*	
Quercus robur		*Pinus mugo*[1]	*Pinus mugo*[1]	
Quercus pubescens		*Pinus cembra*[2]	*Pinus cembra*[2]	
Fraxinus angustifolia		*Larix decidua*[2]	*Larix decidua*[2]	
Fagus sylvatica				
Castanea sativa				
Populus tremula				
Betula pendula				
Quercus coccifera				
Calluna vulgaris[3]				

[1] Feurdean et al., (2019)
[2] Frejaville et al., (2013)
[3] *Calluna vulgaris* can either resprout or germinate after fire.

The post-fire strategy of the dominant species was associated to the selected forest types(Table 2).

Table 2. Dominant species post-fire strategy and associated European forest type.

Post-fire strategy	Dominant species	European Forest type
No fire-related traits	*Abies alba*	2.8 Nemoral silver fir
		10.6 Mediterranean and Anatolian fir forest
	Picea abies	1.1 Spruce and spruce-birch boreal forest
		2.1 Hemiboreal forest
		2.3 Nemoral spruce forest
		3.2 Subalpine and mountainous spruce and mountainous mixed spruce-silver fir forest
		11.1 Spruce mire forest
Post-fire colonizer	*Pinus nigra*	2.4 Nemoral Black pine forest
		10.2.1 Mediterranean Black pine forest
		10.2.2 Anatolian Black pine forest
	Pinus sylvestris	1.2 Pine and pine-birch boreal forest
		2.1 Hemiboreal forest
		2.2 Nemoral Scots pine forest
		2.5 Mixed Scots pine-birch forest
		10.4 Mediterranean and Anatolian Scots pine forest
		11.2 Pine mire forest
	Pinus pinea	10.1.3 Mediterranean pine forest - Pinus pinea
	Pinus mugo	3.1 Subalpine larch-arolla pine and dwarf pine forest
	Pinus cembra	3.1 Subalpine larch-arolla pine and dwarf pine forest
	Larix decidua	3.1 Subalpine larch-arolla pine and dwarf pine forest
Seeder	*Pinus halepensis*	10.1.2 Mediterranean pine forest - Pinus halepensis
	Pinus pinaster	2.7 Atlantic maritime pine forest
		10.1.1 Mediterranean pine forest - Pinus pinaster
	Calluna vulgaris	Heathlands
Resprouter	*Pinus canariensis*	10.3 Canarian pine forest
	Populus tremula	11.6 Aspen swamp forest
		13.4 Aspen forest
	Fagus sylvatica	6.1 Lowland beech forest of southern Scandinavia and north central Europe
		6.2 Atlantic and subatlantic lowland beech forest
		6.3 Subatlantic submountainous beech forest
		6.4 Central European submountainous beech forest
		6.5 Carpathian submountainous beech forest
		6.6 Illyrian submountainous beech forest
		6.7 Moesian submountainous beech forest
		7.1 South western European mountainous beech forest
		7.2 Central European mountainous beech forest
		7.3 Apennine-Corsican mountainous beech forest

		7.4 Illyrian mountainous beech forest
		7.5 Carpathian mountainous beech forest
		7.6 Moesian mountainous beech forest
	Castanea sativa	8.7 Chestnut forest
	Quercus coccifera	9.1 Mediterranean evergreen oak forest
	Quercus ilex	9.1 Mediterranean evergreen oak forest
	Quercus suber	9.1 Mediterranean evergreen oak forest
	Quercus robur	11.5 Pedunculate oak swamp forest
	Quercus pubescens	8.1.1 Downy oak forest - western
		8.1.2 Downy oak forest - Italian
		8.1.3 Downy oak forest - Greek, Anatolian
		8.1.4 Downy oak forest - steppe
	Fraxinus angustifolia	8.8.1 Thermophilous ash forest
	Betula pendula	3.4 Mountainous birch forest
		13.3 Birch forest
	Calluna vulgaris	Heathlands

At each forest type level, we proceed to examine specific studies in the subsequent sections that have investigated the impact of pre-fire vegetation characteristics (species-specific fire-related traits) as well as variables at the individual (e.g. age, DBH) or stand/landscape level (e.g. canopy cover). Additionally, we also investigated associated thresholds that enable them to interact appropriately with their reference fire regime (severity, frequency, fire season). Furthermore, when accessible, we present data on the recuperation or resilience of the predominant species or forest type in relation to topographic and soil characteristics, as well as pre- and post-fire conditions.

4.1 Species without fire-related traits and fire regime factors

4.1.1 Pre fire vegetation: species traits and individual, stand and landscape characteristics.

There are species that are not adapted to any fire regime as these species lack of fire-related traits. Such is the case with *P. abies* and *A. alba*, both distinguished by their thin bark and the absence of a canopy or soil seed bank (Rogers et al., 2015). In fact, Bär & Mayr, (2020) discovered that the bark of *P. abies* provides the least thermal insulation for the internal tissues of the ten central alpine tree species studied. In the same study, *A. alba* exhibited a higher insulating capacity than *P. abies*, albeit with limited overall cambium thermal protection. Therefore, *P. abies* and *A. alba* must be classified as species that lack of fire-related traits, given their high susceptibility to crown and surface fires. However, a DBH above 20 cm may lead to lower mortality after fire (Dupire et al., 2019) and, thus to a higher probability of regeneration from slightly affected trees.

4.1.2 Fire severity

No studies were found on the effect of fire severity (high or low) on post-fire regeneration or resistance to fire of *P. abies and A. alba* .

4.1.3 Fire frequency

There is a scarcity of research concerning the impacts of fire frequency on *P. abies* and *A. alba*. For *P. abies*, studies based on macrofossil and pollen analyses have shown that the abundance of this species remained stable under moderately severe and frequent fires during the Holocene in the Czech Republic (Carter et al., 2018) and in the Carpathians with fire frequencies of 200–300 years (Feurdean et al., 2017) and of 1000–4000 years (Finsinger et al., 2018). A recent study has shown that regeneration of *P. abies* was relatively low during the first 10 years after a surface fire in the Arkhangelsk region (Russia) but gradually increased the years after (Ananyev et al., 2022). In this particular case, fire severity did not influence post-fire regeneration abundance. Regarding *A. alba*, the paleoecological study of Tinner et al., (2000) revealed that high fire severity can lead to its local extinction. More recently, a study based on mid-Holocene data suggested that *P. abies* and *A. alba* forests may be most vulnerable at increased fire frequency and intensity (Feurdean et al., (2019). The authors also conclude that that *A. alba* shows some resilience at intermediate fire frequency.

4.1.4 Fire season

Studies analysing the effect of fire season on the resistance or recovery of the selected dominant species are lacking. However, the effect of fire season on the potential tree mortality of both species has been analysed in a fire simulation study (Dupire et al., 2019). Results show that low mortality can be expected for both species after fires in the cold season but under drier conditions, mortality can reach values above 50%, especially in young forests (DBH < 20cm).

4.2 Post-fire colonizers and fire regime factors

4.2.1 Pre fire vegetation: species traits and individual, stand and landscape characteristics.

Fire regimes suitable for forests dominated by post-fire colonizers fire-resistant species are characterised by a combination of low intensity and frequent wildfires (Pausas, 2015). The majority of the selected fire-resistant species (*P. nigra, P. sylvestris, P. pinea, P. cembra, P. mugo* and *L. decidua*) possess a thick bark when mature and some have the ability to self-pruning, enabling them to safeguard sensitive tissues from fire. These traits not only allow their survival but also facilitate recolonization of the fire-affected open spaces. The seeds of *P. mugo*, *L. decidua*, *P. nigra* and *P. sylvestris* are dispersed by the wind, while the seeds of *P. pinea* are dispersed by gravity and the seeds of *P. cembra* by nutcrackers (Debain et al., 2007; Manso et al., 2012; Tomback et al., 1993; Wyse & Hulme, 2022).

The degree of fire resistance of the species varies. According to Fernandes et al., (2008) the ranking of fire resistance (from highest to lowest) for the most represented pine species would be: *P. pinea* > *P. nigra* > *P. sylvestris*. For a tree of 15 cm of DBH and 8 m height, the time requiered at temperatures above 60º C (at fire intensity of 400 kW m^{-1}) to kill their cambium would be 6.5, 5.4 and 3.7 minutes, respectively (Fernandes et al., 2008). For the other selected species, Bär & Mayr, (2020) ranked the resistance of *L. decidua* and *P. cembra* to cambium death after *P. sylvestris* (with *P. cembra* showing higher resistance than *L. decidua*). In *P. cembra*, bark samples thicker than 8 mm showed a marked increase in heat isolation potential. As noted by Bär & Mayr, (2020), this species has the thinnest bark within the genus. Finally, *P. mugo* is considered a post-fire colonizer species as its branches retain moisture from precipitation and snowmelt under the canopy. In return, it can promote fire spread due to its layering effect that increases fuel connectivity (Leys et al., 2014).

Few studies have addressed the effect of pre-fire stand or landscape variables fire on the post-fire resistance or regeneration of the selected species. In the case of *P. nigra*, Martin-Alcon & Coll (2016) found higher post-fire regeneration in sites with a long history of tree cover and high pre-fire tree cover (> 50%). Moreover, post-fire regeneration was mainly determined by the abundance of unburned patches after the fire (Martín-Alcón & Coll, 2016; Ordóñez et al., 2006). Therefore, the presence of mature pre-fire stands with low fuel loads and high vertical discontinuity is an important factor for ensuring the post-fire regeneration of resistant species. In another study, pre-fire land use history, particularly the time since cropland abandonment, was examined as a potential factor influencing the abundance of different species after the fire (Puerta-Piñero et al., 2012). The authors concluded that time since cropland abandonment did not appear to influence the abundance of *P. nigra* and *P. sylvestris*. Regarding understory composition, Vallejo et al. (2012) pointed out that the recovery of forests dominated by obligate seeders mostly depends on the composition of the understory, as pines take longer to establish. In these cases, burnt areas previously dominated by a forest with a resprouting understory may have lower erosion risk than those dominated by obligate seeders.

4.2.2 Fire severity

The interaction between fire severity, species traits and the age or size of individuals determine the ability of a post-fire colonizer species to survive a fire. Damage to the cambium by fire depends on the fire characteristics (e.g., temperature and residence time) as well as the tree's ability to protect sensitive tissues. The ability to protect tissues and survive depends on the species identity and the bark thickness for a given tree size (Catry et al., 2010). In low to moderate intensity fires, adult post-fire colonizer species usually survive because their bark is thick enough to withstand such intensities. However, at high intensity fires survival depends on the degree of fire damage suffered not only to the cambium but also to the crown. If tree mortality occurs, post-fire recovery may be limited because these species lack fire-related traits for massive post-fire recruitment.

Low severity fires

For most post-fire colonizer species, tree size thresholds that determine survival after low-intensity fires have been defined. In Central Catalonia (NE Spain), *P. nigra* trees with a DBH between 7.5-20 cm and a bole scorched height of 3 m were able to survive a surface fire of moderate intensity (Valor et al., 2013). Furthermore, fire simulations show that low mortality can be expected on stands with *P. nigra* individuals with a DBH > of 20 cm (Dupire et al., 2019).

Tree size also plays a critical role in the resistance of *P. sylvestris* to low intensity fires. After a moderate-intensity experimental fire with bole scorch height of up to 2 m, the probability of tree mortality of this species was below 20% for trees with a DBH > 20 cm (Valor et al., 2017). In fact, the DBH threshold of 20 cm for low to moderate intensity fires seems to be quite consistent across different studies conducted in *P. sylvestris* (see Dupire et al., (2019) for the Alps, Linder et al., (1998) in northern Sweden and Sidoroff et al., (2007) in southern Finland). In the case of *P. pinea*, Madrigal et al., (2019) established a critical threshold for bark thickness of 2 cm. Below this value, the rate of heat transfer increases, reducing the time to reach lethal temperatures in the cambium and thus the resistance to fire. Similarly, *P. pinea* individuals with a DBH of 40 ± 11 cm and mean bark thickness at the base of the trunk of 3.1 ± 0.75 cm did not suffer mechanical damage to stems, nor significant reduction in radial growth after a prescribed burning experiment in Italy (flame length at the base of the trunk never exceeded 1.5 m) (Battipaglia et al., 2016). For *P. cembra*, *P. mugo* and *L. decidua* the lack of available data on low intensity fires does not allow us to provide tree size thresholds.

Moderate and high severity fires

Under conditions of long fire-free intervals, post-fire colonizers species can succumb to fire even when they are mature because fuel accumulation can lead to high fire intensity/severity. Vulnerability to crown kill is highest in *P. sylvestris* followed by *P. nigra* and then by *P. pinea* (Fernandes et al., 2008). Bär et al., (2021) showed that closed buds of *P. cembra* can withstand the highest exposure temperatures after *P. sylvestris* while *L. decidua* would be the least resistant (no data for *P. mugo* exists).

Post-fire regeneration of post-fire colonizer species affected by crown fires is dependent on the survival of individuals or the presence of unburnt patches from which seeds can be dispersed into the completed burned area. For instance, the high intensity wildfire that occurred in Central Catalonia in 1998 burned primarily mature *P. nigra* stands whose understory consisted mainly of oaks (Martín-Alcón & Coll, 2016). Today, these areas are mainly covered with young oaks. Regeneration of pines occurs in areas near the fire site where unburned pines have scattered their seeds into the fire area (Ordóñez et al., 2006), and within the fire perimeter around black pine islands that were not burned (Martín-Alcón & Coll, 2016). In contrast, in the case of *P. pinea*, Rodrigo et al., (2007) show that post-fire regeneration was very low in 8 areas affected by forest fires in Catalonia, due to the short dispersal distance of seeds of this species and the low survival rate of seedlings. While *L. decidua* has a relatively thick bark and is therefore considered a post-fire colonizer species, it has been shown to have strong recruitment after fires of moderate severity. When large areas are affected at high intensity, larch regeneration may be limited (Moris et al., 2017b).

Crown scorch thresholds that determine the probability of post-fire mortality for some of the selected species have been derived from modelling studies. For example, in the margins and in the vicinity of the islands of vegetation that survived a high-intensity fire occurred in 1998 in NE Spain, *P. nigra* individuals were alive when the extent of crown scorched was lower than 1/3. When the proportion of crown scorched varied between 1/3 to 2/3 almost 80% of the individuals survived, and more than 60% did it for crown scorched ratios above 2/3 (Ordóñez et al., 2005). It is worth mentioning that there might be differences in the effect of crown scorch on tree mortality depending on the fire season, with spring scorched being more damaging to the tree than autumn and winter fires. For example, in the case of *P. nigra* and *P. sylvestris*, trees with more than 80% of the damaged crown died one year after a spring fire, but 20% survived after an autumn fire (Valor et al., 2017). Similarly, tree survival three years after a winter fire in France was 91% (*P. nigra*) and 70% (*P. sylvestris*) for both species with less than 2/3 of the crown completely burnt (Rigolot data in Fernandes et al., 2008). In the case of *P. pinea*, about 90% of the individuals were most likely to die when the mean proportion of charred stem length was above 60%, and most likely to survive when it was below 30% (Rigolot, 2004). Similarly, Catry et al., (2010) showed that survival of *P. pinea* was total when charred crown volume was <50%. No data were found for the more central European species.

4.2.3 Fire frequency

Post-fire colonizer species are adapted to relatively short fire frequency intervals. This leads to a low accumulation of fuel and thus to a lower intensity and severity. Dendrochonological and paleobotanical studies can help determine the appropriate fire frequency for the persistence of some of the selected post-fire colonizer species. For example, a relict *P. nigra* forest in the Sierra Turmell in Castellón (eastern Spain) has survived numerous wildfires over several centuries (11 fire dates in the last 172 years) (Fulé et al., 2008). In a *P. sylvestris* forest in Poland and Bielorus, there is evidence of the occurrence low-intensity surface fires at a mean fire interval of 9 ± 7.8 years during the period 1645–2010 (Zin et al., 2015). Paleobotanical studies using sedimentary plant macroremains from two subalpine lakes revealed that to long-term persistence of *P. cembra* was compromised at fire recurrence intervals below 150 years, because this avoids the trees to have enough cambium insulation. Genries determined that fire can affect the cembra pine ecosystem in the Alps if fire frequency is reduced to intervals of less than 80 years. In contrast, recurrence interval of fires lower than 150 years seems to favour *L. decidua* when co-habiting with *P. cembra* while *P. mugo*, abundance seems to be rather stable(Leys et al., 2014).

4.2.4 Fire season

For post-fire colonizer species, we did not find any study that examined post-fire regeneration after crown fires in different seasons. In the case of low to moderate intensity fires, *P. nigra* and *P. sylvestris* are more susceptible to spring than to autumn fires but no data are available on summer conditions (Valor et al., 2017).

4.3 Seeders species and fire regime factors

4.3.1 Pre-fire vegetation: species traits and individual, stand and landscape characteristics.

Fire regimes suitable for forests dominated by seeders species are characterized by high intensity and infrequent forest fires (Pausas, Bradstock, et al., 2004). The selected seeders pine species (*P. halepensis* and *P. pinaster*) are characterized by a dual reproductive strategy, producing both serotinous cones and non-serotinous cones. The seeds in serotinous cones remain sealed in the canopy until the rise in temperature dissolves the resin that keeps them sealed and expels the seeds. The seeds then fall to the ground and germinate the following autumn or spring (Daskalakou & Thanos, 1996). The degree of serotiny varies between the selected species and between and within populations of the same species. In Spain, for example, *P. pinaster* has a lower proportion of serotinous cones than *P. halepensis*. The degree of serotiny of *P. halepensis* is more homogeneous in the Iberian Peninsula, while *P. pinaster* shows greater variability along its geographical range (Tapias et al., 2004). *C. vulgaris* can regenerate either from vegetative growth (i.e., sprouting from the root system) or from seed germination from the soil seed bank.

Differences between individuals or populations of the same species are related to the age of individuals and the frequency of crown fires in a given area (Hernández-Serrano et al., 2013). Serotiny is a heritable trait. It is more pronounced in populations with more frequent crown fires than in areas with lower frequency (Hernández-Serrano et al., 2013). At the individual level, the proportion of serotinous cones is higher in young individuals of both species than in adults (Goubitz et al., 2004). For example, *P. halepensis* was found to have 95% serotinous content in young trees and 48% in adult trees in Greece (Daskalakou & Thanos, 1996). The early age of sexual reproduction of both *P. halepensis* and *P. pinaster* and the fact that young trees contain more serotinous cones than adult trees are important for the early accumulation of a large seed bank in the canopy.

The characteristics of the pre-fire stand, such as canopy cover or stand basal area, as well as land-use legacies, can affect the regeneration abundance of seeders species after a fire. Research has shown that for *P. halepensis*, there is a strong relationship between pre- and post-fire density of pine seedlings, likely due to a greater number of adult pines contributing to the seed bank (Broncano & Retana, 2004; Pausas, et al., 2004). However, no significant effect of land-use legacies has been found (Puerta-Piñero et al., 2012). In contrast, the current post-fire density of *P. pinaster* was found to be largely unpredictable from previous stand history and structure variables in a study developed by Torres et al., (2016). As with post-fire colonizer species, the recovery of vegetation to prevent erosion depends in the short term on the composition of the understory. A dominant understory of resprouts is likely to recover more quickly than an understory dominated by obligate seeders.

4.3.2 Fire severity

In seeder species, the degree of fire severity in the canopy is one of the factors determining seed viability for post-fire recruitment. Although *P. halepensis* and *P. pinaster* have reproductive strategies that allow them to recover from fires (serotinous cones), they also have resistance traits such as thick bark (especially *P. pinaster*). This allows them to survive low intensity fires (Fernandes et al., 2008).

Low to moderate fire severity

Mortality from cambium injury is unlikely in *Pinus pinaster* (Fernandes et al., 2008). Based on prescribed burning experiments, the threshold size given by Fernandes et al., (2008) for this species is in the range of 5–10 cm DBH. In the case of *P. halepensis*, there are not many studies on its degree of resistance, but an age of 30 years has been indicated as the threshold to limit cambium injury during prescribed burning experiments (Liacos, 2015). The bark of *P. pinaster* is thicker than the bark of *P. halepensis* Fernandes et al., (2008). Interestingly, *P. halepensis* bark is thicker than *P. sylvestris*, which has been categorized as a post-fire colonizer species.

High fire severity

In recent decades, the response of *P. halepensis* to fire has been studied in detail. In terms of fire severity, some studies have found no effect on pine seedling abundance (Pausas et al., 2002), while others have reported greater pine regeneration after moderate (Vega et al., 2018) and high severity fires (Elvira et al., 2021; Moya et al., 2020). The differences in the studies can be explained by the different methods used to estimate fire severity. For example, in Pausas et al., (2002), the degree of pine crown consumption was used as an indicator of fire severity: low severity was considered when the crown of trees had > 20% green leaves and high severity when > 80% of crown needles were consumed. The lack of correlation between the density of the seedlings and the severity of the fire could be related to the exposure to heat required to open the serotinous cones that is reached even in low severity fires. In other studies, fire severity was estimated using the delta-normalised burn ratio (dNBR). In all these cases, post-fire regeneration of *P. halepensis* was enhanced by fire severity. In the case of *P. pinaster*, there are fewer studies dealing with recruitment after fire. Martínez et al., (2002) showed that post-fire regeneration was significantly higher in plots affected by surface fire than in plots affected by crown fire. Similarly, Vega et al. (2008) reported that crown damage was negatively (but weakly) related with all parameters of seedling establishment. In another study, Vega et al., (2010) found that scorched trees released the stored seeds more rapidly and to a higher degree than trees with unaffected crown.

In seeder species, regeneration after fire mostly depends on the canopy seed bank. The role of the soil seed bank and of unburnt trees is small. Temperatures reached in the soil might be too high for survival of the seeds dispersed before the fire and the ability of these species to disperse their seeds over long distances is low. Maia et al., (2012) concluded that high fire severity can lead to the combustion of the serotinous cones of *P. pinaster*, resulting in lower seed germination. In contrast, less severe fire (scorched and unburned crowns) contributes to increased germination of the seed bank in the soil. According to Escudero et al., (1999), the probability of germination drops to less than 50% at temperatures above 130º C while the role of exposure time is small. In the case of *P. halepensis*, a temperature around 70º C could be decisive for the failure of germination if the exposure time is more than 10 minutes.

C. vulgaris hardly regenerates when the intensities of fire are high because the seeds are killed by burning the moss and litter (MacDonald et al., 1995). Besides, it has also been noted that seed regeneration can be poor where moss and litter layers remain after burning as these provide a poor medium for seedling establishment (Davies, 2006).

4.3.3 Fire frequency

The frequency of high severity fires is a crucial factor for seeder species, as these species need a sufficient time interval between fires to replenish the soil or the canopy seed bank. In *P. halepensis*, for example, some individuals can form cones as early as 4-8 years of age whereas *P. pinaster* can reach maturity and start producing cones at the age of 4-10 years (Tapias et al., 2004). However, most of trees does not start producing viable cones until 10-20 years after the fire (Tapias et al., 2001; Eugenio & Lloret, 2006). Thus, if the interval between fires is less than 10 years, local extinction of these species may occur. In this sense, the results of Eugenio et al., (2006) show a greater regeneration of *P. halepensis* in places with a lower frequency of fires compared to areas with a higher frequency of fires (25,000 vs. 14,000 seedlings ha^{-1}) and similar results have been obtained by Santana et al., (2010). Recently, Fernández-García et al., (2019) studied the role of fire frequency and fire severity in the recruitment of both species after fire under different environmental conditions. In both species, seedling recruitment was compromised in the driest study area (0.01 seedlings m^{-2}), resulting in low seedling cover (0.01%). In *C. vulgaris*, it is estimated that seeds can remain viable in the soil for up to 30-40 years (Gimingham, 1972).

4.3.4 Fire season

Post-fire recruitment for obligate seeders species seems to be reduced by fires outside their historical temporal range (Tangney et al., 2022). Spring fires seems more harmful to seeders species than summer or autumn fires. Short-lived seeders are killed by spring fires before they can produce seed, while long-lived seeds are not yet ready for dispersal in spring (Buhk et al., 2007). Moreover, in case of effective dispersal after a spring fire the seeds have to survive unprotected the upcoming summer and therefore have less chance of germinating in the following rainy season (Chamorro et al., 2013). Tsafrir et al., (2019), for example, found effects of the fire season only in obligate seed plants, with seed survival being lower after spring than after autumn fires.

4.4 Resprouters species and fire regime factors

4.4.1 Pre fire vegetation: species traits and individual, stand and landscape characteristics.

Resprouting species can form new shoots after the fire either from below-ground or above-ground structures (Bond & Midgley, 2001).

Above-ground buds can be protected by thick bark or by sinking the buds into the stems (Pausas, 2015). Among the selected species, the two species presenting above-ground buds are *P. canariensis* and *Q. suber*. For *Q. suber* and *P. canariensis*, the size of the tree or the thickness of the bark determines the degree of protection of the epicormic buds. *Q. suber* with a DBH below 12 cm is highly likely to die (Pausas, 1997). For *P. canariensis*, we found only one study in which all examined individuals with a DBH greater than 5 cm resprouted after a fire (Otto et al., 2010).

Belowground buds are buried in the soil, which protects them from heat. They can be stored in roots, root crowns, rhizomes, woody burls, fleshy swellings and belowground caudexes (Pausas et al., 2018). For oaks (*Q. ilex, Q. robur* and *Q. pubescens), P. tremula* and *B. pendula* there is much evidence of vigorous resprouting after fire through root and stump suckers. The other selected species (*F. sylvatica, C. sativa* and *F. angustifolia*) are less well studied, but the data on BROT 2.0 prove they can also resprout after fire. Therefore, we have classified them as resprouter species, even though their ability to resprout may be low. Based on studies of tree mortality after fires found in the review by Espelta et al., (2012), the results of Catry et al., (2010) and the database BROT, we ranked the selected species from lowest to highest probability of dying after fires as follows: *Q. ilex, Q. coccifera, Q. robur, Q. pubescens, P. tremula, B. pendula, F. angustifolia, C. sativa* and *F. sylvatica.*

Large specimens usually have a higher survival rate than smaller ones because of the higher number of active buds and the amount of stored carbohydrates (Catry et al., 2010). But specific thresholds for all species have not been found in the literature. In the case of *F. sylvatica*, a DBH of less than 12 cm seems to be critical (Maringer, Ascoli, et al., 2016). For *P. tremula* and *B. pendula*, 100% stem mortality after fire can be expected in individuals with diameters below 6 cm (Ascoli & Bovio, 2010; Brown & Debyle, 2011). For *C. vulgaris*, burning heather at an age between 10 and 15 years is known to allow maximum regeneration of young shoots (Davies & Legg, 2008). Finally, the growth of new shoots in resprouting species is usually positively related to the size of individuals before burning (Espelta et al., 2003).

Post-fire resprouting is also influenced by the stand characteristics prior to the fire and land-use history. For example, the abundance of *Quercus* is highly dependent on its pre-fire stem density, with stands having over 200 stems per hectare typically being dominated by *Quercus* after fire (Torres et al., 2016). In relation to land use history, Puerta-Piñero et al., (2012) found that the abundance of *Quercus* is strongly influenced by the time since the area was abandoned from agriculture.

4.4.2 Fire severity

Resprouter species can survive both low and high intensity fires. Generally high severity does not affect post-fire regeneration (Lloret & López-Soria, 1993). Some studies have shown that more intense forest fires can reduce the ability to resprout, as they can physically damage part of the bud reserve (Casals et al., 2018). Recent studies on *F. sylvatica* have shown that high fire severity, characterised by crown loss above 50% and basal area killed above 60% can result in high mortality, except for polycormic trees (Maringer, Ascoli, et al., 2016).

In the case of *C. vulgaris*, resprouting does not seem to be influenced by the severity or intensity of the fire, as the developmental phase and the loss of *Calluna's* ability to regenerate vegetatively with age are of greater importance (Davies et al., 2010).

4.4.3 Fire frequency

The frequency of fires is an important factor for resprouter species, as these species need a sufficient period between fires to replenish their carbohydrate reserves. In the case of *Q. suber*, a recurrence of about 12 years can impact its post-fire response (Curt et al., 2010). The BROLLA model predicted a decrease from 70% to less than 5% of the total basal area in other *Quercus* species when the fire frequency moves from actual to 5 years (Pausas & Vallejo, 1999). However, in the case of *Q. ilex*, two successive fires in a four-year interval did not limit its ability to resprout (Bonfil et al., 2004). In *Q. robur*, high fire frequency seems to inhibit regeneration, but no specific data on fire recurrence was provided in Monteiro-Henriques & Fernandes (2018). For *F. sylvatica*, basal resprouting from saplings was abundant at fire intervals of 15 years (Moris et al., 2022) whereas in Sweden there is evidence of a *P. tremula* persistence at fire intervals of 30 years (Esseen et al., 1997). No data were found for *P. canariensis*, *Q. pubescens*, *F. angustifolia, B. pendula* and *C. sativa*.

Shrubs forms such as *Q. coccifera* had lower biomass in stands affected by recurrent fires (3 fires in 16 years) than in stands affected by only one fire, but they still resprouted (Ferran et al., 2005). In *C. vulgaris*, a fire frequency of 10-15 years allows maximum regeneration of young shoots (Davies & Legg, 2008). In a study conducted in Italy, burning once in 3–6 years appears to be the most appropriate frequency (Ascoli & Bovio, 2010).

4.4.4 Fire season

The timing of fire relative to the active growing season may influence carbohydrate storage and thus the vigour and survival of resprouting species. Although there is limited information on specific studies on the selected resprouting species (*Q. ilex* and *C. vulgaris* mainly), most studies seem to agree that fires at the end of summer or in autumn reduce resprouting and vigour compared to fires in early summer or spring (Bonfil et al., 2004; Casals et al., 2018; Espelta et al., 2012; Knapp et al., 2005). However, in the case of *C. vulgaris*, new growth after fires was more vigorous in autumn than in spring, but in Scotland where the study was conducted the weather is often dry in early spring, which increases fire damage (Miller & Miles, 2011).

4.5 Topography

The slope or aspect can play an important role in determining erosion risk, but also through its effects on the distribution of soil moisture and thus on the recovery rate of vegetation after fire (Pausas et al., 2004). In Mediterranean areas characterised by a harsh climate, the regeneration rate is usually higher on northern slopes due to lower evapotranspiration and higher moisture content. In wetter climatic areas, the difference may not be relevant.

Species without fire-related traits

We found only one study dealing with the effect of topography on the recovery of species wit no fire-related traits after a fire. In Styria (Austria), a threshold slope of about 35-40 degrees seemed to determine whether erosion or regeneration of *P. abies* prevailed (Malowerschnig & Sass, 2014). They conclude that on gentler slopes, grassland was gradually replaced by immature and mature forest, while in steeper areas (approx. > 35-40°) it was degraded to rocks and debris or grassland. No data was found for the effects of aspect.

Post-fire colonizers

In *P. nigra*, south-facing areas seems to reduce post-fire regeneration (Martín-Alcón & Coll, 2016; Martinez-Garcia et al., 2018), specially under steep slopes (Martin-Alcon & Coll, 2016) as also observed in Greece (Christopoulou et al., 2019). Martinez-Garcia et al., (2018) found that slope-aspect did not have an important effect in both seedling emergence and seed predation but it was an important factor for the survival and growth of the emerged pine seedlings. In the case of *P. sylvestris*, a study carried out in Poland after a forest fire showed that regeneration after the fire was stronger on north-facing slopes than on south-facing slopes in the inland dune areas of Central Europe (Sewerniak, 2016). For *L. decidua*, the study of Malowerschnig & Sass, (2014) reported a threshold slope of about 35-40 degrees. In the case of *L. decidua*, a positive relationship between slope and regeneration was found (with high regeneration in slopes > 50%) (Moris et al., 2017). No data was found for *P. pinea, P. mugo* and *P. cembra.*

Seeders

The density and height of *P. pinaster* seedlings was higher on north-facing slopes than on south-facing slopes in the three years following a forest fire in north-western Spain (Calvo et al., 2008). This was related to the higher soil moisture found on northern slopes, that is necessary for seedling germination and viability. Similarly, regeneration of *P. halepensis* after fire is greater on north-facing slopes (Pausas et al., 1999; Pausas, et al., 2004) and on flat/terraced or moderate slopes (Garcia-Jimenez et al., 2017; Pausas et al., 1999). The threshold for slope was set at > 25% in two multicriteria studies (Arianoutsou et al., 2011; Ruiz-Gallardo et al., 2004), but a study developed in Greece show good recovery for slopes between 0-50% (Tsitsoni, 1997). No studies were found for *C. vulgaris*.

Resprouters

Studies conducted in Portugal showed that *Q. suber* regeneration was negatively affected by slope. Flat areas were associated with less regeneration (Monteiro-Henriques & Fernandes, 2018) while S, SW and E slopes showed lower crown regeneration than W, NW and NE slopes. The xerophytic character of this species may have led to higher physiological stress and thus higher susceptibility to fire (Catry et al., 2009). Similarly, *Q. robur*, sapling density was lower in southern aspects than in less sun-exposed ones (Monteiro-Henriques & Fernandes, 2018). Studies in Spain on *Q. coccifera* show that resprouting after fire is higher in northern orientations (Pausas & Vallejo, 1999), but in Greece growth is higher in eastern and southern orientations (Konstantinidis et al., 2005). Also in Switzerland, beech regeneration after fire is higher on north-east rather than south-west facing slopes (Maringer,et al., 2016). The resprouting probability of this species did also decrease with slope (Moris et al., 2022). For the other species selected we found no studies.

4.6 Soil characteristics

The recovery of plant species following a fire can be significantly influenced by pre-fire soil properties. However,there has been relatively little investigation into how pre-fire soil properties, such as soil type, bedrock type, soil depth, organic matter content, pH, texture, and nutrient levels, affect post-fire regeneration.

Studies have shown that certain pre-fire soil properties can support faster plant growth and lead to better post-fire recovery. For instance, soils with higher levels of organic matter or nitrogen content, as well as clay soils that can retain more water, tend to promote faster regeneration. In Portugal, recent research has found that vegetation recovery (without distinguishing between species) was most effective in humic cambisols and in soils with low pH (Meneses, 2021). Bedrock type, which is related to soil type, can also have a significant impact on post-fire regeneration. In the Baixo Tamega region of Portugal, for example, shrub formations on granite soils tend to harbor more species and develop more vigorously after fire than those on schist-derived soils (Torres et al., 2017). In Greece, *P. nigra* was more abundant in areas underlained by softer basement rock (Christopoulou et al., 2019). Additionally, Pausas et al., (1999) found that the rate of vegetation regeneration after fire, particularly for *Q. coccifera*, depends on bedrock type. Recovery of vegetation also appears to be greater on soils formed over limestone than on soils over marl. Moreover, López-Soria & Castell (1992) found that resprouting was more common among individuals in deep soils than in shallow ones. Further research in this area could help inform post-fire management strategies and promote more effective restoration efforts.

4.7 Pre-fire and post-fire climatic conditions

Species without fire-related traits and post-fire colonizers

Research on pre-fire and post-fire climate conditions is limited, with most studies focused on conditions after the fire. For example, in the case of fire of *P. sylvestris* and *P. abies* in Central Alps, post-fire drought seems to be a critical limiting factor for tree recruitment after fire disturbance (Moser et al., 2010). For both species, the study highlights that the window of opportunity for seedling establishment was short (1-2 years), and moisture deficit was the primary limiting factor for tree recruitment at lower altitudes. The authors found that favourable moisture conditions for seedling establishment in spring were rare at low and medium altitudes. For *L. decidua*, recruitment after fire decreases with the thermal compensated continentality index (Icc), with lower recruitment at Icc values above 27 (Moris et al., 2017). In the case of *P. nigra*, several studies have reported a positive relationship between short-term regeneration and above-average precipitation in the months after fire (Díaz-Delgado et al., 2002, 2003; Viana-Soto et al., 2017).

SeedersRegarding seeders species, most data is limited to *P. halepensis*. A positive relationship between short-term regeneration and above-average precipitation in the months after fire has been found in several studies (Pausas, Ribeiro, et al., 2004; Röder et al., 2008; Viana-Soto et al., 2017). However, a recent study conducted by Elvira et al., (2021) in Catalonia showed that warm conditions before the fire are positively related to pine regeneration, while warm temperatures after the fire have a negative effect on the density of pine trees. Wet conditions after the fire enhanced pine regeneration, while precipitation before the fire had no significant effect. In the case of *P. pinaster*, initially high seedling density decreases significantly after the first summer due to severe drought stress (Calvo et al., 2008).

Resprouters

The resprouting vigour of resprouter species seems to be favoured by precipitation after the fire (Espelta et al., 2012). For instance, in *Q. coccifera*, the identified rainfall episodes after the fire as the decisive positive factor determining resprout development (Konstantinidis et al., 2005). For *F. sylvatica*, spring-summer moisture showed a weak positive effect on beech recruitment (Maringer et al., 2020). Regarding *Q. suber*, post-fire delayed mortality was related to repetitive summer droughts (Curt et al., 2010).

4.8 Other factors

Factors such as competition from pioneers, herbivory and insect outbreaks can also have an important influence on post-fire regeneration but are not considered in this report as the focus here is on variables that can be mapped for WP2.

5 Questionnaire results on factors driving post-fire dynamics

This section presents the results of the questionnaire related to post-fire dynamics (question 9) (Appendix: 8.3 Questionnaire). A total of 35 responses were collected from which 62.8% (n=22) were from the Mediterranean region, 25.7% (n=9) from the continental region, 5.7% (n=2) from the Alpine region, 2.8% (n=1) from the Atlantic region, and 2.8% (n=1) from the temperate region. Most respondents were experts in "fuel management" and "post-fire management" (27.1% and 23.7%, respectively), while 20.3% and 18.6% of respondents were experts in fire behaviour and fire ecology, respectively. The rest of the respondents (10.1%) were experts in other areas of wildland fire research (e.g., risk assessment, social dimension). A large proportion of interviewees were academics (54.2%), followed by fire responders (20.0%), forest managers (17.1%), and other positions (8.5%). The mean years of work experience was 16 years and ranged from 1 to 39 years.

Post-fire dynamics (question 9)

This section presents the results of the questionnaire related with post-fire dynamics (question 9) (Appendix: 8.3 Questionnaire).

Question 9 asked the experts to select a maximum of two vegetation types from a list and then to give a rating from 1 to 10 according to their importance in limiting post-fire recovery in terms of fire regime, pre-fire vegetation, short-term post-fire competition, and climatic, soil and topographic factors. 13 out of 35 experts selected one or two vegetation types. Of all the vegetation types listed, the following were selected: hemiboreal and continental *P. sylvestris* pine forests (n=6), alpine *P. sylvestris* or *P. nigra* in the Alps or *P. uncinata* in the Pyrenees (n=5), *Picea abies* forests (n=3), tall deciduous oak *(Quercus* sp.) forests (n=2), beech (*Fagus* sp.) forests (n=1), *Abies alba* forests (n=1) and mixed *Quercus* sp. and *Fraxinus* forests (n=1). The following forest types were not selected: Hemiboreal mountain pine forests (*Pinus mugo*), subalpine larch forests (*Larix* sp.) and stone pine forests (*Pinus cembra*).

In the case of hemiboreal and continental *P. sylvestris* pine forests, the first five factors, from highest to lowest score, limiting post-fire recovery were fire severity, followed by young forest and high erosion, spring fire and pre-fire drought (Figure 3).

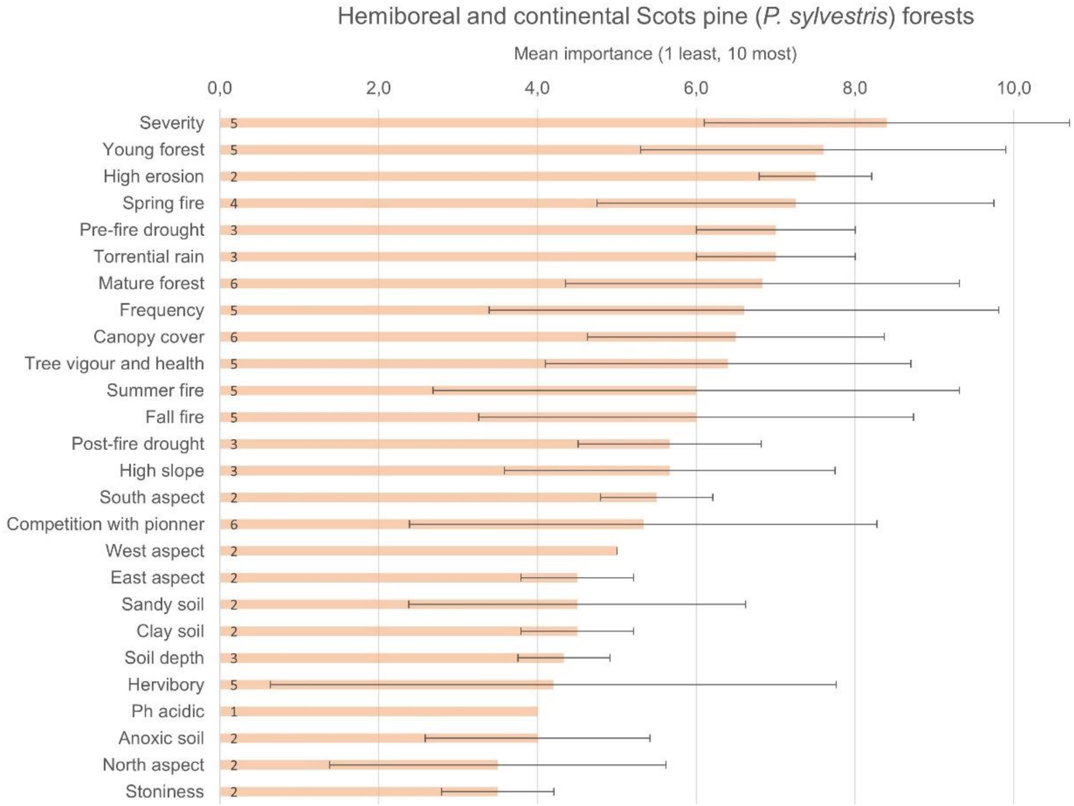

Figure 2. Mean importance and standard deviation of punctuation assigned by experts for fire regime, pre-fire vegetation, post-fire short-term competition, climatic, soil and topographic factors influencing post-fire recovery of hemi boreal and continental Scots pine (P. sylvestris) forests. The order of the factors was ranked from most important to least important. The number of responses given to each factor is indicated within the bars.

For alpine *P. sylvestris* or *P. nigra* in the Alps or *P. uncinata* in the Pyrenees, within the first five factors, from highest to lowest score, the first two factors limiting post-fire recovery were related with fire regime factors: fire severity and frequency, followed by post-fire drought. Then, high erosion and torrential rain were punctuated as fire severity, followed by young forest and high erosion, spring fire and pre-fire drought (Figure 3).

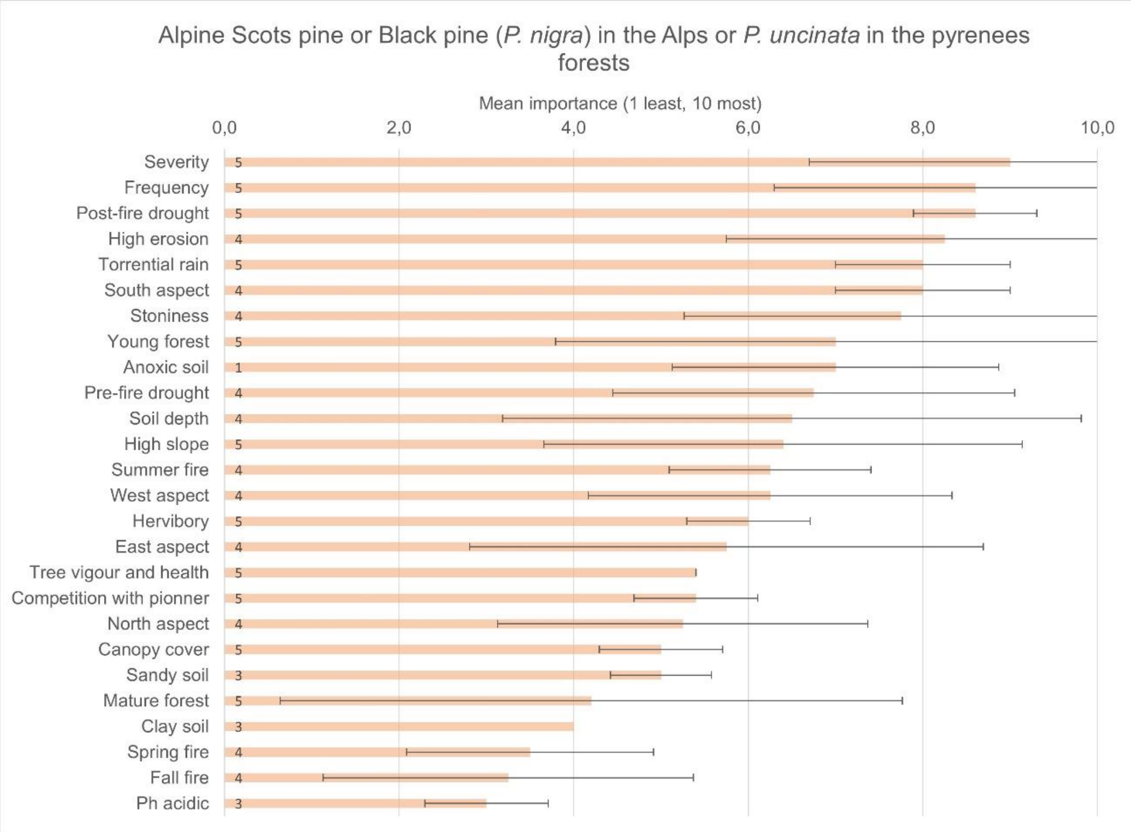

Figure 3. Mean importance and standard deviation of punctuation assigned by experts for fire regime, pre-fire vegetation, post-fire short-term competition, climatic, soil and topographic factors influencing post-fire recovery of alpine P. sylvestris or P. nigra in the Alps or P. uncinata in the Pyrenees. The order of the factors was ranked from most important to least important. The number of responses given to each factor is indicated within the bars.

For spruce *P. abies*, three of the five top factors were related with climatic conditions (pre- and post-fire drought and torrential rain). Fire frequency was considered the main factor and the age of the forest was positioned in the third place (Figure 4).

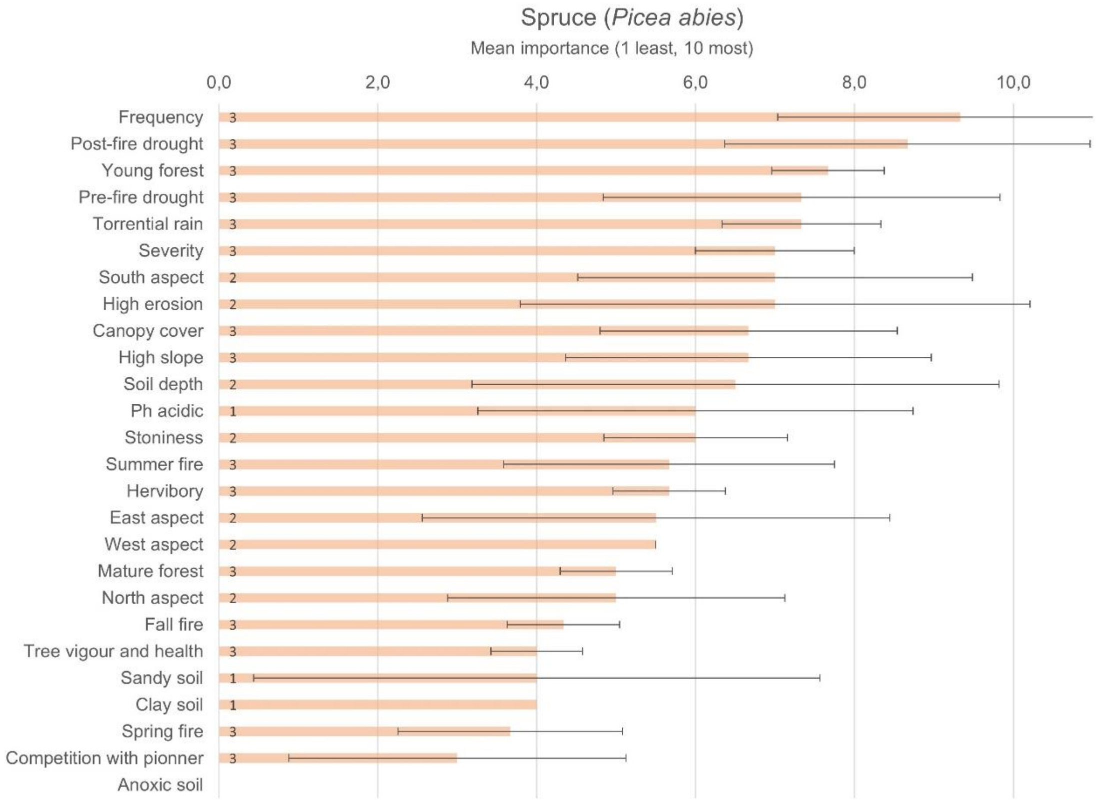

Figure 4. Mean importance and standard deviation of punctuation assigned by experts for fire regime, pre-fire vegetation, post-fire short-term competition, climatic, soil and topographic factors influencing post-fire recovery of spruce (Picea abies). The order of the factors was ranked from most important to least important. The number of responses given to each factor is indicated within the bars.

In the case of *Quercus* sp. the first five factors affecting post-fire recovery were: post-fire drought, pH acidic, fire severity, anoxy soil and tree vigor and health (Figure 5). It is important to mention that only one or two answers were provided.

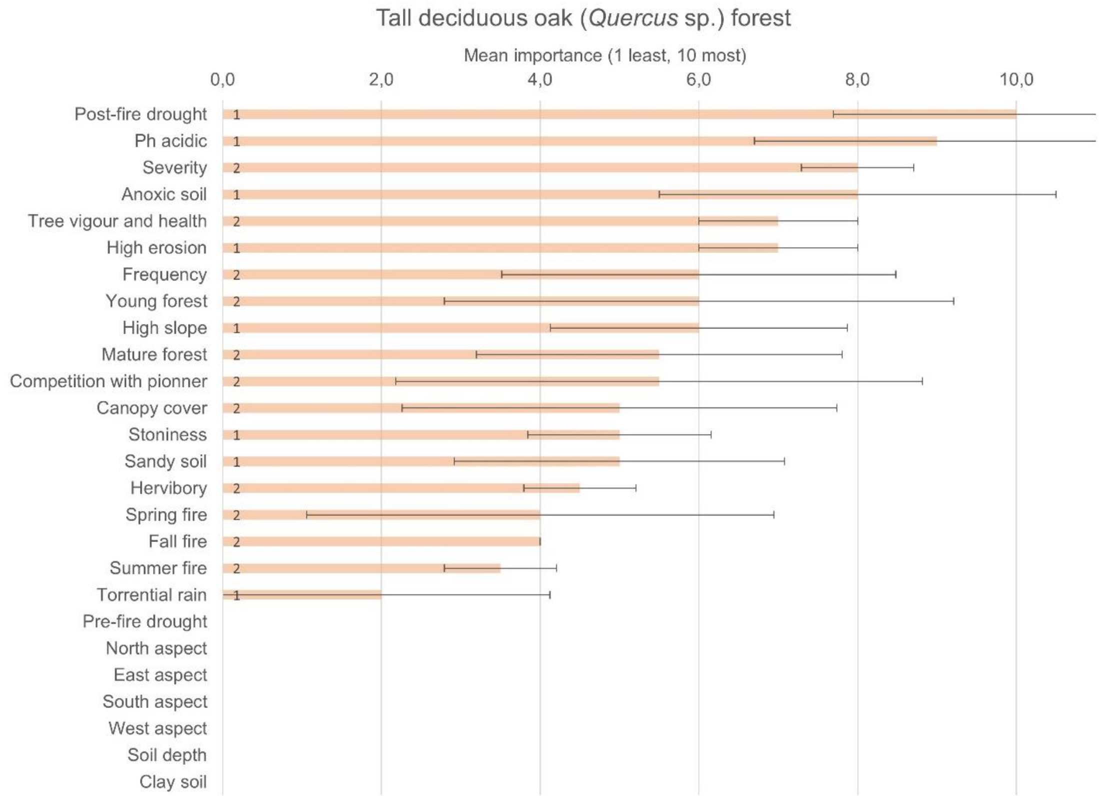

Figure 5. Mean importance and standard deviation of punctuation assigned by experts for fire regime, pre-fire vegetation, post-fire short-term competition, climatic, soil and topographic factors influencing post-fire recovery of tall deciduous oak (Quercus sp.) forest. The order of the factors was ranked from most important to least important. The number of responses given to each factor is indicated within the bars.

For mixed forests of *Quercus* sp. and *Fraxinus* as well as *A. alba*, there was only one answer, which was found in Figure 6 and Figure 7.

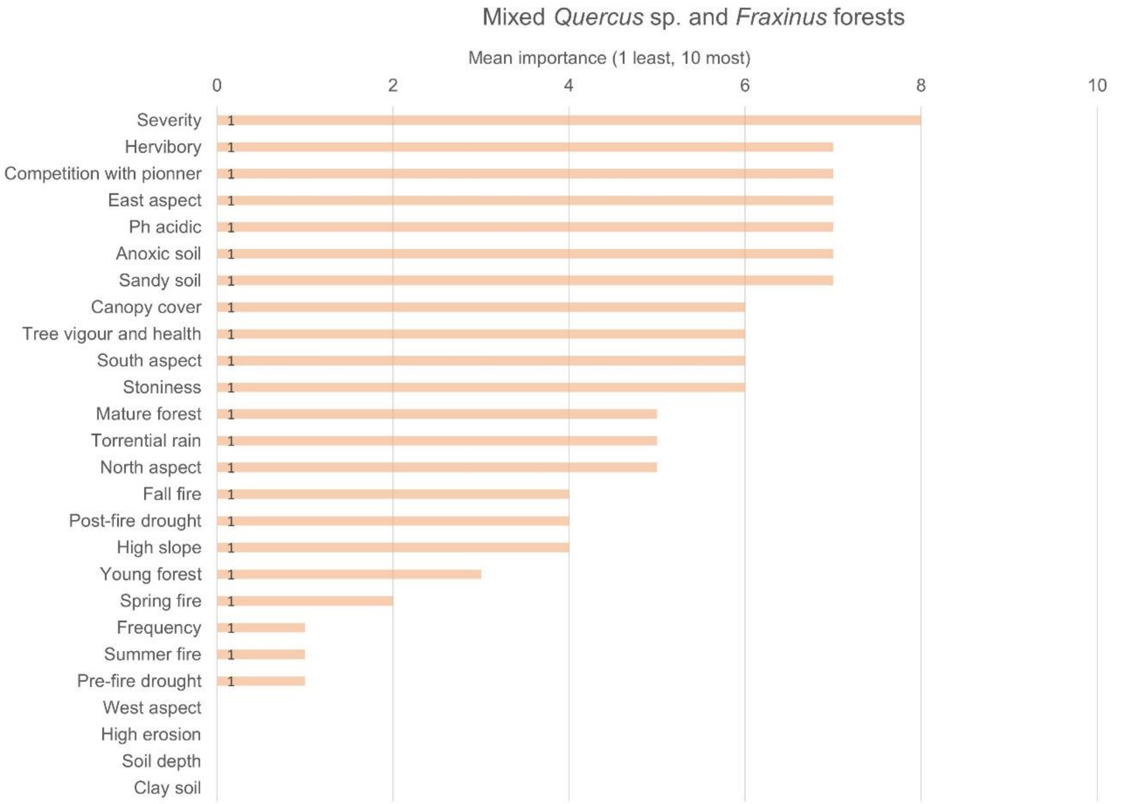

Figure 6. Mean importance and standard deviation of punctuation assigned by experts for fire regime, pre-fire vegetation, post-fire short-term competition, climatic, soil and topographic factors influencing post-fire recovery of mixed Quercus sp. and Fraxinus forests. The order of the factors was ranked from most important to least important. The number of responses given to each factor is indicated within the bars.

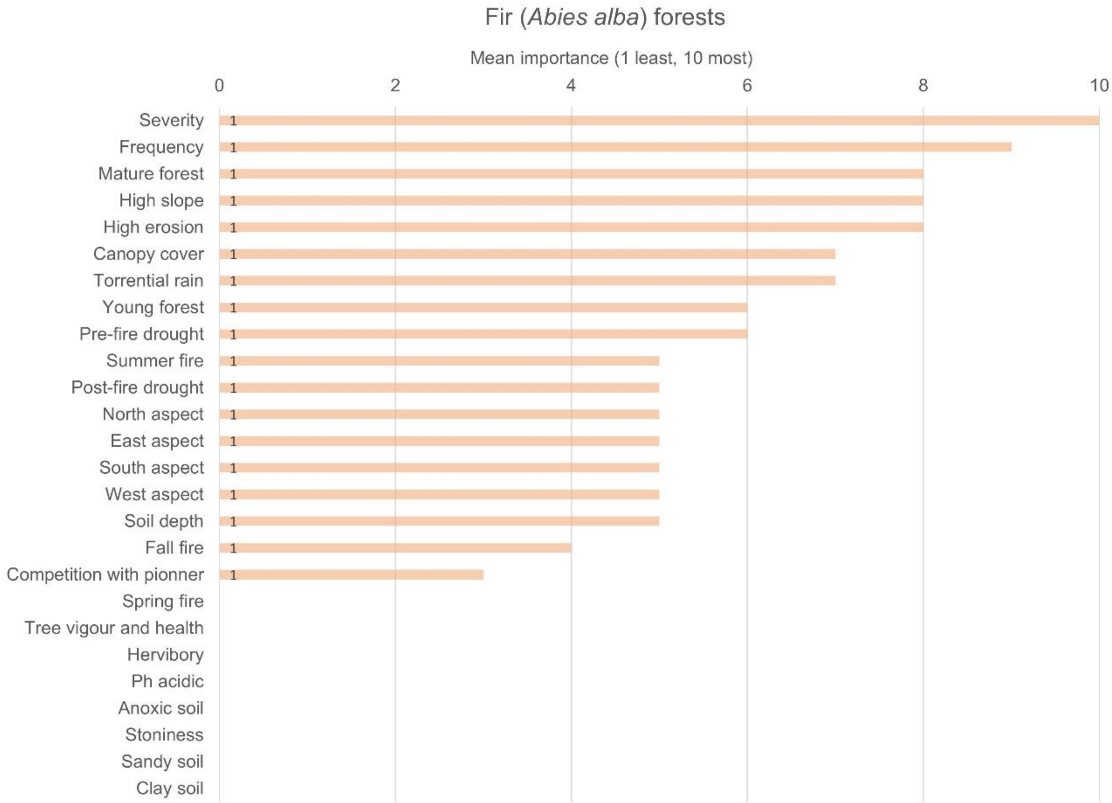

Figure 7. Mean importance and standard deviation of punctuation assigned by experts for fire regime, pre-fire vegetation, post-fire short-term competition, climatic, soil and topographic factors influencing post-fire recovery of fir Abies alba forests. The order of the factors was ranked from most important to least important. The number of responses given to each factor is indicated within the bars.

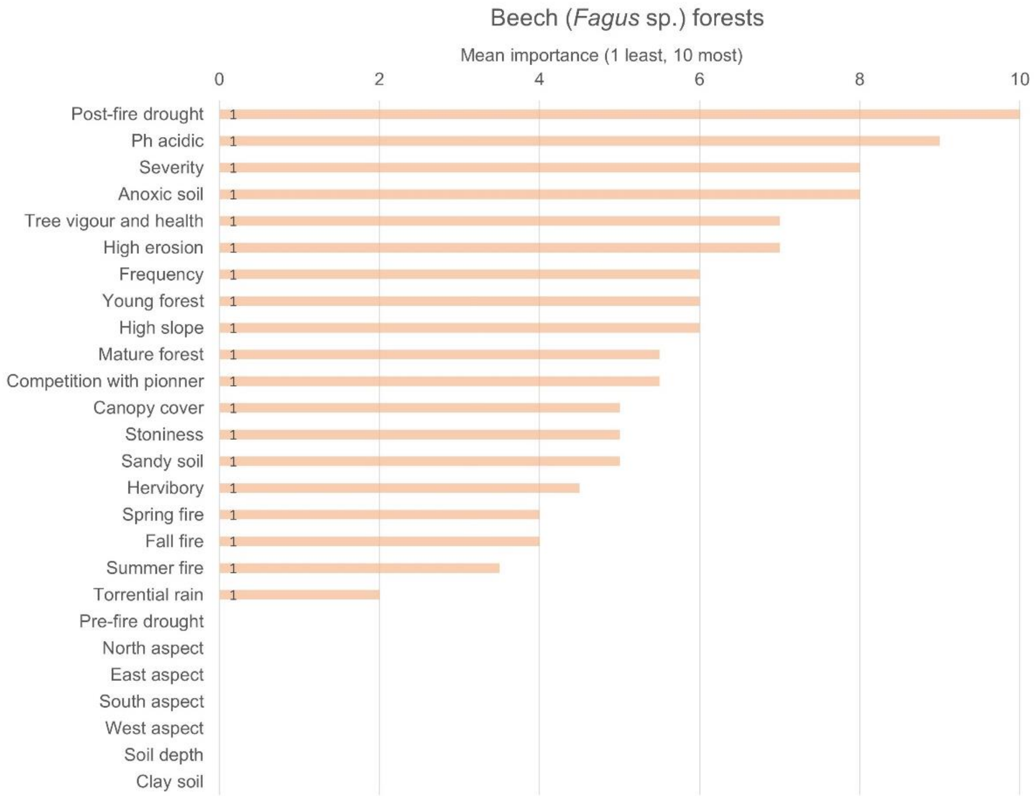

Figure 8. Mean importance and standard deviation of punctuation assigned by experts for fire regime, pre-fire vegetation, post-fire short-term competition, climatic, soil and topographic factors influencing post-fire recovery of beech (Fagus sp.) forests. The order of the factors was ranked from most important to least important. The number of responses given to each factor is indicated within the bars.

6 Summary: criteria to identify vulnerable areas for restoration before and after fire occurrence

Based on the literature review and the results of the survey presented in section 5, a summary table has been developed outlining key factors, metrics, and thresholds for predicting the areas that may show (at the short-term) slow post-fire plant recovery rates. Restoration action to avoid soil degradation should be prioritized in these areas.

Table 3. Summary of key factors, metrics and thresholds for identifying high priority areas for post-fire restoration. The threshold values given are from the literature review, (-) denotes thresholds not found. The priority of forest types and species was determined based on their fire-related traits and assuming that they burn outside their reference fire regime.

Dominant species post-fire regeneration strategy	**Species priority**	**Pre-fire factors and associated thresholds**						**Post and fire-regime factors and associated thresholds**		
		Individual characteristics	**Pre-fire stand or landscape characteristics**	**Aspect**	**Slope**	**Soil**	**Pre-fire drought**	**Fire frequency (years)**	**Fire season**	**Post- fire drought**
1. Lack of post-fire related traits	*1. P. abies*	DBH <20 cm	Canopy cover[2]	South	>35º	Depth[2]	Important [2]	<200	Summer[1]	Moisture deficit in spring
	2. A. alba	DBH <20 cm	-	-	-	-	-	<200	Summer[1]	-
Post-fire colonizer	*1. P. mugo*	-	-	-	-	-	-	No effect	-	-
	2. L. decidua	-	-	-	-	-	-	>150	-	-
	3. P. cembra	-	-	-	-		-	<80	-	-
	4. P. sylvestris	DBH <20 cm	Canopy cover[2]	-	-	-	Important [2]	>10	Spring	Moisture deficit in spring
	5. P. nigra	DBH < 20 cm	Canopy cover< 50%	South	-	-	-	>10	-	Below-average precipitation in the months after fire
	6. P. pinea	Bark thick. < 2cm		-	-	-	-	-	-	-
3. Seeders	*1. P. pinaster*	Age < 20 years		South	-		-	<10	Spring	Drought stress in the

			Undestory of obligate seeders							first post-fire summer
	2. P. halepensis	Age < 20 years	Low tree density Undestory of obligate seeders	South	>25%	-	No effect	<10	Spring	Warm conditions
	3. C. vulgaris	Age > 40 years	-	-	-	-	-	> 40	-	-
4. Resprouters	*1. F. sylvatica*	DBH < 12 cm	-	South	Negative effect	-	-	< 15	No data for all species. For resprouting species, the end of summer or autumn seems worse.	-
	2. C. sativa	No specific data but the smaller the individual the less resprouting vigour.		-	-	-	-			-
	3. F. angustifolia		-	-	-	-	-			Continentality index >27
	4. B. pendula		-	-	-	-	-			-
	5. P. tremula		-	-	-	-	-			-
	6. Q. pubescens		Tree density <200 tree ha^{-1} Time since cropland abandonment	-	-	-	-			-
	7. Q. robur			South	-	-	-			-
	8. Q. coccifera			South	-	Bedrock: marls	-	<5		-
	9. Q. ilex			-	-		-	<5		-
	10. C. vulgaris	Age < or > 15 years	-	-	-	-	-	< or > 15	Spring	-
	11. Q. suber	DBH < 12 cm	-	South, Southwest, East	Flat	-	-	< 12	No data but end	-

									summer or fall.	
	12. P. canariensis	No effect		-	-		-		No data but end summer or fall.	

[1]As compared with winter fires.
[2] From the questionary results.

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8 Appendices

8.1 Preliminary dominant species selected

Table 3. Preliminary selection of species for conducting the literature review on the influence of different factors on post-fire recovery. The selection of species was based on the work of Pividori et al., (2016)*, who classified the species presence for each European forest type (EFT) of the EFT classification into three classes: the species is abundant and dominant in the EFT; the species presence in the EFT is either secondary or predominant, but under particular and uncharacteristic ecological conditions of the EFT; the presence in the EFT is in some cases both dominant and secondary. Only species that were abundant and dominant in a given EFT were selected from these categories.*

Dominat species	Category	Forest type
Abies alba	2. Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest	2.8 Nemoral silver fir
	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.6 Mediterranean and Anatolian fir forest
Picea abies	1. Boreal forest	1.1 Spruce and spruce-birch boreal forest
	2. Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest	2.1 Hemiboreal forest
		2.3 Nemoral spruce forest
	3. Alpine coniferous forest	3.2 Subalpine and mountainous spruce and mountainous mixed spruce-silver fir forest
	11. Mire and swamp forest	11.1 Spruce mire forest
Larix decidua	3. Alpine coniferous forest	3.1 Subalpine larch-arolla pine and dwarf pine forest
Pinus pinaster	2. Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest	2.7 Atlantic maritime pine forest
	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.1.1 Mediterranean pine forest - Pinus pinaster
Pinus nigra	2. Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest	2.4 Nemoral Black pine forest
	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.2.1 Mediterranean Black pine forest
		10.2.2 Anatolian Black pine forest
Pinus sylvestris	1. Boreal forest	1.2 Pine and pine-birch boreal forest
	2. Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest	2.1 Hemiboreal forest
		2.2 Nemoral Scots pine forest
		2.5 Mixed Scots pine-birch forest

	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.4 Mediterranean and Anatolian Scots pine forest
	11. Mire and swamp forest	11.2 Pine mire forest
Pinus mugo	3. Alpine coniferous forest	3.1 Subalpine larch-arolla pine and dwarf pine forest
Pinus halepensis	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.1.2 Mediterranean pine forest - Pinus halepensis
Pinus pinea	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.1.3 Mediterranean pine forest - Pinus pinea
Pinus cembra	3. Alpine coniferous forest	3.1 Subalpine larch-arolla pine and dwarf pine forest
Pinus canariensis	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.3 Canarian pine forest
Cupressus sempervirens	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.8 Cypress forest
Cedrus libani	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.9 Cedar forest
Cedrus brevifolia	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.9 Cedar forest
Tetraclinis articulata	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.10 Tetraclinis articulata stands
Taxus baccata	10. Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions	10.11 Mediterranean yew stands
Populus tremula	11. Mire and swamp forest	11.6 Aspen swamp forest
	13. Non riverine alder, birch, or aspen forest	13.4 Aspen forest
Betula pubescens	3. Alpine coniferous forest	3.4 Mountainous birch forest
	13. Non riverine alder, birch, or aspen forest	13.3 Birch forest
Betula pendula	11. Mire and swamp forest	11.4 Birch swamp forest
	13. Non riverine alder, birch, or aspen forest	13.3 Birch forest
Alnus viridis	13. Non riverine alder, birch, or aspen forest	13.1 Alder forest
Alnus cordata	13. Non riverine alder, birch, or aspen forest	13.1 Alder forest
		13.2 Italian alder forest
Carpinus betulus	5. Mesophytic deciduous forest	5.1 Pedunculate oak–hornbeam forest
		5.2 Sessile oak–hornbeam forest
	6. Beech forest	6.2 Atlantic and subatlantic lowland beech forest
Carpinus orientalis	8. Thermophilous deciduous forest	8.8.4 Oriental hornbeam (Carpinus orientalis) forest
Ostrya carpinifolia	8. Thermophilous deciduous forest	8.8.3 Hop-hornbeam (Ostrya carpinifolia) forest

Fagus sylvatica	6. Beech forest	6.1 Lowland beech forest of southern Scandinavia and north central Europe
		6.2 Atlantic and subatlantic lowland beech forest
		6.3 Subatlantic submountainous beech forest
		6.4 Central European submountainous beech forest
		6.5 Carpathian submountainous beech forest
		6.6 Illyrian submountainous beech forest
		6.7 Moesian submountainous beech forest
	7. Mountainous beech forest	7.1 South western European mountainous beech forest
		7.2 Central European mountainous beech forest
		7.3 Apennine-Corsican mountainous beech forest
		7.4 Illyrian mountainous beech forest
		7.5 Carpathian mountainous beech forest
		7.6 Moesian mountainous beech forest
Fagus moesiaca	6. Beech forest	6.5 Carpathian submountainous beech forest
		6.7 Moesian submountainous beech forest
	7. Mountainous beech forest	7.4 Illyrian mountainous beech forest
		7.6 Moesian mountainous beech forest
		7.7 Crimean mountainous beech forest
Fagus orientalis	6. Beech forest	6.5 Carpathian submountainous beech forest
Castanea sativa	8. Thermophilous deciduous forest	8.7 Chestnut forest
Quercus coccifera	9. Broadleaved evergreen forest	9.1 Mediterranean evergreen oak forest
Quercus ilex	9. Broadleaved evergreen forest	9.1 Mediterranean evergreen oak forest
Quercus suber	9. Broadleaved evergreen forest	9.1 Mediterranean evergreen oak forest
Quercus trojana	8. Thermophilous deciduous forest	8.5 Macedonian oak forest
Quercus robur	11. Mire and swamp forest	11.5 Pedunculate oak swamp forest
Quercus pubescens	8. Thermophilous deciduous forest	8.1.1 Downy oak forest - western
		8.1.2 Downy oak forest - Italian
		8.1.3 Downy oak forest - Greek, Anatolian

		8.1.4 Downy oak forest - steppe
Ulmus grabra	5. Mesophytic deciduous forest	5.8 Ravine and slope forest
Celtis australis	8. Thermophilous deciduous forest	8.8.7 Celtis australis forest
Acer pseudoplatanus	5. Mesophytic deciduous forest	5.8 Ravine and slope forest
Tilia cordata	5. Mesophytic deciduous forest	5.7 Lime forest
Tilia platyphyllos	5. Mesophytic deciduous forest	5.8 Ravine and slope forest
Fraxinus excelsior	5. Mesophytic deciduous forest	5.8 Ravine and slope forest
Fraxinus angustifolia	8. Thermophilous deciduous forest	8.8.1 Thermophilous ash forest

8.2 Literature review: search strategy

For the species that were abundant and dominant in a given European Forest Type we conducted a systematic literature review and searched in the ISI Web of Knowledge for European studies that addressed how, fire regime, soil characteristics, topography, landscape structure influences post-fire regeneration. The keyword search used various combinations of relevant terms (Table 4). The search resulted in a significant number of articles, that were filtered by country and only those conducted in Europe were selected. Then, those papers containing thresholds for each factor driving post-fire recovery or regeneration were selected.

Table 4. Keyword searches for each factor driving post-fire regeneration.

Factor	Keywords	Number of selected studies
Fire severity	Species scientific name AND fire severity AND post-fire regeneration OR post-fire recovery OR resistance	21
	Selected studies for fire severity: 1. Bär, A., Schröter, D. M., & Mayr, S. (2021). When the heat is on: High temperature resistance of buds from European tree species. *Plant Cell and Environment*, *44*(8), 2593–2603. https://doi.org/10.1111/pce.14097 2. Battipaglia, G., Savi, T., Ascoli, D., Castagneri, D., Esposito, A., Mayr, S., & Nardini, A. (2016). Effects of prescribed burning on ecophysiological, anatomical and stem hydraulic properties in Pinus pinea L. . *Tree Physiology*, *36*(8), 1019–1031. https://doi.org/10.1093/treephys/tpw034 3. Casals, P., Valor, T., Rios, A. I., & Shipley, B. (2018). Leaf and bark functional traits predict resprouting strategies of understory woody species after prescribed fires. *Forest Ecology and Management*, *429*(July), 158–174. https://doi.org/10.1016/j.foreco.2018.07.002 4. Catry, F. X., Rego, F., Moreira, F., Fernandes, P. M., & Pausas, J. G. (2010). Post-fire tree mortality in mixed forests of central Portugal. *Forest Ecology and Management*, *260*(7), 1184–1192. https://doi.org/10.1016/j.foreco.2010.07.010 5. Davies, G. M. (2006). *Fire behaviour and impact on heather moorland*. 6. Fernandes, P. M., Vega, A., & Jime, E. (2008). *Forest Ecology and Management Fire resistance of European pines*. 1–10. https://doi.org/10.1016/j.foreco.2008.04.032 7. Liacos, L. G. (2015). Present Studies and History of Burning in Greece. *Fire Ecology*, *11*(3), 3–13. https://doi.org/10.1007/BF03400631 8. Lloret, F., & López-Soria, L. (1993). Resprouting of Erica multiflora after experimental fire treatments. *Journal of Vegetation Science*, *4*(3), 367–374. 9. MacDonald, A. J., Kirkpatrick, A. H., Hester, A. J., & Sydes, C. (1995). Regeneration by Natural Layering of Heather (Calluna vulgaris): Frequency and Characteristics in Upland Britain. *Journal of Applied Ecology*, *32*(1), 85–99. https://doi.org/10.2307/2404418 10. Madrigal, J., Souto-García, J., Calama, R., Guijarro, M., Picos, J., & Hernando, C. (2019). Resistance of *Pinus pinea* L. bark to fire. *International Journal of Wildland Fire*, *28*(5), 342–353. https://doi.org/10.1071/WF18118 11. Maringer, J., Ascoli, D., Kuffer, N., Schmidtlein, S., & Conedera, M. (2016). What drives European beech (Fagus sylvatica L.) mortality after forest fires of varying severity? *FOREST ECOLOGY AND MANAGEMENT*, *368*, 81–93. https://doi.org/10.1016/j.foreco.2016.03.008 12. Martín-Alcón, S., & Coll, L. (2016). Unraveling the relative importance of factors driving post-fire regeneration trajectories in non-serotinous Pinus nigra forests. *Forest Ecology and Management*, *361*, 13–22. 13. Martínez, E., Madrigal, J., Hernando, C., Guijarro, M., Vega, J. A., Pérez-Gorostiaga, P., Fonturbel, M. T., Cuiñas, P., Alonso, M., & Beloso, M. C. (2002). Effect of fire intensity on seed dispersal and early regeneration in a Pinus pinaster forest. *Forest Fire Research and Wildland Fire Safety: Proceedings of IV International Conference on Forest Fire Research 2002 Wildland Fire Safety Summit, Luso, Coimbra, Portugal, 18-23 November 2002*. 14. Matt Davies, G., Adam Smith, A., MacDonald, A. J., Bakker, J. D., & Legg, C. J. (2010). Fire intensity, fire severity and ecosystem response in heathlands: Factors affecting the regeneration of Calluna vulgaris. *Journal of Applied Ecology*, *47*(2), 356–365. https://doi.org/10.1111/j.1365-2664.2010.01774.x 15. Moris, J. V, Vacchiano, G., Ravetto Enri, S., Lonati, M., Motta, R., & Ascoli, D. (2017). Resilience of European larch (Larix decidua Mill.) forests to wildfires in the western Alps. *NEW FORESTS*, *48*(5),	

663–683. https://doi.org/10.1007/s11056-017-9591-7

16. Ordóñez, J. L., Molowny-Horas, R., & Retana, J. (2006). A model of the recruitment of Pinus nigra from unburned edges after large wildfires. *Ecological Modelling*, *197*(3–4), 405–417.
17. Ordóñez, J. L., Retana, J., & Espelta, J. M. (2005). Effects of tree size, crown damage, and tree location on post-fire survival and cone production of Pinus nigra trees. *Forest Ecology and Management*, *206*(1–3), 109–117.
18. Rigolot, E. (2004). Predicting postfire mortality of Pinus halepensis Mill. and Pinus pinea L. *Plant Ecology*, *171*(1–2), 139–151.
19. Rodrigo, A., Quintana, V., & Retana, J. (2007). Fire reduces Pinus pinea distribution in the northeastern Iberian Peninsula. *Ecoscience*, *14*(1), 23–30. https://doi.org/10.2980/1195-6860(2007)14[23:FRPPDI]2.0.CO;2
20. Valor, T., González-Olabarria, J. R., Piqué, M., & Casals, P. (2017). The effects of burning season and severity on the mortality over time of Pinus nigra spp. salzmannii (Dunal) Franco and P. sylvestris L. *Forest Ecology and Management*, *406*(June), 172–183. https://doi.org/10.1016/j.foreco.2017.08.027
21. Vega, J. A., Fernández, C., Pérez-Gorostiaga, P., & Fonturbel, T. (2010). Response of maritime pine (Pinus pinaster Ait.) recruitment to fire severity and post-fire management in a coastal burned area in Galicia (NW Spain). *Plant Ecology*, *206*(2), 297–308. https://doi.org/10.1007/s11258-009-9643-y

Fire frequency

Species scientific name AND fire frequency AND post-fire regeneration OR post-fire recovery OR resistance	21

Selected studies for fire frequency:

1. Ananyev, V. A., Timofeeva, V. V., Kryshen’, A. M., Pekkoev, A. N., Kostina, E. E., Ruokolainen, A. V., Moshnikov, S. A., Medvedeva, M. V., Polevoi, A. V., & Humala, A. E. (2022). Fire Severity Controls Successional Pathways in a Fire-Affected Spruce Forest in Eastern Fennoscandia. *Forests*, *13*(11). https://doi.org/10.3390/f13111775
2. Ascoli, D., & Bovio, G. (2010). Tree encroachment dynamics in heathlands of north-west Italy: the fire regime hypothesis. *IForest - Biogeosciences and Forestry*, *3*(5), 137. https://doi.org/10.3832/IFOR0548-003
3. Bonfil, C., Cortés, P., Espelta, J. M., & Retana, J. (2004). The role of disturbance in the co-existence of the evergreen Quercus ilex and the deciduous Quercus cerrioides. *Journal of Vegetation Science*, *15*(3), 423–430. https://doi.org/10.1111/j.1654-1103.2004.tb02280.x
4. Carter, V. A., Moravcová, A., Chiverrell, R. C., Clear, J. L., Finsinger, W., Dreslerová, D., Halsall, K., & Kuneš, P. (2018). Holocene-scale fire dynamics of central European temperate spruce-beech forests. *Quaternary Science Reviews*, *191*, 15–30. https://doi.org/10.1016/j.quascirev.2018.05.001
5. Curt, T., Bertrand, R., Borgniet, L., Ferrieux, T., & Marini, E. (2010). The impact of fire recurrence on populations of Quercus suber in southeastern France. *VI International Conference on Forest Fire Research*, 10-p.
6. Davies, G. M., & Legg, C. J. (2008). The effect of traditional management burning on lichen diversity. *Applied Vegetation Science*, *11*(4), 529–538. https://doi.org/10.3170/2008-7-18566
7. Esseen, P.-A., Ehnström, B., Ericson, L., & Sjöberg, K. (1997). Boreal forests. *Ecological Bulletins*, 16–47.
8. Fernández-García, V., Fulé, P. Z., Marcos, E., & Calvo, L. (2019). The role of fire frequency and severity on the regeneration of Mediterranean serotinous pines under different environmental conditions. *Forest Ecology and Management*, *444*(March), 59–68. https://doi.org/10.1016/j.foreco.2019.04.040
9. Ferran, A., Delitti, W., & Vallejo, V. R. (2005). Effects of fire recurrence in Quercus coccifera L. shrublands of the Valencia Region (Spain): II. plant and soil nutrients. *Plant Ecology*, *177*, 71–83.
10. Feurdean, A., Florescu, G., Vannière, B., Tanţău, I., O’Hara, R. B., Pfeiffer, M., Hutchinson, S. M., Gałka, M., Moskal-del Hoyo, M., & Hickler, T. (2017). Fire has been an important driver of forest dynamics in the Carpathian Mountains during the Holocene. *Forest Ecology and Management*, *389*, 15–26. https://doi.org/10.1016/j.foreco.2016.11.046
11. Feurdean, A., Tonkov, S., Pfeiffer, M., Panait, A., Warren, D., Vannière, B., & Marinova, E. (2019). Fire frequency and intensity associated with functional traits of dominant forest type in the Balkans during the Holocene. *European Journal of Forest Research*, *138*(6), 1049–1066. https://doi.org/10.1007/s10342-019-01223-0
12. Finsinger, W., Fevre, J., Orbán, I., Pál, I., Vincze, I., Hubay, K., Birks, H. H., Braun, M., Tóth, M., & Magyari, E. K. (2018). Holocene fire-regime changes near the treeline in the Retezat Mts. (Southern Carpathians, Romania). *Quaternary International*, *477*(May), 94–105. https://doi.org/10.1016/j.quaint.2016.04.029
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Fire season

Species scientific name AND fire season AND post-fire regeneration OR post-fire recovery OR resistance	12

Selected studies for fire season:

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<table>
<tr><td></td><td colspan="2"></td></tr>
<tr><td rowspan="2">Topography (Aspect and Slope)</td><td>Species scientific name AND aspect/slope AND post-fire regeneration OR post-fire recovery OR resistance</td><td>19</td></tr>
<tr><td colspan="2">Selected studies for topography:
1. Arianoutsou, M., Koukoulas, S., & Kazanis, D. (2011). Evaluating Post-Fire Forest Resilience Using GIS and Multi-Criteria Analysis: An Example from Cape Sounion National Park, Greece. ENVIRONMENTAL MANAGEMENT, 47(3), 384–397. https://doi.org/10.1007/s00267-011-9614-7
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11. Monteiro-Henriques, T., & Fernandes, P. M. (2018). Regeneration of native forest species in Mainland Portugal: Identifying main drivers. Forests, 9(11). https://doi.org/10.3390/f9110694
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<tr><td rowspan="2">Soil characteristics</td><td>Species scientific name AND soil AND post-fire regeneration OR post-fire recovery OR resistance</td><td>5</td></tr>
<tr><td colspan="2">Selected studies for soil charactersitics:
1. Christopoulou, A., Mallinis, G., Vassilakis, E., Farangitakis, G. P., Fyllas, N. M., Kokkoris, G. D., &</td></tr>
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<table>
<tr><td></td><td colspan="2">Arianoutsou, M. (2019). Assessing the impact of different landscape features on post-fire forest recovery with multitemporal remote sensing data: The case of Mount Taygetos (southern Greece). International Journal of Wildland Fire, 28(7), 521–532. https://doi.org/10.1071/WF18153
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<tr><td rowspan="2">Climate</td><td>Species scientific name AND fire severity AND post-fire regeneration OR post-fire recovery OR resistance</td><td>13</td></tr>
<tr><td colspan="2">Selected studies for climate:
1. Calvo, L., Santalla, S., Valbuena, L., Marcos, E., Tárrega, R., & Luis-Calabuig, E. (2008). Post-fire natural regeneration of a Pinus pinaster forest in NW Spain. Plant Ecology, 197(1), 81–90. https://doi.org/10.1007/s11258-007-9362-1
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7. Konstantinidis, P., Tsiourlis, G., & Galatsidas, S. (2005). Effects of wildfire season on the resprouting of kermes oak (Quercus coccifera L.). Forest Ecology and Management, 208(1–3), 15–27. https://doi.org/10.1016/j.foreco.2004.09.021
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11. Pausas, J. G., Ribeiro, E., & Vallejo, R. (2004). Post-fire regeneration variability of Pinus halepensis in the eastern Iberian Peninsula. FOREST ECOLOGY AND MANAGEMENT, 203(1–3), 251–259. https://doi.org/10.1016/j.foreco.2004.07.061
12. Röder, A., Hill, J., Duguy, B., Alloza, J. A., & Vallejo, R. (2008). Using long time series of Landsat data to monitor fire events and post-fire dynamics and identify driving factors. A case study in the Ayora region (eastern Spain). Remote Sensing of Environment, 112(1), 259–273. https://doi.org/10.1016/j.rse.2007.05.001
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8.3 Questionnaire

FACTORS DRIVING RESISTANT AND RESILIENT LANDSCAPES TO EXTREME WILDFIRE EVENTS AND POST-FIRE DYNAMICS

FIRE-RES -Innovative technologies and socio-ecological-economic solutions for re resilient territories in Europe - (https:// re-res.eu/) is an ongoing Horizon 2020 project (2021-2025). FIRE-RES aims to promote the implementation of an integrated re management approach and support the transition to more resilient landscapes and communities to extreme wild re events (EWE) in Europe. The mission of FIRE-RES is to promote the European Union's socio-ecological transition to a resilient continent through the development of a series of innovation actions.

One of the objectives is to develop general recommendations and management alternatives to promote adaptive management for resilient landscapes to EWE. To this end, we conducted a systematic literature review to identify ecological factors, metrics, and thresholds that determine landscape and stand resistance and resilience to EWE and post- re dynamics. Most of the identified factors and thresholds were found for southern Mediterranean countries and are related to large and intense wild res only a few for EWE. Therefore, the main objective of the questionnaire is to collect experts' views on the thresholds of different fuel-related factors to prevent the development of EWE and data for Central and Northern Europe, where wildfires are not yet so common in these relatively humid regions, but where an increase in the frequency and intensity of wild res can be expected. This is a key issue because the importance of fuel-related factors and thresholds that determine resistance and resilience may vary by biogeographic area and wildfire type. By examining the relative importance of factors, we hope to provide a basis for developing recommendations for building or maintaining stand and landscape resilience and resistance to intense wild re and EWE.

The survey consists of three main sections: First, some brief questions about your background, then questions about the factors that determine the resilience and resistance of stands and landscapes to EWE, and finally questions about the factors that determine post- re dynamics.

IT SHOULD NOT TAKE MORE THAN 15 MINUTES TO FILL OUT THIS SURVEY

Thank you in advance for taking the time to complete this survey.

*Required

INFORMED CONSENT*

Within FIRE-RES Project, part of the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101037419, you are invited to participate in the following survey on fuel-related factors, metrics and thresholds driving extreme wildfire events and post-fire dynamics. From CTFC, we thank you for your participation.

The information collected in this questionnaire is anonymous and absolutely confidential. Your name will not appear in any report or result. The results will be used for reseach/technical purposes only.

Your participation in this research study is voluntary. You may choose not to participate. If you decide to participate in this activity, you may withdraw at any time.

Tick all that apply.

☐ I have understood the contents and objectives of the questionnaire and I consent to participate voluntarily.

DATA PROTECTION *

CTFC as Data controller, collects this data through Google Forms to carry out a study on experts' views on the thresholds of different fuel-related factors to prevent the development of EWE and data for Central and Northern Europe. By checking the acceptance box, you give your consent. The data will not be transferred to any country or international organization outside European Union. This information will be stored on Google's servers. You can see their privacy policy at https://policies.google.com/privacy?hl=en and the CTFC Privacy Policy at https://www.ctfc.cat/en/protecciodades.php

INFORMATION ON DATA PROTECTION

Data controller: Forest Science and Technology Centre of Catalonia (CTFC) Aim: Data collection to assess the factors, metrics and thresholds driving extreme wildfire events and post-fire dynamics.

Data processor: Google Ireland Limited.

Type of data: name and surnames, email, profession, expertise, country. Rights: Acces, rectify, oppose the use, limit the use and delete your data specify in CTFC privacy policy. You can also contact us at: dpd.ctfc@ctfc.cat Duration: Your data will be stored for the time necessary to carry out the purposes for which it was collected or until you revoke your consent.

Tick all that apply.

☐ I have read and accept the CTFC Privacy Policy.

YOUR BACKGROUND

Q1) We need basic information on your expertise.

A) Can you tell us which bioregion you consider yourself an expert? Please, * select just one.

Mark only one oval.

- Macaronesia
- Mediterranean
- Atlantic
- Alpine
- Continental
- Boreal
- Other:

B) Can you tell us what aspects of wildfires you consider yourself an expert in? * Select as many options as you need.

Tick all that apply.

- Fire behaviour
- Fuel management
- Fire ecology
- Post- re management
- Other:

C) What is your professional position? *

Mark only one oval.

- Academic (Researcher, Post-doctoral researcher, PhD student)
- Forest manager
- Fire responder (Wildfire analyst, fire fighter)
- Other:

D) How many years of experience do you have in your position? *

E) Can you tell us in which specific country do you carry out your activity? *

FACTORS DRIVING RESISTANT AND RESILIENT LANDSCAPES TO EWE

Definitions of EWE, forest resistance and resilience are provided below to be considered while answering to the questionnaire.

EWE: wild res with large-scale complex interactions between re and atmosphere generating pyroconvective behaviour, coupling processes, that results in fast, intense, uncertain, and fast-paced changing re behaviour. It results in re behaviour exceeding the technical limits of control (fireline intensity 10.000 kW/m; rate of spread >50 m/min; spotting distance >1 km and exhibiting prolific to massive spotting based on Tedim et al. 2018, and extreme growth of rate (surface per hour, ha/h) values). At the same time, given current operational models, this extreme re behaviour is unpredictable, with moments of observed re behaviour well surpassing the expected. This overwhelms the decision-making capabilities from the emergency system. It may represent a heightened threat to crews, population, assets, and natural values, as well as have relevant negative socioeconomic and environmental impacts.

FOREST RESISTANCE: the ability of the ecological system to persist through the disturbance event. That is, the capacity to continue providing functions and ecosystem services immediately after the event. At the stand level, resistance could be inferred from the influence of forest structure and composition on severity and intensity. At the landscape level, resistance could be inferred from the spatial configuration and composition of patches on the rate of re spread (Derose and Long, 2014).

FOREST RESILIENCE: the ability of the ecological system to recover the functions and ecosystem services that the system provided before the re. In the case of wild re, resilience could be de ned as the effect of re on subsequent forest structure and composition (at the stand level) and on subsequent proportions of age classes and on species dominance in the landscape (at the landscape level) (Derose & Long, 2014). Resilience depends on the characteristics of the system (e.g., diversity of plant responses to re), the event (e.g., intensity), and the presence of additional stresses before and after the re event (e.g., prolonged drought, pest outbreaks, torrential rains, etc.).

Tedim, F., Leone, V., Amraoui, M., Bouillon, C., Coughlan, M. R., Delogu, G. M., ... & Xanthopoulos, G. (2018). De ning extreme wild re events: Di culties, challenges, and impacts. Fire, 1(1), 9.

Derose, R. J., & Long, J. N. (2014). Resistance and resilience: a conceptual framework for silviculture. Forest Science, 60 (6), 1205–1212.

POST-FIRE DYNAMICS

Previous studies have shown that fire impacts and post-fire dynamics are influenced by a number of factors related to pre-fire vegetation, fire event, landscape structure, soil properties, and topography. However, most of these studies have been conducted in fire-prone areas or are related to a specific fire event, while there is a lack of information for boreal, continental, and alpine regions.

Q9) The dropdown menu in A and B (below) includes some vegetation types from boreal, alpine, and continental bioregions for which there is not as much information on post-fire impacts and dynamics. In order to make recommendations for post-fire management and set priorities, we need to know the importance of the different factors that influence their post-fire dynamics. Select a maximum of two vegetation types (one from A and the other, if you wish, from B) for which you have more experience or knowledge, and then go to C, D, E (First vegetation type) and F, G and H (Second vegetation type).

If you select "I have limited experience or knowledge of these types of vegetation" from the BOTH dropdown menu of A and B, you can skip C, D, E, F, G, and H and submit your answers.

A) FIRST vegetation type *

Mark only one oval.

- I have limited experience or knowledge of these types of vegetation.
- Hemiboreal Mountain pine (Pinus mugo) forests
- Hemiboreal and continental Scots pine (Pinus sylvestris) forests
- Alpine Scots pine or Black pine (Pinus nigra) in the Alps or Pinus uncinata in the pyrenees forests
- Subalpine larch (Larix sp.) forests
- Spruce (Picea abies) forests
- Fir (Abies alba) forests
- Tall deciduous oak (Quercus sp.) forest
- Mixed Quercus sp. and Fraxinus forests
- Beech (Fagus sp.) forests
- Swiss stone pine (Pinus cembra) forests

B) SECOND vegetation type *

Mark only one oval.

- I have limited experience or knowledge of these types of vegetation.
- Hemiboreal Mountain pine (Pinus mugo) forests
- Hemiboreal and continental Scots pine (Pinus sylvestris) forests
- Alpine Scots pine or Black pine (Pinus nigra) in the Alps or Pinus uncinata in the pyrenees forests
- Subalpine larch (Larix sp.) forests
- Spruce (Picea abies) forests
- Fir (Abies alba) forests
- Tall deciduous oak (Quercus sp.) forest
- Mixed Quercus sp. and Fraxinus forests
- Beech (Fagus sp.) forests

C) FIRST vegetation type (if selected):

For each of the following metrics related to fire regime, pre-fire vegetation, and postfire short-term competition, give a rating from 1 to 10 according to its importance in limiting post-fire recovery of the selected vegetation type (1 irrelevant, 10 very important; move the horizontal scroll bar to view all ratings).

Mark only one oval per row.

	I do not know	1	2	3	4	5	6	7
Fire severity	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Fire frequency	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Summer fire	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Spring fire	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Fall fire	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Young forest	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Mature forest	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Canopy cover (%)	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Tree vigour and health	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Hervibory	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Competition with pioneer species	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

Is there any comment you would like to share (e.g., any missing factor, explain in more detail a factor)?

D) FIRST vegetation type (if selected):

For each of the following metrics related to climatic and topographic factors, give a rating from 1 to 10 according to its importance in limiting post-fire recovery of the selected vegetation type (1 irrelevant, 10 very important; move the horizontal scroll bar to view all ratings).

Mark only one oval per row.

	I do not know	1	2	3	4	5	6	7
Pre-fire: Long drought event								
Post fire: Long drought event								
Post-fire: Torrential rain								
Slope: High								
Aspect: North								
Aspect: East								
Aspect: South								
Aspect: West								

Is there any comment you would like to share (e.g., any missing factor, explain in more detail a factor)?

E) FIRST vegetation type (if selected):

For each of the following metrics related to soil characteristics, give a rating from 1 to 10 according to its importance in limiting post-fire recovery of the selected vegetation type (1 irrelevant, 10 very important; move the horizontal scroll bar to view all ratings).

Mark only one oval per row.

	I do not know	1	2	3	4	5	6	7
pH acidic								
High erosion								
Anoxic soil								
Stoniness								
Soil depth								
Sandy soil								
Clay soil								

Is there any comment you would like to share (e.g., any missing factor, explain in more detail a factor)?

F) SECOND vegetation type (if selected):

For each of the following metrics related to fire regime, pre-fire vegetation, and postfire short-term competition, give a rating from 1 to 10 according to its importance in limiting post-fire recovery of the selected vegetation type (1 irrelevant, 10 very important; move the horizontal scroll bar to view all ratings).

Mark only one oval per row.

	I do not know	1	2	3	4	5	6	7
Fire severity	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Fire frequency	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Summer fire	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Spring fire	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Fall fire	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Young forest	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Mature forest	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Canopy cover (%)	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Tree vigour and health	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Hervibory	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Competition with pioneer species	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

Is there any comment you would like to share (e.g., any missing factor, explain in more detail a factor)?

G) SECOND vegetation type (if selected):

For each of the following metrics related to climatic and topographic factors, give a rating from 1 to 10 according to its importance in limiting post-fire recovery of the selected vegetation type (1 irrelevant, 10 very important; move the horizontal scroll bar to view all ratings).

Mark only one oval per row.

	I do not know	1	2	3	4	5	6	7
Pre-fire: Long drought event								
Post fire: Long drought event								
Post-fire: Torrential rain								
Slope: High								
Aspect: North								
Aspect: East								
Aspect: South								
Aspect: West								

Is there any comment you would like to share (e.g., any missing factor, explain in more detail a factor)?

H) SECOND vegetation type (if selected):

For each of the following metrics related to soil characteristics, give a rating from 1 to 10 according to its importance in limiting post-fire recovery of the selected vegetation type (1 irrelevant, 10 very important; move the horizontal scroll bar to view all ratings).

Mark only one oval per row.

	I do not know	1	2	3	4	5	6	7
pH acidic	◯	◯	◯	◯	◯	◯	◯	◯
High erosion	◯	◯	◯	◯	◯	◯	◯	◯
Anoxic soil	◯	◯	◯	◯	◯	◯	◯	◯
Stoniness	◯	◯	◯	◯	◯	◯	◯	◯
Soil depth	◯	◯	◯	◯	◯	◯	◯	◯
Sandy soil	◯	◯	◯	◯	◯	◯	◯	◯
Clay soil	◯	◯	◯	◯	◯	◯	◯	◯

Is there any comment you would like to share (e.g., any missing factor, explain in more detail a factor)?

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