FIRE-RES

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

D1.11 ECOLOGICAL FACTORS DRIVING RESISTANT AND RESILIENT LANDSCAPES TO HIGH INTENSITY AND EXTREME WILDFIRE EVENTS

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Project Acronym: FIRE-RES

Project name: Innovative technologies and socio-ecological-economic solutions for fire resilient territories in Europe

Call ID: H2020-LC-GD-1-1-2020 (Preventing and fighting extreme wildfires with the integration and demonstration of innovative means)

Work Package: 1

Task Number: 1.4.1

Lead beneficiary: Forest Science and Technology Centre of Catalonia (CTFC)

Contributing beneficiary(ies): Institut National de la Recherche Agronomique (INRAE), Catalan Fire and Rescue Service (CFRS), Instituto Superior de Agronomia (ISA), Forest Owners' Association of the Sousa Valley (AVFS), Institut Européen de la Forêt Cultivée (IEFC), University of Forestry of Sofia (US), Corporación Nacional Forestal (CONAF), Corporación Chilena de la Madera A.G. (CORMA).

This document was produced under the terms and conditions of Grant Agreement No. 101037419 of the European Commission. It does not necessarily reflect the view of the European Union and in no way anticipates the Commission's future policy in this area.

Publication

Publication date: 31/03/2023

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Abstract (100 words):

This report aims to facilitate the assessment of one of the dimensions of resilient landscapes, namely the physical environment. Based on a literature review and the results of a survey of wildfire experts, this report highlights key fuel-related factors, metrics, and thresholds for determining resistance and resilience to extreme fire events and high-intensity fires. Factors such as fuel load, fuel structure, connectivity, land cover and land- use structure were identified as influencing landscape resistance (i.e., the ability of a system to withstand a disturbance), while fire-related plant traits and fire regime attributes have been identified as influencing resilience. The main output of this deliverable is a tabular summary with all identified fuel parameters and their associated thresholds influencing resilient landscapes to EWE and intense fires.

Key words: EWE, disaster, fire behavior, resilience, fuel factors, fire-related plant traits

Quote as: Valor, T; Coll, L; Pique, M; Dupuy J.L; Casals, P. (2023). FIRE-RES Ecological factors driving resistant and resilient landscapes to hight intensity and extreme wildfire events. Deliverable D1.11 FIRE-RES project. 73 pages. DOI: 10.5281/zenodo.7785271.

DOI: 10.5281/zenodo.7785271

Acknowledgments: We thank Lana Coste (IEFC) and Momchil Panayotov (UF) for proofreading the deliverable. We also thank the wildfire experts who took the time to answer the questionnaire.

Dissemination level (please select the type of dissemination level with one X)

[X] PU- Public: must be available in the website

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[ ] CI – Classified: As referred in to Commission Decision 2001/844/EC

Document history

Edition	Date	Status	Author
Version 1	21/02/2023	Draft	Teresa, Valor (CTFC), Lluís, Coll, (UdL; JRU CTFC-AGROTECNIO), Míriam Piqué (CTFC), Jean-Luc, Dupuy (INRAE), Pere, Casals (CTFC)

Version 2	27/03/2023	Revision	Edgar, Nebot (CFRS), Brigite, Botequim (Forestwise)
Version 3	30/03/2023	Final Version	Teresa, Valor (CTFC), Lluís, Coll, (UdL; JRU CTFC-AGROTECNIO), Míriam Piqué (CTFC), Jean-Luc, Dupuy (INRAE), Pere, Casals (CTFC)

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1 Introduction: resistance and resilience

The overall objective of this report is to identify the ecological factors that influence the capacity of forest stands and landscapes to withstand extreme and high-intensity wildfires in European area. Fire-resistant forests are those that are able to mitigate the spread and intensity of a fire event. As a result, they show lower post-fire impacts (with exceptions such as underground fires that have limited spread and intensity (kW m^{-1}) but high impacts). Fire-resilient forests are those that are able to return to a state of equilibrium (i.e., recover) after the fire event (i.e., species and functions recover after the fire).

Resistance has been considered a component or integral part of resilience in several studies (Hodgson et al., 2015; Lloret et al., 2011). In these studies, the two concepts are considered related, but also clearly measurable components of ecosystem responses to disturbance (Sánchez-Pinillos et al., 2019). As stated in the review of the use of resilient concepts in forest science by Nikinmaa et al., (2020), some authors prefer to integrate resistance into the concept of resilience (Folke et al., 2010) while others advocate separating the two concepts to provide conceptual clarity and better operationalize resilience (Derose & Long, 2014). To better operationalize resilience in the field, we separate the two concepts here, assuming that the two are interrelated. In this sense, resistance and resilience need to be assessed at both stand and landscape levels, and both levels should be considered when formulating goals and designing and implementing agrosilvicultural systems to build resistance and resilience (Derose & Long, 2014) (Box 1).

Box 1 Definitions of the concepts resistance and resilience, which are based on the frameworks developed by Derose & Long (2014) and Nimmo et al., (2015).

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 characterized from the influence of forest structure and composition on fire severity and intensity. At the landscape level, resistance could be characterized from the spatial configuration and composition of patches (e.g., fuel continuity, land cover land use types diversity) on the rate of fire spread (Derose and Long, 2014).

Resilience: the ability of the ecological system to recover the functions and ecosystem services that the system provided before the fire. In the case of wildfire, resilience could be characterized as the effect of fire 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 fire), the event (e.g., intensity), and the presence of additional stresses before and after the fire event (e.g., prolonged drought, pest outbreaks, torrential rains, etc.).

The relationship between resistance and resilience is a key aspect to provide insight into the post-disturbance state and the need for restoration (Figure 1). For instance, a system with low resistance and resilience affected by a wildfire may transition to a degraded state with a significant loss of functions and in the provision of ecosystem services and will require urgent restoration to mitigate the impacts. Thus, this relationship can help to determine the post-disturbance state of an ecological unit (e.g., full recovery, net gain, or net loss of community species diversity) and, importantly, whether that state is the result of a loss of resistance, a loss of resilience, or both (Nimmo et al., 2015). This allows identification of ecological units (e.g., species, communities…) that may require management intervention and the type of intervention required (i.e., whether management should prioritise building resistance, resilience, or both).

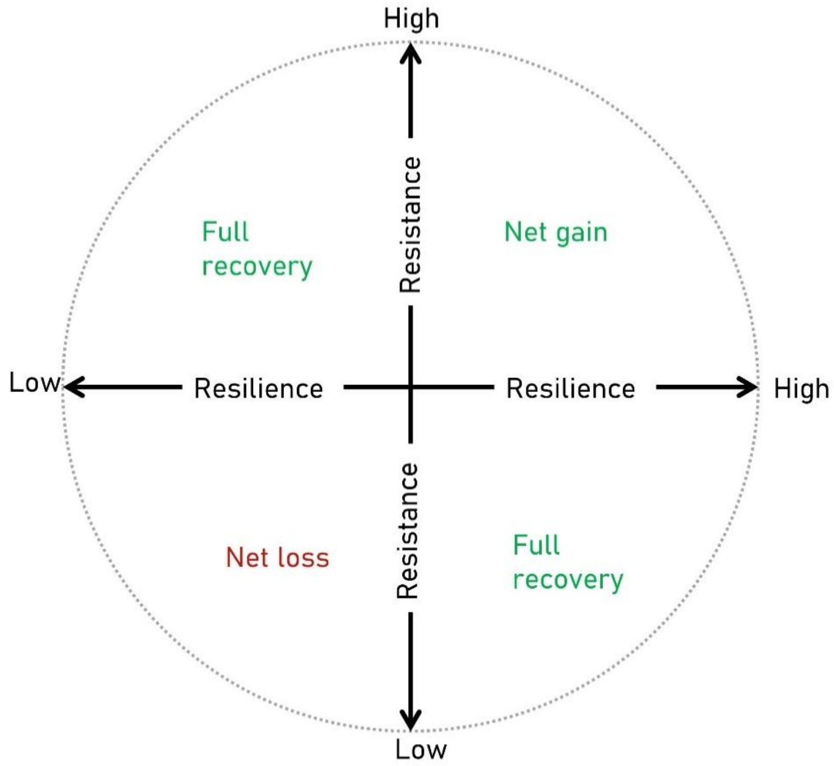

Figure 1 Post-disturbance state of an ecological unit based on the relationship between resilience and resistance. Based on Nimmo et al. 2015.

2 Deliverable aims

The general purpose of the deliverable is to identify the factors, metrics and thresholds associated with fuel characteristics that influence stand and landscape resistance and resilience to EWE and high-intensity wildfire.

For each factor and its associated metrics and thresholds, we present a summary of its impact on some of the components of fire behaviour (i.e., fire intensity, severity, spread and occurrence). The parameters and thresholds identified are the basis for developing recommendations to build or maintaining forest fire resistance at stand and landscape level. Therefore, this report provides the necessary information for the elaboration of *D.1.13. Basis for resilient landscapes: Recommendations and novel adaptive management scenarios to create resilient landscapes to EWE (subtask 1.4.3)* and *subtask 2.1.3 Parametrization of management alternatives.*

3 Methodology

The data presented in this deliverable were collected through 1) a systematic literature review limited to European studies (with some exceptions) and 2) a questionnaire distributed to FIRE-RES participants, foresters, and forest scientists. The main result of this deliverable is a tabular summary with all the identified parameters and their associated thresholds. The specific methodology used in each case can be found in *Appendices*, 10.1 *Literature review: search strategy* and 10.2 *Questionnaire*.

3.1 Literature review

Based on data from the literature review, and considering the framework developed by Derose & Long (2014), factors, metrics, and thresholds were identified and classified in terms of their expected influence on resistance and resilience to EWE and wildfire at two scales: stand and landscape. The review on resistance, is presented in section 4, and on resilience in section 6.

3.2 Questionnaire on factors affecting resistant and resilient stand and landscapes

The results of the literature review were used to design a questionnaire on the factors and thresholds that determine the resistance and resilience of landscapes to EWE and conventional but large and intense fires in Europe. The questionnaire also includes questions on post-fire dynamics, which are discussed in *D 1.12 Factors driving post-fire dynamics*. The objectives of the questionnaire with respect to this report are:

- Assess the relative importance of the identified resistance and resilience factors to EWE, as we note a lack of studies on EWE.
- Assess possible differences in factors and thresholds in Northern/Central and Southern Europe, and get expert knowledge from boreal, alpine and continental bioregions on these topics, as studies on these regions are lacking.

The questionnaire was sent to experts from Europe and Chile in the field of wildfire. In section 5, the results of the questionnaire on resistance are presented and in section 6 those related with resilience.

4 Review on resistance to EWE and high-intensity wildfires

Studies reviewed were classified according to whether the identified factor and associated metrics primarily affect stand or landscape resistance to wildfire and which component of fire behaviour was studied (i.e., fire intensity, severity, spread, size, and occurrence), resulting in the schema shown in Figure 2. Fire severity is the impact of a fire on the ecosystem that is usually estimated from the amount of plant biomass consumed (Keeley, 2009). Hence fire severity is usually correlated with fireline intensity as the latter, to a first order, is proportional to the amount of fuel consumed. For stand and landscape resistance a general description of the factor follows along with an overview of the metrics and thresholds that control a particular component of fire behaviour. For most metrics, there are currently no known thresholds that prevent the development of EWE; instead, values are provided for conventional or experimental fires.

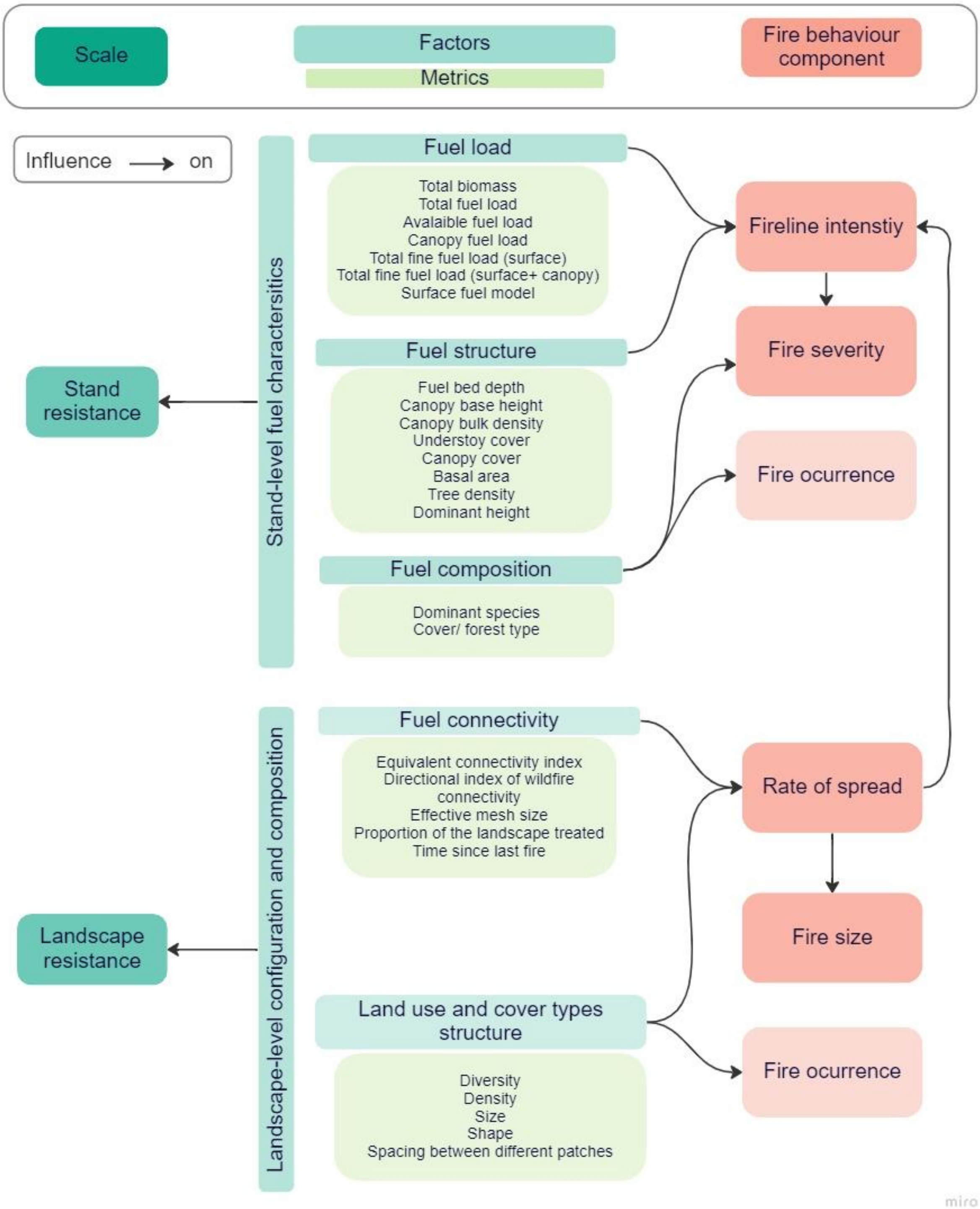

Figure 2. Schematic representation of the factors and metrics that influence the resistance of stands and landscapes to wildfire, and the various components of fire behaviour that are influenced by these factors.

4.1 Fire resistant stands

Stand resistance can be defined as the influence of stand-level fuel characteristics on fire severity (Derose & Long, 2014) and thus, on fireline intensity, as the two are correlated, at least above ground (Alexander & Cruz, 2012). Here, studies that analyse the influence of stand-level fuel characteristics on either fire intensity or fire severity, or both, have been reviewed. Fireline intensity is the rate of heat release per unit length of fire front. It is directly proportional to fuel consumption (Alexander & Cruz, 2020), and is an important determinant of aboveground fire severity and can be used as an indicator of fire suppression difficulty (Alexander & Cruz, 2012).

Fire behaviour is strongly influenced by stand-level fuel characteristics. When an ignition occurs in a forest stand, several types of wildfires can develop depending on which layer is involved in the spread (Frandsen, 1987; Van Wagner, 1977): i) ground fires burn duff, organic soils, and roots, ii) surface fires burn needles, leaves, grass, dead and down branch wood and logs, low brush, and short trees and, iii) crown fires burn fuels in the canopy. The physical characteristics of the forest structure that affect fire behaviour are (Cruz et al., 2022):

- **Fuel load**: by layer, size class, and condition (live and dead).
- **Fuel structure**: includes fuel bed depth, height or thickness, bulk density or compactness, arrangement (vertical and horizontal continuity), cover, and number of layers involved (ground, surface, ladder, and crown).
- **Fuel composition**: species composition of a fuel complex influences the arrangement and morphological and chemical characteristics of fuel particles.

4.1.1 Fuel load and structure: description and metrics

Fuel load

Fuel load is the amount of fuel expressed as dry weight of fuel per unit area, i.e., the potential energy accumulated at the ground or/and in the canopy. In the literature, one can find different terms related with fuel load that are sometimes confounded (Scott & Reinhardt, 2001):

- **Total biomass (kg m^{-2}):** The total amount of living and dead vegetation per unit area, including vegetation that is never consumed in a fire, such as live tree boles and large live branches.
- **Total fuel load (kg m^{-2}):** The maximum amount of fuel (live and dead) per unit area than can be consumed in the worst-case scenario.
- **Available fuel (kg m^{-2}):** The total amount of fuel per unit area that is consumed by a fire, including duff, organic soils, and large woody fuel like logs.
- In case of EWE or under the driest conditions, total fuel load and available fuel would be the same.

The effect of fuel load and structure on fire behaviour can be studied using fire simulation softwares. Most fire modelling systems link Rothermel (1972) for predicting surface spread rates and crown fires with models from Van Wagner (1977) for canopy fire transition and spread. Crown fires result from the combination of different elements of the fuel complex and fire environment (i.e., fuel, weather, and topography), and the varying combination of these elements results in a wide range of fire behaviour in terms of fire spread, intensity, spotting, fire type, and severity (Scott & Reinhardt, 2001).

Crown fires undoubtedly pose the greatest threat to fire suppression systems and fire managers and depend on the succession of available fuels from the ground surface to the canopy (Graham et al., 2004). The path that an ignition follows in a stand begins with the surface fuel bed. Leaving apart weather and topography, the properties of the fuel bed, particularly fuel load, determine the rate of fire spread and the intensity of fire in the lowest layer of the forest structure with higher loads increasing fire intensity (Rothermel, 1972). Fine fuel load, both living and dead, contribute most to fire spread as they dry quicker and their moisture content changes dramatically depending on environmental conditions because they have a greater surface-to-volume ratio (Rothermel, 1972). If fire intensity at the surface is enough, and fuel structure facilitates the transition from the surface to the crown, the load in the canopy will determine fire behaviour. The fuel-load related metrics used in these systems are the first to be identified in this review as important in determining fire behaviour (Box 2).

Box 2. Fuel-load related metrics used in fire simulator softwares'.

Fuel model: In fire simulator systems, fuel load is specified by choosing a set of standard fuel models, usually the NFFL stylised fuel models developed for U.S. vegetation (Anderson, 1981; Scott & Burgan, 2005). However, for scenarios outside the U.S., custom fuel models are preferable because the results of fire behaviour simulators are otherwise not very reliable. These fuel models are used by most fire simulator systems to predict surface fire spread using Rothermel's (1972) equation. Each fuel model is represented by a set of fuel bed properties such us load by size classes (fine, medium, and coarse) and condition (live and dead). Dead fuels are also divided into four timelag categories (1, 10, 100, 1000 h) depending on their diameter (0-6, 6-25, 25-75, > 75 mm). Timelag refers to the time required for a fuel particle to reach 2/3 of the difference between its initial moisture content and the moisture content of the current environment, which depends on its diameter and its ability to lose or gain moisture (Brown, 1982).

Canopy fuel load (kg m^{-2}): The portion of the aerial crown that is consumed in a crown fire, and can be determined by using allometric equations to estimate foliage biomass (e.g., Mitsopoulos & Dimitrakopoulos, 2007;García-valdés et al., 2022). It is usually assumed that only the fine canopy fuels are consumed, i.e., the foliage and a small portion of the branch wood are available for combustion (Scott & Reinhardt, 2001).

In the workshop on Fire Resilient Landscapes held in Solsona on June 14-15, 2022, **total fine fuel load, including both dead and live canopy and surface fuel**, was cited as an important parameter for determining the conditions for the development of an EWE.

However, the approach to estimate such a parameter was not discussed. In Box 3 a short description about potential methodologies to estimate it is provided:

Box 3. Estimation of surface + canopy fine fuel load (t/ha)

If destructive sampling is not available to characterise fuel properties (e.g., load by size class and condition), allometric equations relating species-specific biometric characteristics or stand variables can be used to estimate fuel loads (e.g., biomass, fine fuel). It is important to note whether these equations estimate biomass or fine fuel load, because assuming that all (i.e., biomass) or most of the biomass (i.e., fine or available fuel) is consumed can result in a significant overestimation of fire behaviour. Equations are now available for several tree and shrub species.

At the tree level, for instance, crown fuel load can be estimated for *P. pinea* using DBH and crown projection area as predictors (Molina et al., 2011), or in the case of *P. pinaster* and *P. radiata* using DBH (Gómez-Vázquez et al., 2013). For *P. brutia* and *P. halepensis*, canopy features can be estimated by stand variables such as basal area, dominant height or SDI (Mitsopoulos & Xanthopoulos, 2016). See also García-valdés et al., (2022) for a wider range of tree species. At the shrub level, allometric equations exist for shrub species in different regions to estimate both total biomass (Conti et al., 2013; De Cáceres et al., 2019; Oyonarte & Cerrillo, 2003) and fine fuel fractions (De Cáceres et al., 2019; Huff et al., 2017; Pimont et al., 2018). For example, equations developed in DeCaceres et al. 2019 estimated biomass and fine fuel fractions of 26 Mediterranean shrub species using percent cover and average height of each species as predictors. These equations estimate live fine fuel load and establish a proportion of the live fine fuel load as dead fine fuel load.

In the absence of field measures, canopy and surface fine fuel load can be determined when equations for key species or functional groups in the study area exist and biometric variables for shrubs and trees have been measured in field campaigns or determined by remote sensing (e.g., DeCaceres et al. 2019; Botequim et al., 2019) to model fine fuel loads over large heterogeneous study areas.

Fuel structure

Fuel structure refers to the spatial configuration of the forest stand, and includes fuel bed depth, height or thickness, bulk density or compactness, arrangement (vertical and horizontal continuity), cover, and number of layers involved (ground, surface, ladder, and crown). Vertical continuity can be assessed by measuring **canopy base height** and **fuel bed depth**, which, along with the intensity of the surface fire, sets the conditions for crown fire initiation. Once a crown fire has started, canopy fuel load and **canopy bulk density** (which indicate how densely fuels are packed in the canopy) determine aerial horizontal continuity, and positively affect fire intensity and the rate of spread of the crown fire, resulting in a much higher rate and intensity of spread than if the fire remained at the surface (Scott & Reinhardt, 2001). Thus, if a stand has a low mean canopy base height, crown initiation is easier, but if the crown bulk density is also low, active crowning is hindered, resulting in a period of passive crowning. The main parameters related to fuel structure used in most fire simulation systems are defined in Box 4.

Box 4. Fuel structure metrics used in fire simulator softwares

Fuel bed depth (m): Average height of surface fuel in the combustion zone of a spreading fire front.

Canopy base height (m): The lowest height above the ground above which there is sufficient canopy fuel to propagate fire vertically (Scott & Reinhardt, 2001).

Canopy bulk density (kg/m^3): Mass of available canopy fuel per canopy volume unit. It is determined by dividing canopy fuel load between canopy depths, assuming that canopy biomass is homogeneously distributed within the stand (Scott & Reinhardt, 2001).

Silvicultural variables

In order to improve silvicultural recommendations for fuel management, information from field or modelling studies relating forest structure with crown fire potential is very relevant. Fuel-related variables such as **basal area, stand density, dominant height, tree size, percent cover of different layers, and vertical continuity** can be controlled and could be used in forest planning systems.

4.1.2 Fuel load and structure: thresholds related with fire intensity and severity

Outside of North America, there are few studies linking stand structure and fire behaviour to provide a quantitative basis for wildfire management. We reviewed studies that analyse the influence of stand-level fuel characteristics on either fire intensity or fire severity, or both, to characterise stand resistance to wildfire. For each factor, metrics and thresholds for crown fire probability are provided, as this is an important aspect for assessing and building fire-resistant stands.

4.1.2.1 Influence of fuel load and structure on fire intensity

Fuel load

As mentioned earlier, in fire simulation systems, fuel loads are specified by selecting a set of standard fuel models developed for U.S. vegetation (Anderson, 1981; Scott & Burgan, 2005). Outside the U.S., customized fuel models have been developed. In European areas, for example, customized fuel models have been developed at local, regional, and national scales (Table 1). Some of these models are tied to forest type (e.g., Ascoli et al., 2020; Fernandes, 2009). Such fuel models have been obtained using allometries or in the field through destructive sampling to characterize the properties of the fuelbed (e.g., loading by size class and condition). Others have calibrated existing standard fuel models (e.g., Krsnik et al., 2020 using the NFFL stylised fuel models, Aragoneses & Chuvieco, 2021 using Prometheus).

Table 1. Examples of custom fuel models developed in European areas at different scales.

Country	Scale	Objective	Reference
Greece	National	Fuel models	Dimitrakopoulos (2002)
Portugal	Local	Fuel treatment effectiveness	Fernandes et al. (1999)
Portugal	Local	Fuel treatment effectiveness	Fernandes et al. (2004)
Portugal	Local	Fuel treatment effectiveness	Fernandes (2009b)
Portugal	Regional (North)	Fuel models	Cruz & Fernandes (2008)
Portugal	National	Fuel models	Fernandes (2009a)
Spain	Local	Fuel treatment effectiveness	Piqué & Domènech (2018)
Spain	Local	Fuel treatment effectiveness	Piqué et al. (2022)
Spain	Local	Fuel treatment effectiveness	Palmero-Iniesta et al. (2017)
Spain	Regional (Andalucía)	Fuel models	Rodríguez y Silva & Molina-Martínez (2012)
Spain	National	Fuel models	Aragoneses & Chuvieco (2021) (adaptation of Prometheus)
Spain	Regional (Catalunya)	Fuel models	Krsnik et al., 2020 (adaptation of NFFL models)
Italy	National	Fuel models	Ascoli et al. (2020)
Italy	Regional (Apulia)	Fuel models	Elia et al. (2015)
Germany	Local	Fuel models	Heisig et al. (2022)
Austria	National	Fuel models	Neumann et al. (2022)
Switzerland	National	Fuel models	Allgöwer et al. (1998)

Studies linking potential fire behaviour to custom surface fuel models using fire simulation systems help to determine which fuel models are critical for resistance to fire. For instance, according to fire simulations from BEHAVE, closed forest needle litter of P. halepensis and P. brutia (> 85%) produced the lowest fuel load, 2.3 t ha^{-1}, and a maximum intensity of 500 kWm^{-1} (Dimitrakopoulos, 2002). Instead, the shrubland fuel models (evergreen sclerophyllous and kermes oak) showed the greatest fire potential due to the higher fuel load, between 25.5 and 53.0 t ha^{-1} and an associated fire intensity between 2900 kW m-1 and 50900 kW m-1 (Dimitrakopoulos, 2002). In closed forest, such in Austria, for example, the fuel model with the highest total fuel load has about 12 t ha1 (Neumann et al., 2022). Other studies listed in Table 1 can be used not only to identify fuel loading thresholds that limit fire intensity, but also to *parameterize fuel management operations, as these studies aim to evaluate the effectiveness of different fuel treatments.*

Table 2 provides a compilation of load values and corresponding fire behaviour for several European simulation studies that evaluate the effectiveness of different fuel treatments.

Table 2. Fuel load and structure and associated fire behaviour in European studies that simulated fire behaviour in the worst-case scenario to assess fuel treatments effectiveness. TST, time since treatment; TFL, total fuel load; 1h FL, 1-hour fuel load; FBD, fuel bed depth; CFL, canopy fuel load; CBD, canopy bulk density; CBH, canopy base height; FLI, fire line intensity. Type of fire, when numerical reflect the probability of crown fire.

Fuel treatment	**TST (yrs)**	**Stand structure**			**Surface layer**			**Crown layer**			**Fire behaviour**		**Weather conditions**		**Reference**
		Dominant spp.	**DBH (cm)**	**Density (trees ha-1)**	**TFL (t ha-1)**	**1h FL (t ha-1)**	**FBD (cm)**	**CFL (t m2)**	**CBD (kg m3)**	**CBH (m)**	**FLI (kW m-1)**	**Type of fire**	**1h fuel moisture**	**Wind speed**	
Unmanaged	NA	*P. nigra*	17.8	1592	40.41	17.64	152.9	NA	0.23	6.9	7917	Passive	5	14.1	Piqué & Domènech (2018)
Low thinning	2	*P. nigra*	17.5	1411	56.68	28.06	35.50	NA	0.19	7.0	938	Surface	5	14.1	
Low thinning + PB	2	*P. nigra*	17.5	1411	22.95	8.86	15.00	NA	0.20	7.0	100	Surface	5	14.1	
High thinning	2	*P. nigra*	20.6	690	72.41	32.46	42.00	NA	0.09	7.9	969	Surface	5	14.1	
High thinning + PB	2	*P. nigra*	20.6	690	34.12	10.41	20.00	NA	0.09	7.6	110	Surface	5	14.1	
Unmanaged	NA	*P. halepensis*	4.2	11579	29.6	11.7	180	NA	0.1	0	3631	Active	7.2	14	Palmero-Iniesta et al. (2017)
Thinning	0	*P. halepensis*	6.0	1100	52.39	15.6	35	NA	0.1	1.5	446	Passive	7.2	14	
Thinning	1	*P. halepensis*	6.0	1100	46.0	12.7	27	NA	0.1	1.5	223	Passive	7.2	14	
Unmanaged	NA	*P. halepensis*	4.9	12117	40.1	33.8	100.7	NA	0.16	3.5	1643		6	9.3	Piqué et al. 2022
Pre-com. thinning	0.5	*P. halepensis*	10.5	1293	107.6	50.8	64.3	NA	0.06	3.4	1167		6	9.3	
Pre-com. thinning	2	*P. halepensis*	12.2	1119	66.2	37.8	55.3	NA	0.09	3.9	721		6	9.3	
Pre-com. thinning	4	*P. halepensis*	10.5	1097	59.1	31.2	96.4	NA	0.05	2.6	1413		6	9.3	
Pre-com. thinning	10	*P. halepensis*	11.9	1401	56.2	27.2	109.0	NA	0.05	2.7	1643		6	9.3	
Unmanaged	NA	*P. pinaster*	12.4	2192	NA	45.46	52	10.56	0.24	4.7	4925	100	4.8	12	Fernandes et al. (2004)
PB	13	*P. pinaster*	12.4	1480	NA	36.41	50	8.45	0.19	4.0	1520	35	4.8	12	
PB	3	*P. pinaster*	13.4	1856	NA	12.07	31	10.85	0.23	5.4	939	0	4.8	12	
PB	2	*P. pinaster*	12.3	1760	NA	11.23	30	8.57	0.22	5.2	399	0	4.8	12	
Unmanaged		*P. pinaster*	NA	NA	16.2	7.91	35				2356		3		Fernandes (2009b)
Before PB		*P. pinaster*	NA	NA	12.4	4.75	54				3406		3		
Post PB	10	*P. pinaster*	NA	NA	12.9	6.77	31				2170		3		

Extreme wildfire events and fuel load

A necessary condition for the development of EWE is a landscape with enough stored energy, i.e., a sufficient amount of available fuel. Under extreme weather conditions, available fine fuel loads greater than 10-12 t ha^{-1} might result in EWE exceeding firefighting capabilities (Burrows et al., 2000; Fernandes et al., 2016). The threshold for available fine fuel load depends on vegetation type and meteorological conditions. However, as shown in

Table 2, this threshold is easily exceeded even in managed stands and when only surface fine fuel loads are considered (without including canopy fuels).

Fuel structure

Regarding **aerial horizontal continuity**, for the development of active crown fires a threshold for bulk density of 0.1 kg m^{-3} has been established by Agee (1996) and Cruz et al. (2005). In Europe, a similar threshold 0.08 kg m^3 for the development of active crown fires has been identified (Botequim et al., 2019; Gómez-Vázquez et al., 2014). In terms of **vertical continuity**, a threshold of 1.9 m of canopy base height for a crown value greater than 0.08 resulted in active crown fires (when shrubs were medium or tall) while fire activity was low at a canopy base height greater than 1.9 m in stands with short shrubs (Botequim et al., 2019). In maritime pines, canopy base height of 7 m proved to be the most important threshold for dramatic changes in fire type (Botequim et al., 2017).

Heuristic approaches and expert opinion have also been used to determine parameters and thresholds for estimating rate of spread (Fahnestock, 1970) and ladder fuel hazard (Menning & Stephens, 2007). In Europe, a Crown Fire Hazard Chart (CFHC) has been developed for stand-level assessment and is currently widely used in the Catalonia region (north-eastern Spain) (Piqué et al., 2011). The chart uses silvicultural variables that are easily estimated in common forest inventories, such as canopy cover and surface fuel cover to assess the vulnerability of a given stand to crown fire development. The CFHC provides forest managers with numerical data (i.e., thresholds) to assist them in taking fuel management decisions for the main forest species in Catalonia. However, because these tools have not yet been validated, thresholds are not provided.

Stand-level variables

Few studies have classified the potential of stands to withstand different types of crown fires based on stand variables. Although these specific case studies vary in fuel, topographic, and meteorological conditions, and few are available, a summary of the silvicultural metrics and thresholds can be seen in Table 3.

Table 3. Thresholds for different silvicultural variables and associated fire types. In some cases, thresholds are conditioned by other variables. Only thresholds for the worst-case scenario are shown.

Silvicultural metric	Threshold	Fire type	Condition	Reference
Basal area (m^2 ha^{-1})	≥14.72	Active		Fernández-Alonso et al., 2013
Basal area (m^2 ha^{-1})	≤10-14	Passive		Gómez-Vázquez et al., 2013
Dominant height (m)	<10.5	Crown	Open stand	Gómez-Vázquez et al., 2013
Dominant height (m)	>14	Passive	Closed stand	Gómez-Vázquez et al., 2013
Density (tree ha^{-1})	<500	Passive	Variable proportion of large trees	Alvarez et al., 2012a
Density (tree ha^{-1})	<1300	Surface	>85% of one layer of large trees	Alvarez et al., 2012a
Density (tree ha^{-1})	>1300	Active or Passive	>85% of one layer of large trees	Alvarez et al., 2012a
Density (tree ha^{-1})	>1300	Active or Passive	60-85 % of one layer of large trees with a second layer	Alvarez et al., 2012a
Density (tree ha^{-1})	<1300	Active or Passive	< 60 % of one layer of large trees	Alvarez et al., 2012a
Density (tree ha^{-1}	>1300	Active	< 60 % of one layer of large trees	Alvarez et al., 2012a

4.1.2.2 Influence of fuel load and structure on fire severity

Studies linking fuel structure variables to post-wildfire fire severity provide empirical evidence of fire-resistant stands and can be used to define the key parameters and associated thresholds that determine resistance. Two main types of approaches have been pursued in the studies reviewed: the use of remote sensing to relate pre-fire fuel loads and structure to a vegetation index (e.g., NDVI), and the characterization of stand structures of unburned patches within a perimeter.

Remote sensing studies typically attempt to determine the relative importance of various fuel-related and non-fuel-related parameters in explaining fire severity within a perimeter. Most of these studies use partial dependence plots from which threshold values for the various variables can be derived. It is important that these types of studies make an effort and explicitly define the thresholds for each parameter. The following fuel-related parameters are typically considered: LIDAR variables related to height distribution and cover, canopy base height, canopy bulk density, understory cover, understory height, and fuel standard models. Non-fuel parameters such as burning conditions, topography, or fire behaviour are usually considered. These studies show that of all these parameters, non-fuel related factors such as fire spread rate, topographic location, or wind speed are the most influential variables in explaining fire severity. However, fuel-related factors play a moderate role in all studies reviewed, in the form of fuel structure (e.g., canopy base height, mean stand height, shrub cover and height, *coefficient of variation in LIDAR heights and diameters) and fuel load parameters (e.g., biomass, total available fuel load (understory and overstory), surface fuel load) (*

Table 4). In addition, for convective fires, a study identified canopy base height as the most important parameter for determining fire severity (see Fernández-Alonso et al., (2017) in

Table 4). This confirms that convective fires are associated with controllable factors that can be modified by forest management, while, for instance, wind-driven fires are more difficult to control through proactive forest management because they are strongly associated with unmanageable factors (Duane et al., 2015). In summary, generally heterogeneous stands with complex vertical structure and a homogeneous shrub layer have been associated with high severity, likely because these conditions are optimal for canopy fire development and spread.

Unburned forest stands within the perimeter of a wildfire provide sound evidence of the structural characteristics of fire-resistant stands. In northern Portugal, *P. pinaster* forest stand with a basal area of < 20 m^2 ha^{-1} and a tree density of < 200 ha^{-1} exhibited low fire severity (Fernandes et al., 2015). In Spain, among other biotic and abiotic factors leading to unburned island formation, *P. nigra* stands with a wood volume > 35 m^3 ha^{-1} with high tree heights and large DBH survived a wildfire (Román-Cuesta et al., 2009).

Extreme wildfire events and fire severity

There are few examples of how forest structure can influence the severity of fires under extreme conditions. However, there is evidence that fuels treatments, and thus forest structure, can have a local influence on the severity of such fires. At the Fire Resilience Workshop, it was reiterated that fuel management efforts should focus on reducing the severity rather than the potential extent of EWE. Nevertheless, the fact that EWE exhibits irregular behaviour could lead to a mosaic of fire severity after a fire. In any case,

Table 4, shows that even if fuel load or structure are not the most influential factor in explaining fire severity, they are relatively important as they occupy a middle position in the ranking of influential variables.

Table 4. Remote sensing studies linking fire severity to various weather, burning conditions, fire behaviour, and fuel parameters. The most influential parameter and the first and second most important factors associated with fuel are shown. For fuel parameters, the relative position with respect to the total number of factors considered is given in parentheses, along with the associated thresholds, if any.

Wildfire: type, year, location	Dominant species	Most influential factor	First important fuel factor		Second important fuel factor		Reference
			Fuel factor and relative importance variables in ()	Threshold[1]	Fuel factor and relative importance variables in ()	Threshold[1]	
2 wind-driven fires, 1 topographic fire, 1 convective fire between 2010-2013 (NW Spain)	*P. pinaster*	Wind speed	Shrub cover (5/17)	NA	Canopy base height (7/17)	NA	Fernández-Alonso et al., (2017)
Convective fire in 2013 Ponte Caldelas (NW Spain)	*P. pinaster*	Canopy base height	Canopy base height (1/14)	NA	Coefficient of variation of LIDAR heights (3/14)	NA	Fernández-Alonso et al., (2017)
High intensity fire in 2017 in Yeste (Spain)	*P. halepensis*	Rate of spread of the fire front	Biomass (LAI/fPAR) (2/9)	LAI (1.05) fPAR(0.2)	Understory height: density of LiDAR points at 1-2 m (4/9)	>10 points	Viedma et al., (2020)
Convective fire in 2005 in Riba de Saelices (Central Spain)	*P. pinaster*	Rate of spread of the fire front	Biomass *Pinus* (2/10)	>60 t ha^{-1}	Mean stand height	<5 m	Viedma et al., (2015)
Convective fire in 2012, Leon (NW Spain)	*P. pinaster*	Pre-fire vegetation greenness	Coefficient of variation of LIDAR heights (5/5)	>0.3			Garcia-Llamas et al., (2019)
Large fire event occurred in 2016 Thasos (Greece)	*P. brutia*	Topographic position index	Total fuel load available (5/20)	NA	Surface fuel load (7/20)	NA	Mitsopoulos et al., (2019)

[1] Values > or < than the threshold indicate higher fire severity.

4.1.3 Fuel composition: description and metrics

The flammability of plants depends on their ignitability (i.e., the ability of a fuel to ignite), their combustibility (i.e., how plants burn once ignited), and their sustainability (i.e., the ability of a fuel to burn over time) (White & Zipperer, 2010). Because forest composition is largely determined by environmental conditions, the species dominating a given forest type determine the "baseline" level of flammability (Xanthopoulos et al., 2012). Accordingly, stand structure can alter the baseline flammability that can be expected on average (Xanthopoulos et al., 2012). Moreover, fuel characteristics strongly depend on the species composition of the overstory and understory layers. To assess the forest vulnerability to fire is important to consider the spatial variation of fuel characteristics of overstory and understory strata, which can be significantly different and poorly correlated to each other. Furthermore, the variation of fire hazard is primarily explained by the species characteristics of the understory (Sánchez-Pinillos et al., 2021).

4.1.4 Fuel composition: thresholds related with fire occurrence and severity

A relatively large number of studies have examined the relationship between fire occurrence and forest cover type (e.g.,González et al., 2006; Nunes et al., 2005; Silva et al., 2009). Xanthopoulos et al. (2012) provided a table for 60 vegetation types of Europe and North Africa in terms of fire hazard through expert assessment. Instead, few studies have examined the effects of forest composition on fire severity, likely due to difficulties in its analysis, as observed differences in fire severity due to forest composition may be confounded with the effects of other factors (e.g., fire suppression, topography, stand structure). Studies using remote sensing techniques have linked fire severity (NDVI as a proxy) to a variety of factors, including forest composition (e.g., Fernandes et al., 2019; Garcia-Llamas et al., 2019; Viedma et al., 2020). In these studies, the most influential factors affecting fire severity were generally factors other than forest composition (Table 5), but pre-fire vegetation composition did play a role. Other studies based on field observations have found a decrease in fire severity when moving from one forest type to another (Fernandes et al., 2010), even under conditions of high to extreme weather conditions. Most studies have been conducted in Portugal and consistently show that shrublands and maritime pine forests are the cover types experiencing the highest fire severity, while broadleaves forests have the lowest. Moreover, fire intensity, and thus fire severity, may actually increase in pine forests and shrublands due to climate change, to levels that exceed the ability to suppress wildfires, especially from spring to fall, while deciduous forests generally will not exceed such thresholds (Aparício, et al., 2022).

Table 5. Studies analysing the effect of forest composition on fire severity.

Forest composition metric	Type of study	Wildfire	Fire severity in decreasing order	Most influential variable	Country	Reference
Dominant species	Case study	High intensity fire in 2017 in Yeste (Spain)	*P. halepensis* > *P. halepensis* & *P. pinaster* > *P. pinaster* & *P. nigra*	Rate of spread of the fire-front	Spain	Viedma et al. (2020)
Cover type	Case study	Convective fire in 2012 in Sierra del Teleno (NW Spain)	Shrub> Forest > Fruit type > grassland	Pre-fire vegetation composition	Spain	Garcia-Llamas et al. (2019)
Cover type	Case study	Multiple fires, including nine 2017 fires larger than 10 ha (Portugal)	Scrublands > maritime pine > deciduous oaks and chestnut> other broadleaves > eucalypt	Between 8–39% of the variance	Portugal	Fernandes et al. (2019)
Fuel type	Simulation	NA	Pine forests > shrublands > deciduous and evergreen broadleaf forests	NA	Portugal	Aparício et al., (2022)
Forest type	Case study	Multiple fires in 2005 and 2006 (NW Portugal)	*P. pinaster* > Broadleaved & short-needled conifer forest types	51% to the overall explanation	Portugal	Fernandes et al. (2010)
Canopy composition	Case study	Mixed-severity fire in 2006 in Peneda-Gerês National Park (Portugal)	*P. pinaster* > Broadleaves	NA	Portugal	Proença et al. (2010)

<u>Extreme wildfire events and fuel composition</u>

Fuel characteristics and stand structure have a greater influence on fire behaviour and thus fire severity than vegetation type per se (Fernandes et al. 2010). Nonetheless, broadleaves species experience less fire severity than shrublands or pine forest.

4.2 Fire resistant landscapes

We define landscape resistance as the influence of landscape configuration and composition on fire spread (Derose & Long, 2014). Landscape configuration and composition affect both fire spread and intensity, but silvicultural recommendations for building a fire-resistant landscape usually aim to limit fire rate of spread (or size) more than fire intensity, even though they do so inherently.

4.2.1 Landscape configuration and composition

A homogeneous fuel landscape generally favours fire spread (Baker, 1994) while a fragmented landscape with heterogeneous fuel patches reduces fire spread (Turner et al., 1989). Fire spread is influenced by the spatial arrangement of land cover and land use types (LULC) and their characteristics. However, fire spread under extreme conditions, such as those found at EWE (fire spread rate is ≥ 50 m min[1] (Tedim et al., 2018)), appears to be insensitive to landscape structure and is primarily determined by weather conditions (Moritz et al., 2010; Turner & Romme, 1994; Moreira et al., 2020). Together with fire spread rate, growth rate (area/ha), is a key variable to describe extreme fire behaviour and growth patterns of EWE. However, to date there are no published studies examining the effects of landscape composition on growth rate.

4.2.1.1 Effect of landscape configuration on fire spread and size: metrics and thresholds

The connectivity of a landscape is the extent to which the landscape facilitates or impedes movement between resource patches (Taylor et al., 1993). Graph theory analysis and percolation theory are two approaches to analysing which landscapes constrain or promote wildfire spread. Graph theory quantifies the connectivity of patch networks and the movement of the disturbance. Within the graph theory framework, there are numerous metrics for assessing the connectivity of landscapes with varying characteristics (e.g., percentage of like adjacencies, centrality, euclidean nearest neighbour distance, equivalent connectivity index, effective mesh size). These indices were developed in the context of wildlife conservation. The equivalent connectivity index (Saura et al., 2011) is the surface (hectares) of a single and maximally connected patch based on the probability of connectivity (Saura & Pascual-Hortal, 2007), i.e., the probability that two randomly placed points on the landscape fall within areas reachable from one to the other, given a set of n patches and the connections between them. Recently, two new connectivity indices have been developed in the context of wildfires that take into account the estimated intensity of the fireline and the effects of wind direction on fuel connectivity (Aparicio et al., 2022): the directional index of wildfire connectivity and the index of wildfire connectivity (IWC), which are based on the connectivity indices developed by Saura & Pascual-Hortal, (2007). Percolation theory is also based on graph theory, but also on probability theory, as it describes the probability of transition from a connected to an unconnected system (i.e., the percolation threshold) (Gardner et al., 1987; Turner et al., 1989).

The studies reviewed here evaluate the effects of spatial landscape configuration on fire spread and/or fire size (as a surrogate for fire spread), using different approaches to quantify landscape connectivity. Percolation theory studies suggest that reducing fuel connectivity is an effective approach to mitigating fire spread across the landscape, but the thresholds for percolation (i.e., the threshold at which functional landscapes transition from unconnected to connected) reported in different studies vary. Using generic landscapes, Bevers et al., (2004) determined a percolation threshold of 59% of landscapes resistant to fire spread, and Loehle (2004) determined a lower value of about 18%. According to Loehle (2004), this difference is due to the fact that Bevers et al., (2004) assume that if the treated areas do not connect, fire can penetrate whereas in Loehle's (2004) study it does not matter if the fire starts at a random location on a map with some degree of treated stands it does not matter if the entire map percolates (untreated stands are connected somewhere from one side to the other), but only what the local neighbourhood looks like. In either case, the results obtained in these theoretical studies have heuristic value but are not necessarily predictive. Using real landscapes and wildfires and the equivalent connectivity index, Duane et al., (2021) identified a percolation threshold of 40%, and their results suggest that landscape connectivity thresholds that favour or limit fire spread depend on weather conditions and the primary factor driving fire spread.

Another approach to assessing landscape configuration that limits fire spread is to apply fire modelling techniques to analyse the potential for landscape-level fire spread in response to the timing and location of fuel treatments. This allows for the establishment of fuel connectivity thresholds in relation to flammable LULC types, which is critical for forest stand spatial planning (i.e., flammable patches) to increase fuel heterogeneity across the landscape and thereby reduce fire spread and fire size. For example, in Central Catalonia, Alcasena et al., (2018) showed that treating approximately 15% of the landscape with prescribed burns, strategically distributed is effective in interrupting large wildfires. This value is similar to that of Fernandes, (2015) who shows that 5-10% of the landscape in strategic locations should be treated with prescribed fire annually to reduce wildfire size. Simulation models have also shown that the spatial distribution of fuels strongly influences fire spread and behaviour (Duguy et al., 2007). Outside of Europe, Finney et al., (2007) and Ager et al., (2014) indicated that there are diminishing returns with investments in fuel treatments after 10–20% of landscapes are treated. To be effective, the planning of these treatments must also consider how treatment effort and fuel re-accumulation relate to each other (Finney et al., 2007). Moreover, treatment effectiveness depends on fire weather, landscape positioning relative to wind, and fire spread direction, as well as fire plume dynamics, which can influence fire growth and behaviour regardless of local weather conditions (Johnson et al., 2019; Salis et al., 2016).

Previous fires can also affect landscape configuration by reducing fuel load and fuel connectivity as it is inversely related to fire frequency (Fernandes et al., 2016 used effective mesh size as fuel connectivity index; Miller & Urban, 2000). However, the effects of fuel reduction from past fires on future fire activity are short-lived: only the cumulative area burned over the past 6-7 years reduces fire frequency (Duane et al., 2019). In contrast to the short-term positive effects on fuel loads and connectivity, past fires contribute to the long-term homogenization of post-fire landscapes (Loepfe et al., 2010; Moreira et al., 2011).

Extreme wildfire events and landscape configuration

Under extreme conditions and unknown processes that drive fire spread (atmospheric dynamics), landscape configuration may have little effect on fire spread and size (Cruz et al., 2022). However, targeting the reduction of the amount and connectivity of fuels would reduce fire growth rate, increase the potential for fire suppression, and mitigate fire damage (Moreira et al., 2020).

4.2.1.2 Effect of landscape composition (LULC types) on fire occurrence and fire size

A number of studies have used metrics of landscape structure (i.e., density, size, shape, spacing between different patches, diversity) to assess relationships between land use change and fire occurrence (Lloret et al., 2002; Loepfe et al., 2010; Vega-García & Chuvieco, 2006). These studies show that fires occur more frequently in landscapes with low LULC diversity than in more heterogeneous landscapes with a mosaic of different LULC. In addition, low-fuel patches in heterogeneous landscapes increase the opportunities of fire suppression. Some thresholds or characteristics for resistant landscapes can be derived from these studies. Fire prone landscapes are homogeneous landscapes characterized by low density but large patches and a low diversity index, resulting in a more uniform distribution of land cover types (Lloret et al., 2002). In terms of LULC types, dense forests and shrublands burned most frequently, followed by open forests, while agricultural fields burned less readily than other land use/cover types (Garcia-Llamas et al., 2019; Lloret et al., 2002; Loepfe et al., 2010). In addition, Nunes et al., (2005) data indicate that small fires have a stronger preference for land cover than large fires: with a clear preference for shrubland, followed by other forest cover types, while agriculture is clearly avoided.

Research on the effects of LULC types on fire size or spread has yielded mixed results. Viedma et al., (2009) linked fire size to structural features of the landscape and found that the diversity of LULC types increased from inside the perimeter to the edge and outside the fire. Pastures, followed by shrublands, croplands, and hardwood forests, were the most common contact types with pine forests that contained fire. Azevedo et al., (2013), found that holm oak forests influence fire behaviour by interrupting fire spread in the perimeter zone. Sousa et al., 2021 shows that vegetation types, especially the presence of shrubs, and the absence of human activities, such as agriculture, are the main causes of fire spread in this region. Considering only land cover types, Fernandes et al., (2019) showed that fire size was essentially independent of land cover composition, including forest type, and increased when fuel connectivity was high and pyrodiversity was low.

Extreme wildfire events and landscape composition

The 2017 Portuguese megafires were analysed in Fernandes et al., (2019). Land cover composition had a modest effect on fire severity. This was expected as fire severity reflects the combination of multiple influences. While flammable cover types have a moderate effect on the severity of EWE, its influence on fire size seems irrelevant (Fernandes et al., 2020). However, less flammable land use or land cover types, such as agricultural land, could have a greater impact on fire size than variations in flammable land cover types.

5 Questionnaire results on resistance to EWE

This section presents the results of the questionnaire related with factors driving resistant landscapes to EWE and high-intensity fires (questions 2 to 7) (Appendix: 10.2 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.

Factors driving resistant landscapes to EWE and intense fires (questions 2 to 7)

The first part of the questionnaire (questions 2 to 7) was designed to provide information on factors and thresholds that determine the resistance of landscapes to EWE and intense fires in different bioregions.

Question 2 asked experts to rank the fuel-related factors that may influence the development of EWE in their bioregion from highest (1) to lowest (5) in importance. Regardless of bioregion, experts ranked fuel load as the most important factor (46%), fuel structure as the second (46%), fuel composition as the third (51%) and fuel connectivity (43%) and LULC (46%) as the fourth and last, respectively (Figure 3). The order of importance is similar to that derived from the literature review.

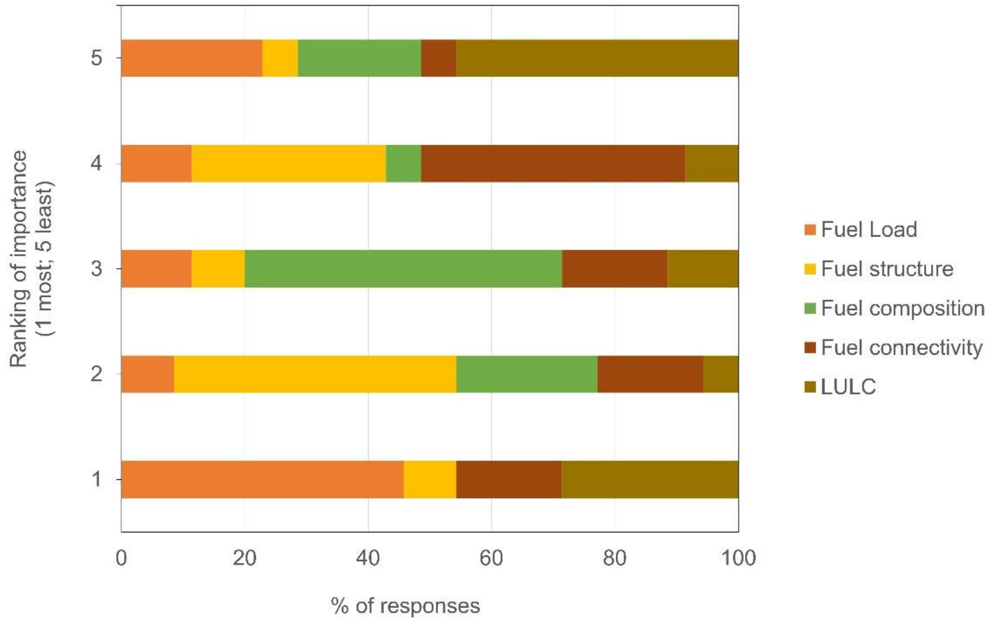

Figure 3. Within each ranking (1 most important; 5 least important), bars show the percentage of responses for each fuel-related factor driving resistant landscapes to EWE.

Interestingly, the order of importance was the same when the data were split by bioregion for the Mediterranean and Continental bioregions (Figure 4). In the case of the Atlantic, Temperate, and Alpine bioregions, the number of responses was too small to draw any conclusions. In addition, some experts suggested other factors, such as "primary sector activity," "fuel seasonality," and "climatic characteristics," but in this deliverable only ecological fuel related factors are considered. One expert noted that fuel loading should be considered as part of the fuel structure.

Question 3 asked experts to select from a list of fuel load metrics (total biomass, total fuel load, available fuel load, surface fine fuel load, and total fine fuel load) those for which they knew thresholds to prevent the development of a EWE or intense wildfire. 7 of 35 experts provided one or more metrics and corresponding thresholds. As noted during the review and workshop, two experts cited a value of 10 t ha^{-1} of surface fine fuel load (one of the experts) and available fuel load (the other expert) as thresholds for fuel load to limit development of EWE, with one of the experts indicating that thresholds would vary by vegetation type. However, fire responders (personal comment) referred to total fine fuel load (surface + canopy). Other experts gave thresholds for total fuel load but for intense fires or did not specify the type of fire and ranged from 2 to 4 kg m^{-2}.

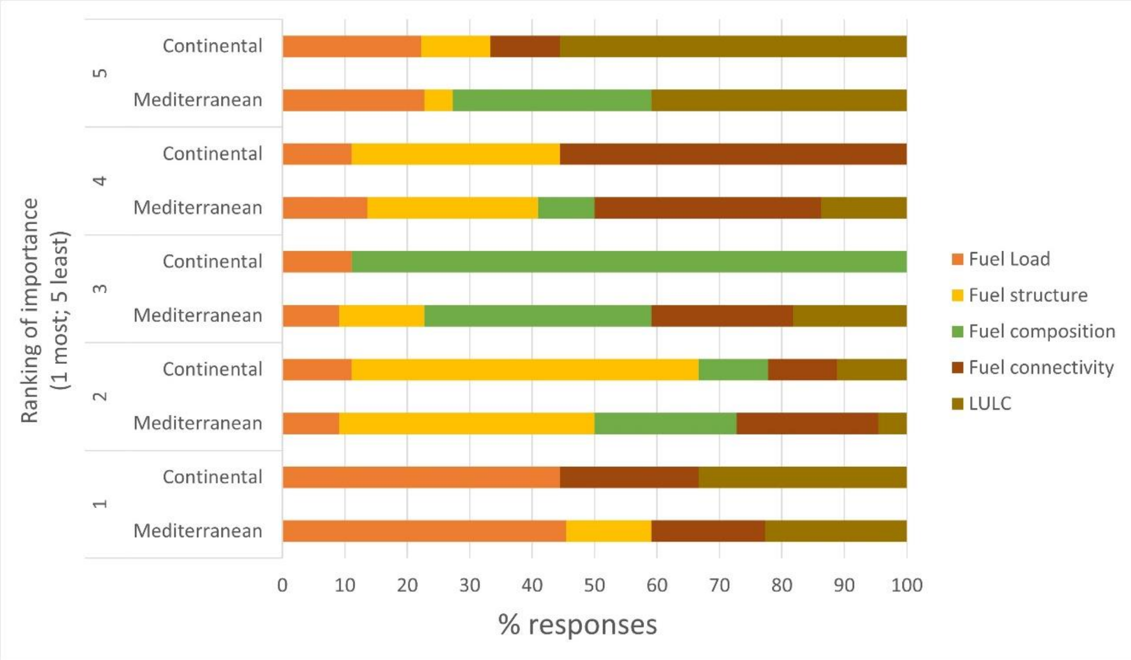

Figure 4. Within each ranking (1 most important; 5 least important), bars show the percentage of responses from Mediterranean and continental bioregion experts for each fuel-related factor driving resistant landscapes to EWE.

Question 4 asked experts to select from a list of vertical continuity metrics (fuel bed depth, ladder gap, canopy base height, and dominant height) those for which they knew thresholds to prevent the development of an EWE or an intense wildfire. 10 of 35 experts named one or more metrics and a corresponding threshold. Experts considered that values for canopy base height between 2 m and 10 m were needed, but most experts gave values greater than 5 m. One expert noted that for vertical continuity, it makes no sense to try to separate EWE from intense fires because the transition in EWE is largely determined by fire-atmosphere interactions. With respect to fuel bed depth, one expert gave 1 m as a threshold for understory height but did not specify the type of wildfire. Two experts gave thresholds values of ladder fuel gap for intense fires, ranging from 2.5 to 5 m.

Question 5 asked experts to select from a list of horizontal continuity metrics (understory cover, canopy bulk density, canopy cover, basal area, tree density) those for which they knew thresholds to prevent the development of an EWE or an intense wildfire. 12 of 35 experts provided one or metrics and a corresponding threshold. The thresholds for canopy bulk density for intense fires given by two experts were in the line to those found in the literature review (0.05 and 0.1 kg m^3). On the other hand, the experts considered that values below a canopy cover of 60-80%, a basal area of 20 m^2 ha^{-1} or 70% of the theoretical maximum basal area, and a tree density of 100-250 trees ha^{-1} are required to limit intense fires. Regarding understory cover, most experts indicated values below 50% for limiting intense fires, with 30% being the most frequently cited threshold.

Question 6 asked experts to select from a list of fuel connectivity metrics (functional fuel connectivity, proportion of landscape treated at strategic locations, time since last fire) those for which they knew thresholds to prevent the development of an EWE or an intense wildfire. 7 of 35 experts indicated one or more metrics and a corresponding threshold. The experts considered that a threshold of 9 and 10 years since the last fire can prevent the development of an intense fire and that the proportion of the landscape in strategic locations that should be treated to avoid intense fires is between 10% and 30%, with most experts indicating a value of 30%. Only one expert gave a functional connectivity threshold, the effective mesh size of flammable fuel types, which was 1000ha for intense fires. The effective mesh size is the average size of the area that a randomly located fire will burn in a fuel type without encountering a barrier or other fuel type (see Fernandes et al., 2016 for an example).

Question 7 asked experts to provide metrics to quantify landscape heterogeneity. 18 experts out of 35 provided a metric (Table 6).

Table 6. List of landscape heterogeneity metrics provided by a total of 18 experts.

Landscape heterogeneity metrics
Connectivity between land cover types
Ratio of forest to non-forest land
Number of species
The effective mesh fire of the sum of the flammable vegetation types
Functional coverage by cadastre (area)
Total biomass (kg/m2)
% of native and/or shrubland vs % of monocultures measured along a decade
% of different land uses
Variety of species composition, difference in tree heights, distribution by area of the tree stand of each age class and others.
Patch type diversity, edge and shape
Tree/ha
% of each tree species in an area, composition of minimum 3 species
% agricultural land
Species used taking into account flammability and combustibility, size of mosaics
Proportion of the landscape treated in strategic locations (%)
Diversity of habitat types and number, size and arrangement of habitat patches.

6 Review on resilience to EWE and high-intensity wildfires

As mentioned at the beginning of this report, we define resilience as the ability of the ecological system to recover the functions and ecosystem services that the system provided before the fire. Among other variables, resilience depends on the characteristics of the system (e.g., diversity of plant fire-related traits, soil and topographic characteristics), the characteristics of the fire regime (e.g., fire severity, frequency, and season), and the presence of additional stressors before and after the fire event (e.g., prolonged drought, pest outbreaks, torrential rains, etc.). The role played by fire season, topographic variables, soil characteristics, and climatic factors on post-fire resilience are discussed in *D 1.12 Factors driving post-fire dynamics*. Then, in this section we focus our analysis on the role played by species traits (that allow plants to survive or recover after fire) and two components of fire regime: fire frequency and severity (two components of fire regime) on the resilience of the system. Fire severity depends not only on fireline intensity, but also on fire-related traits. Fire frequency indicates how often fires occur within a given area and time period. This section presents key fire-related plants traits and their interactions with appropriate fire regimes and shifts in fire regimes that may limit the resilience of different vegetation types at stand and landscape scales. The data collected in this section will be used in *D.1.13. Basis for resilient landscapes: Recommendations and novel adaptive management scenarios for creating resilient landscapes to EWE (subtask 1.4.3)* that provide critical information to define silvicultural interventions to build resilience.

6.1 Factors influencing the success of post-fire regeneration

6.1.1 Fire-related traits

A first step in assessing the potential resilience of a stand or landscape to fire is to determine the presence/absence, dominance, and type of post-fire strategies found in a particular forest type. Fire-related traits include resprouting and regeneration from seed (Pausas & Keeley, 2014). These are fire-related functional traits that can occur in a plant either alone or in combination to favour post-fire regeneration. Plants can be classified as resprouters (R+), non-resprouters (R-), seeders (S+), or nonseeders (S-) depending on the presence or absence of these traits. Based on these two broad categories, plants can be further categorized as obligate resprouters, facultative seeders/resprouters, obligate seeders, and fire colonizers depending on their post-fire regeneration strategy (*Box 5*, see Pausas & Keeley, 2014).

Box 5. 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).

Resprouters can form new shoots even though the above-ground part of the plant has disappeared after the fire, either from below-ground structures or epicormic from above-ground structures (Bond & Midgley, 2001). These plants protect buds from fire in different ways. Some plants hide the buds in the soil, which is a poor conductor of heat (e.g., *Quercus coccifera* L.), others with the base of the old leaves (e.g., *Chamaerops humilis* L.) or with the bark (*Quercus suber* L.)]. The protection of the buds and the accumulation of carbohydrate reserves allow these plants to resprout after fire.

Seeders can cope with fires because they are able to accumulate a seed bank in the soil or in the canopy, from which germinate after a fire. For example, gorse (*Ulex parviflorus* Pourr.) accumulates seeds in the ground until the rise in temperature during the fire breaks the dormancy of these seeds (Baeza & Roy, 2008). In *P. halepensis* Mill., seeds are stored in serotinous cones (Daskalakou & Thanos, 1996) which remain closed in the canopy until the rise in temperature dissolves the resin that keeps them closed and expels the seeds, which fall to the ground and germinate the following spring.

Post-fire **colonizer** species avoid getting burnt by reducing flammability or locating important parts outside the flame zone (Pausas, 2019). For example, species with thick bark and self-prunning capacity, such as *P. nigra*, survive surface fires when mature (Fulé et al., 2008; Valor et al., 2013).

6.1.2 Interaction between fire-related traits and shifts in fire regime

The presence of fire-related traits in a forest ensures to some degree the persistence of the same species after fire, but the interaction between species-specific fire-related traits and shifts in fire regime can negatively affect post-fire regeneration. In the previous section, we highlighted the traits that allow certain species to recover from or survive fires. However, these traits enable them to recover from or survive a particular fire regime, not just any regime. The term "fire regime" refers to the characteristics of fires that are prevalent in a given ecosystem, such as intensity, type of fire, spread pattern, severity, size, frequency, and seasonality (Keeley et al., 2011).

Theoretically, **fire-tolerant forests** (i.e., dominated mainly by resprouters) may be threatened by short fire intervals because stored carbohydrate reserves could be depleted, reducing their ability to resprout. However, the effects of increasing fire frequency on resprouting ability are unclear. In this sense, the review by Nolan et al., (2021) presents studies demonstrating that resprouting species are resilient to frequent low-intensity fires (e.g., Bennett et al., 2013; Watson et al., 2020), as well as repeated crown fires (e.g., Collins, 2020). For **fire-sensitive forests** (i.e, dominated by obligate seeders), there is much more evidence that short fire intervals may affect their ability to recover from fire because these species are exposed to "immaturity risk" (i.e., young individuals may not yet have established a canopy or soil seed bank when fire arrives) (Zedler, 1995), but long fire intervals also pose "senescence risk" for these species. For example, results from Màrcia et al., (2006) show better regeneration of *P. halepensis* in stands with lower fire frequency compared to areas with higher fire frequency (25,000 vs. 14,000 seedlings ha^{-1}). Not only fire frequency can influence obligate seeders, as increases in fire intensity can kill the seed bank in the canopy or soil, reducing their availability (e.g., Etchells et al., 2020). In **fire-resistant forests** (i.e., dominated by individuals that can resist fire and are post-fire colonizers), resilience is also limited by age, as the bark of young trees or shrubs may not be thick enough to withstand moderate-intensity fires. Under conditions of long fire-free intervals, fire-resistant forests can succumb to fire even when they are mature because fuel accumulation can lead to high fire intensity/severity. For example, 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 et al., 2015). 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). Thus, *P. nigra* represents a post-fire colonization strategy because it does not have a mechanism for local post-fire persistence, but recruits after fire through seeds dispersed from unburned areas or from populations outside the fire perimeter.

In summary, the resprouting, seeder and colonizer capacity of fire-tolerant, sensitive, and resistant forest, respectively, depend, among other factors, on fire frequency and fire intensity/severity, the importance and signs of which vary according to species-specific fire-related traits and the age of individuals displaying specific traits (Table 7). Fire resilient stands are those whose fire-related traits match the fire regime characteristics of the ecosystem (Rodman et al., 2021). Fire regimes suitable for forests dominated by fire-resistant species are characterized by frequent low-intensity surface fires (Pausas, 2015), while infrequent high-intensity crown fires are suitable for forests dominated by fire-sensitive species (Pausas et al., 2004). Fire-tolerant species are adapted to both frequent and infrequent fires, as well as low and high intensity fires.

Table 7. A summary of positive (+), negative (-) or indifferent (=) effects of fire frequency and fire severity on the success of the post-fire regeneration in fire tolerant, sensitive and resistant forest. Note that highly frequent and intense fires are unlikely.

Fire regime	Fire tolerant forest dominated by resprouters	Fire sensitive forest dominated by seeders	Fire resistant forest dominated by post-fire colonizers
High frequency	-	--	++
Low frequency	=	-	--
High severity	=	+	---
Extreme severity	-	--	----

6.2 Resilient stands and landscapes to fire and EWE

6.2.1 Characterizing stand resilience to fire

Stand resilience could be characterized as the influence of fire on subsequent mortality and species composition relative to those that are desired after a fire (Derose & Long, 2014). For instance, in the case of *P. nigra* stand resilience to wildfire could be defined as low mortality in the overstory as a result of a fire and in such case the strategies for building *P. nigra* stand resilience would encompass the retention of large trees. According to Derose & Long (2014), stand resilience differs from resistance in that resilience explicitly focuses on long-term strategies to maintain desired vegetation structure and composition rather than the influence of vegetation structure and composition on fire intensity. The degree of fire resilience at the stand level depends on the composition of the overstory (i.e., fire sensitive, tolerant and resistant species), its structure (i.e., fuel arrangement, fuel age) and the characteristics of the fire regime and the desired vegetation after fire.

Forest type

A variety of fire-related plant characteristics usually coexist within a forest type, but vegetation communities are often identified based on the response of the dominant or most readily identifiable vegetation, which is usually the dominant overstorey species (Nolan et al., 2021). Therefore, a forest type can be classified as fire tolerant (dominated by endurers species), fire sensitive (dominated by evasive species), fire resistant (dominated by resisters species), or fire intolerant (dominated by avoider species) depending on the post-fire strategies of overstory dominant species. The BROT 2.0 database developed by Tavşanoğlu & Pausas, (2018) may be helpful to classify forest types in terms of fire resilience. This database contains trait data from an extensive literature review and some field and experimental observations (it contains 25,764 individual records on 44 traits of 2,457 plant taxa distributed among 119 taxonomic families), including information on some fire-adaptive 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). These traits can be used to classify plant species of a given forest type as obligate seeders, resprouters, facultative resprouters, or colonizers. Most of the records in BROT 2.0 are from studies conducted in the Iberian Peninsula, followed by Greece, Anatolia, Mediterranean France, and Italy. For the Mediterranean and Atlantic bioregions, this database provides a considerable amount of information that can be used to classify a particular forest as tolerant, sensitive, or resistant to fire. While the BROT 2.0 database does not include studies conducted in the boreal, continental, and alpine bioregions, it does contain information on species that occur in these regions (e.g., *Pinus mugo*, *Fagus sylvatica*, *Abies alba*). To sum up, a first step in evaluating stand resilience to fire is to identify the dominant overstorey species' post-fire regeneration strategies.

Forest structure

Each forest type can be associated with a forest structure that favours its short- or long-term resilience after a wildfire. Given the fire-related traits of obligate seeders, **a resilient, fire-sensitive stand** would be characterized by 1) mature individuals (i.e., the age of obligate seeders species should be between the risk of senescence and immaturity) and 2) intermediate fuel loads to avoid excessive fire intensity because high temperatures can kill the canopy seed bank. Because overstory obligate seeders need some time to regenerate and become resilient again, it is important to consider time in characterizing stand resilience. In contrast, a **non-resilient, fire-sensitive stand** would be a young forest where the age of the individuals is lower than the reproductive age of the species.

The forest structure of **a resilient, fire-resistant stand** would be characterized by 1) mature or single large trees post-fire colonizer species with thick bark to protect meristematic tissues from lethal temperatures, and 2) low fuel loads and high vertical discontinuity to avoid high temperatures in sensitive tissues. For example, *P. nigra* stands with a wood volume > of 35 m^3 ha^{-1} with high tree heights and large DBH survived a forest fire (Román-Cuesta et al., 2009). On the other hand, **a non-resilient, fire-resistant stand** would be composed of young post-fire colonizer, or adult species inhabiting in a stand with high fuel loads; in such cases, fire can lead to lethal meristem temperatures and regeneration depends on the presence of unburned stands near the fire perimeter. It is important to note that there are species that exhibit both fire-sensitive and fire-resistant traits. For example, *P.*

halepensis or *P. pinaster* have serotinous cones, but exhibit relatively thick bark as adults. In northern Portugal, *P. pinaster* forest stands with a basal area of 20 m^2 ha^{-1} and a tree density of > 200 ha^{-1} exhibited low fire severity (Fernandes et al., 2015). In fact, adult individuals of any species can survive surface fires of low to moderate intensity as long as fuel loads do not result in high fire intensity and bark is thick enough to protect meristematic tissue from lethal temperatures. The work by Fernandes et al., 2008 on the fire resistance of European pines, which reviewed existing quantitative knowledge of their ability to survive fire, and the work by Bär & Mayr, 2020 on the fire resistance and thermal insulation of the bark of alpine species can be used to determine which species have thick bark and can therefore benefit from forest structures with low fuel loads and high vertical discontinuity.

In contrast to fire-sensitive and fire-resistant forest types, a **resilient, fire-tolerant stand** may be more diverse in terms of forest structure because resprouters species can withstand different fire frequencies and severities (Buhk et al., 2007). In any case, forest structures with lower fuel loads may be more suitable, as resprouting may be limited if fire kills protected buds.

Desired forest type after fire

A fire resilient stand would be the one in which the interaction between forest structure, fire frequency, and fire severity results in the desired forest type within a given time period. The desired post-fire forest type may be the same as the pre-fire forest type or an alternative resilient forest type.

To maintain the same forest type in the short or long term after fire, the fire regime and forest structure should be matched to the plant fire-related traits of the forest, as discussed earlier. If the fire regime and/or forest structure are not suitable for maintaining such a forest type, managers should consider whether the alternative state is resilient to the current fire regime and therefore the transition to a new condition is suited. If the alternative state is not resilient, the stand could be restored to the pre-fire forest type, seeking a forest structure adapted to the fire regime of the area (adaptative resilience), or it could be converted to a less flammable forest type (transformative resilience).

6.2.2 Characterizing landscapes resilience to fire

Landscape resilience can be characterised as the influence of fire on the distribution of age classes and the dominance of species relative to desirable species (Derose & Long, 2014). That is, landscape resilience could be characterised as reflecting the goal of maintaining *P. halepensis* dominance in the long-term. Such resilience could be represented by ensuring a high proportion of mature stands in the landscape, as mature stands that have reached reproductive maturity will ensure the maintenance of *P. halepensis* dominated stands in the landscape when threatened by fire. Factors that influence the resilience of a landscape include biological legacies, age class diversity, size class diversity and the diversity of successional stages (Agee & Skinner, 2005) of different forest types within a given landscape and fire regime.

6.2.3 Landscape resilience to EWE

The resilience of multiple stands to fire disturbance depends on the frequency and intensity of the disturbance. EWEs are characterized by low (albeit increasing) frequency and extreme intensity. Therefore, fire intensity rather than frequency should have the greatest impact on post-EWE vegetation recovery. However, EWEs do not necessarily lead to ecological disasters, because the erratic behavior of EWE can lead to a mosaic of different severities, with extreme intensity in certain locations. Following this rationale, fire-resistant species would be most affected by EWE because they are more sensitive to extreme fire intensity than obligate seeders and resprouters species. Furthermore, when fire-resistant stands are exposed to extreme fire intensities, overall mortality of resistant species can be expected, regardless of fuel load, vertical discontinuity, or tree size, because EWEs occur in such severe weather and fuel (dryness) conditions that fire spreads to the crown regardless of vertical discontinuity.

In the context of EWE and setting the management goal of maintaining the predominant forest type on the landscape:

- A resilient landscape dominated by post-fire colonizer species should be composed of a high proportion of stands with low fuel load and large tree size classes. This might ensure that unburned or low impact areas can be found after EWE due to its unpredictable behavior.

- A resilient landscape dominated by obligate seeder species could consist of a variety of age classes to ensure reproductive maturity, with a high proportion of mature stands with low fuel loads to decrease the severity of a potential EWE and preserve to some extent the availability of the seed bank.

- A resilient landscape dominated by resprouter species could be composed of a high proportion of stands with low fuel loads to avoid extreme severity resulting in reduced resprouting vigor.

A common factor, regardless of forest type, is the need for low fuel loads to reduce the severity of EWE as much as possible. Reducing fuel load confers not only resilience to EWE but also, as discussed in the first section of this report, on resistance to EWE.

7 Questionnaire results on resilience to EWE

This section presents the results of the questionnaire related with factors driving resilient landscapes to fire (question 8) (Appendix: 10.2 Questionnaire). **Question 8** asked experts to select a maximum of two vegetation types from a list of and then provide stand and landscape level indicators for a silvicultural strategy aimed at maintaining the same pre/post-fire vegetation types (either short- or long-term post-fire). 13 experts out of 35 provided one or more metrics and a corresponding threshold (Table 8).

Table 8. Stand-level indicators tied to the vegetation types selected by a total of 13 experts. Similar answers were coded with the same category/indicator.

Stand-level resilience indicators	Vegetation types
Open stands; low tree density; spaced trees	Hemiboreal and continental Scots pine (*P. sylvestris*) forests
	Swiss stone pine (*P. cembra*) forests
	Tall deciduous oak (*Quercus* sp.) forests
	Alpine Black pine (*P. nigra*) in the Alps
	Hemiboreal Mountain pine (*P. mugo*) forests
Large trees; mature stage	Hemiboreal and continental Scots pine (*P. sylvestris*) forests
	Mixed *Quercus* sp. and *Fraxinus* forests
	Tall deciduous oak (*Quercus* sp.) forests
Low understory	Alpine Black pine (*P. nigra*) in the Alps
	Fir (*Abies alba*) forests
	Spruce (*Picea abies*) forests
Pruned	Fir (*A. alba*) forests
	Spruce (*P. abies*) forests
	Tall deciduous oak (*Quercus* sp.) forests
Mixed broadleaves	Spruce (*P. abies*) forests
Uneven age	Beech (*Fagus* sp.) forests

8 Resilient landscapes to EWE and high intensity fires

8.1 Summary: resistance to EWE and high intensity wildfires

Based on the literature review and survey results, a summary table of key factors (and their relative importance), metrics, and thresholds that determine landscape resistance to EWE and high intensity fires was developed (Table 9). There are two aspects that are important to note. First, here only fuel factors have been reviewed, and the influence of other factors (e.g., atmospheric conditions, weather, relative humidity) have not been considered in this report. Second, the fact that the wildfire behaviour varies according to the combination of the influence of several metrics.

Table 9. Summary of the main factors, metrics and thresholds influencing resistance to high intense wildfires and extreme wildfire events. Not avail., not available; Not appl., not applicable. The values provided are derived from the literature review and the survey results.

Scale	Ranking of importance (from most 1 to least important 5 or 6)	Resistant factors	Metrics	High intensity wildfires threshold	EWE thresholds	Fire behaviour component influenced
Stand	1	Fuel load	Fine fuel load (t ha^{-1})	10	10	Fire intensity and severity
Stand	2	Horizontal continuity	Canopy bulk density (kg m^{-3})	0.05-0.1	Not avail.	
			Canopy cover (%)	70-80		
			Basal area (m^2 ha)	20		
			Understory cover (%)	30		
Stand	3: high intensity fires	Vertical continuity	Canopy base height (m)	7	Not appl.	
Landscape	4: high intensity fires 3: EWE	Fuel connectivity	Time since last fire (years)	9	Not avail.	Fire spread
			Landscape treated in strategic locations (%)	20		
			Effective mesh size[1] (ha)	Not avail.	Not avail.	Fire spread

Stand	5: high intensity fires 6: EWE	Fuel composition	Dominant species	Conifers and shrublands vs. broadleaves	Not appl.	Fire severity

[1]Average size of the area that a randomly located fire will burn in a fuel type without encountering a barrier or other fuel type (see Fernandes et al., 2016)

The factors that determine resistance to EWE are, in order of importance, fuel load, horizontal continuity, fuel connectivity, LULC structure, and fuel composition. The results of the questionnaire suggest that the order of the identified factors should be the same regardless of the bioregion. Vertical continuity is excluded as a factor that may affect the development of EWE because as noted by one of the experts the transition of fire from the surface to the canopy occurs due to plume-atmosphere interaction. The effects of fuel composition on the spread of EWE is irrelevant but may play a role in reducing fire severity. In this sense, less flammable land use or land cover types, such as agricultural land, may have a greater influence on fire spread than variations in flammable land cover types. For high intensity fires, thresholds that matched both literature review and experts' results are provided, and for such fires vertical continuity is included as it negatively influences resistance.

8.2 Summary: ecological resilience to EWE and high intensity fires

Based on the literature review and survey results, a summary table of the influence of fire regime factors on the resilience of different forest types has been developed (Table 10). The table also shows the desired forest structure at the stand and landscape level to ensure the maintenance of the same forest type after the fire (basic resilience). However, an alternative state can be even more resilient and this needs to be considered (transformative resilience).

Table 10. Influence of fire regime factors, that characterize EWE or high-intensity wildfires on the resilience of fire-tolerant, -sensitive, and -resistant forests. The sign of the effect of each factor on the resilience of different forest types is indicated in parentheses. If the effect is negative, the desired forest structure at the stand and landscape level to ensure the same forest type after the fire event is indicated.

Forest type	EWE		High intensity wildfires	
	Low frequency	Extreme intensity	Moderate frequency	High intensity
Fire tolerant	(=)	(--) High proportion of stands with low fuel loads to avoid extreme severity resulting in reduced resprouting vigour.	(=)	(=)
Fire sensitive	(=)	(--) High proportion of mature stands with low fuel loads to avoid extreme severity resulting in reduced seed availability.	(--) Variety of successional age classes to ensure reproductive maturity.	(=)
Fire resistant	(=)	(---) High proportion of fire-resistant stands within the landscape (i.e. low fuel load and large tree size or mature successional stage) respect to non-fire-resistant stands. This might ensure that unburned or low impact areas can be found within the EWE perimeter due to unpredictable behavior of EWE.	(=)	(--) Moderate proportion of fire-resistant stands (i.e. low fuel load and large tree size or mature successional stage) within the landscape respect to non-fire-resistant stands.

8.3 Multidimensional assessment of fire resilient landscapes

Within the framework FIRE-RES, the assessment of a fire resilient landscape aims to embrace all elements of the socio-ecological system (e.g., physical, ecological, economic, or social). Using a multidimensional approach the assessment of a fire resilient environment is more realistic than using only one dimension (Figure 5). The challenge for FIRE-RES is in operationalizing the dimensions of fire resilient landscapes. Here, we have provided factors, metrics and thresholds for the assessment of the physical environment dimension.

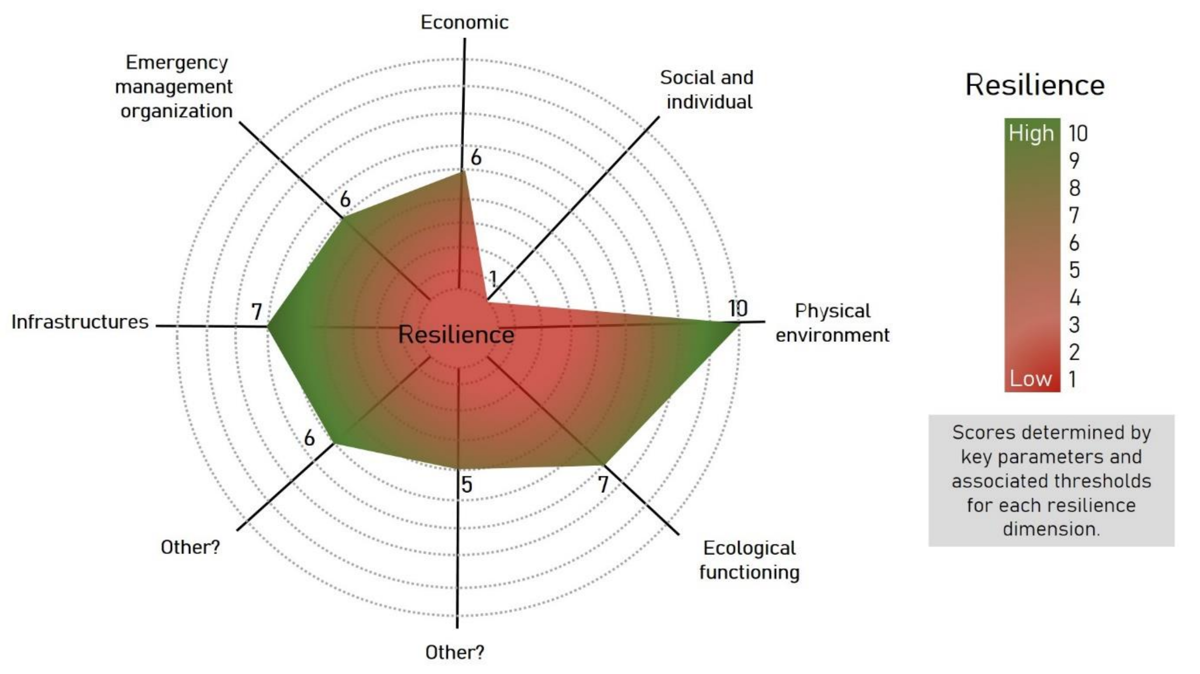

Figure 5. Framework for guiding the assessment of fire resilient landscape status across key dimensions. Based on the KHT innovation readiness level.

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10 Appendices

10.1 Literature review: search strategy

Previous research has shown that several factors play a role in the resilience and resistance of forests and landscapes to EWE and large wildfires: 1) fuel load and arrangement, 2) forest structure and composition and 3) fuel connectivity. Based on these factors, we conducted a systematic literature review and searched in the ISI Web of Knowledge for European studies that addressed each of these factors, as well as others that emerged during the review process. The keyword search used various combinations of relevant terms for resistance (Table 11).

Table 11. Keyword searches and number of selected studies for each fuel-related factors associated with stand and landscape resistance.

	Keywords
Stand Resistance	
Fuel load and structure	Fuel arrangement OR forest structure AND fire behaviour OR fire severity OR fire intensity
Fuel composition	Fuel composition OR forest type AND fire behaviour OR fire severity OR fire ocurrence
Landscape Resistance	
Fuel composition	Forest type OR cover type AND landscape AND fire behaviour OR fire spread OR fire size
Fuel connectivity	Fuel connectivity AND fire behaviour OR fire spread OR fire size
Land use heterogeneity	Land use OR land cover AND fire behaviour OR fire spread OR fire occurrence

10.2 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://fire-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 research/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.

Q2) Fire-resistant forests are those that are able to reduce the intensity and spread of a fire event. The most important fuel-related factors that can influence the resistance of stands and landscapes to fire are fuel load, structure, composition, connectivity, and land use and land cover type patterns.

- Fuel load: amount of fuel expressed as dry weight of fuel per unit area, i.e., potential energy accumulated on the ground or/and in the canopy.
- Fuel structure: spatial configuration of the forest stand, and includes fuel bed depth, height or thickness, bulk density or compactness, arrangement (vertical and horizontal continuity), cover, and number of layers involved (ground, surface, ladder, and crown).
- Fuel composition: species composition of a fuel complex.
- Fuel connectivity: the extent to which the landscape facilitates or impedes movement between resource patches.
- Land use and land cover patterns: density, size, and diversity of patches, among others.

A) For your bioregion, please rank in order of importance, from most (1) to least (5) important, the following list of fuel-related factors that can influence the development of an EWE. *

Mark only one oval per row.

	1	2	3	4	5
Fuel load	⬭	⬭	⬭	⬭	⬭
Fuel structure	⬭	⬭	⬭	⬭	⬭
Fuel composition	⬭	⬭	⬭	⬭	⬭
Fuel connectivity	⬭	⬭	⬭	⬭	⬭
Land cover and land use types patterns	⬭	⬭	⬭	⬭	⬭

B) Is there any comment you would like to share (e.g., any missing factor)?

Q3) Below are some metrics that can be used to quantify fuel load at the stand or landscape level. In order to make management recommendations to prevent the development of an EWE or an intense wildfire, we need to establish fuel loading thresholds to modify fire intensity (Kw/m). Based on your experience, please select the metric (s) for which you know thresholds and indicate them in A (below).

Tick all that apply.

- [ ] Total biomass (kg/m2)
- [ ] Total fuel load (kg/m2)
- [ ] Avalaible fuel load (kg/m2)
- [ ] Surface FIne fuel load (kg/m2)
- [ ] Total fine fuel load (Surface + canopy) (kg/m2)

I do not know

A) Based on your experience, please provide fuel load thresholds for * your chosen metric(s) to prevent the development of EWE or intense but conventional wildfire, or both. Indicate the fire type(s) for which you are providing thresholds. If you do not know them, please indicate so.

Q4) Below are some metrics that can be used to quantify fuel structure at the * stand level, particularly vertical continuity. In order to make management recommendations to prevent the development of an EWE or intense wildfire, we need to establish thresholds for vertical continuity to modify fire intensity (kW/m). Based on your experience, please select the metric(s) for which you know thresholds and indicate them in A (below) for EWE and/or intense wildfires.

Tick all that apply.

- [ ] Fuel bed depth (m)
- [ ] Ladder gap (m)
- [ ] Canopy base height (m)
- [ ] Dominant height (m)
- [ ] I do not know

Other:

A) Based on your experience, please provide vertical continuity thresholds for your chosen metric(s) to prevent the development of EWE or intense but conventional wildfire, or both. Indicate the fire type(s) for which you are providing thresholds. If you do not know them, please indicate so.

Q5) Below are some metrics that can be used to quantify fuel structure at the * stand level, particularly horizontal continuity. In order to make management recommendations to prevent the development of an EWE or intense wildfire, we need to establish thresholds for horizontal continuity to modify fire intensity (Kw/m) at the stand level. Based on your experience, please select the metric(s) for which you know thresholds and indicate them in A (below) for EWE and/or intense wildfire.

Tick all that apply.

- [ ] Undestory cover (%)
- [ ] Canopy bulk density (Kg/m3)
- [ ] Canopy cover (%)
- [ ] Basal area (m2/ha)
- [ ] Tree density (tree/ha)
- [ ] I do not know

Other:

A) Based on your experience, please provide horizontal continuity thresholds for your chosen metric(s) to prevent the development of EWE or intense but conventional wildfire, or both. Indicate the fire type(s) for which you are providing thresholds. If you do not know them, please indicate so.

Q6) Below are some metrics that can be used to quantify fuel connectivity at the landscape level. In order to make management recommendations to prevent the development of an EWE or intense wildfire, we need to establish landscape fuel continuity thresholds to modify rate of spread (km/h) or growth rate (surface unit/h). Based on your experience, please select the metric(s) for which you know thresholds and indicate them in A (below) for EWE and/or intense wildfires.

Tick all that apply.

- [ ] Functional connectivity metrics (e.g., equivalent connectivity index, mesh size)
- [ ] Proportion of the landscape treated in strategic locations (%)
- [ ] Time since last re (years)
- [ ] I do not know
- [ ] Other

A) Based on your experience, please provide landscape fuel continuity thresholds for your chosen metric(s) to prevent the development of EWE or intense but conventional wildfire, or both. Indicate the fire type(s) for which you are providing thresholds. If you do not know them, please indicate so.

Q7) Heterogeneous landscapes are considered more resistant to EWE and * are characterised by a diversity of land use and land cover types. Which metric would you use to quantify landscape heterogeneity?

Q8) 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 aspects related with their fire resilience. Select a maximum of two vegetation types (one from A and the other, if you like, from B) for which you have more experience or knowledge, and then go to C and D.

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 move on to the next question.

Most of the vegetation types listed here are a selection of those included in Xanthopoulos et al. 2012, where various vegetation types in Europe were assessed for ammability by distributing a questionnari to 20 experts. The correspondence between the vegetation types and the European forest types classi cation was mostly made by the same experts according to the description and keys in the European Environment Agency (2007).

Xanthopoulos, G., Calfapietra, C., & Fernandes, P. (2012). Fire hazard and ammability of European forest types. In Post- re management and restoration of southern European forests (pp. 79-92). Springer, Dordrecht.

European Environment Agency (2007) European forest types: categories and types for sustainable

forest management reporting and policy. European Environment Agency. Technical report No 9/2006 (2nd edn), Copenhagen, Denmark. p 111

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
- Swiss stone pine (Pinus cembra) forests

C) At the stand level, resilience can be characterized as the influence of fire on subsequent mortality and species composition relative to desired post-fire vegetation types (Derose & Long, 2014). For the selected vegetation type(s) (FIRST or FIRST and SECOND), please provide stand-level indicators for a silvicultural strategy aimed at maintaining the same pre/post-fire vegetation types (either short- or long-term post-fire).

Example: Building resilient stands of the non-serotinus Pinus nigra could be done by creating and maintaining large, widely spaced trees of this species. During wildfires, these stands are more likely to have limited mortality of the largest trees, which may promote post-fire regeneration of black pines.

FIRST VEGETATION TYPE (if selected)

SECOND VEGETATION TYPE (if selected)

D) At the landscape level, resilience could be defined as the effect of fire on subsequent proportions of age classes and on species dominance relative to those desired after fire (Derose & Long, 2014). For the selected vegetation type(s) (FIRST or FIRST and SECOND), please provide landscape-level indicators for a silvicultural strategy aimed at maintaining the same pre/post-fire vegetation types (either short- or long-term post-fire).

Example: Building resilient landscapes of the non-serotinus Pinus nigra could be done by ensuring that a certain percentage of stands across a landscape are characterized by large size classes or mature successional stages.

FIRST VEGETATION TYPE (if selected)

SECOND VEGETATION TYPE (if selected)

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)?

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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)?

FIRE-RES