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FIRE-RES

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

D1.13 RECOMMENDATIONS AND NOVEL ADAPTATIVE MANAGEMENT SCENARIOS TO CREATE RESILIENT FOREST LANDSCAPES TO EWE (part I)

Bases for the parametrization of forest management options for resilient landscapes: integration of stand level parameters into fire simulators

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Abstract: Deliverable *1.13 Recommendations and novel adaptative management scenarios to create resilient forest landscapes to EWE* is composed by two deliverables. This document is the first deliverable (part I), prepared for month 18 to feed IAs and subtasks of WP2, while the second deliverable submitted at the end of the project will focus on specific recommendations and novel adaptive management scenarios. Thus, in WP2, there is the need to parameterize forest management options to move towards resilient landscapes to EWE, based on general recommendations and concepts developed within WP1 and specific forest management guidelines/silvicultural models available for main forest species in LLs. This deliverable presents general recommendations and concepts for forest management, which are then parameterised to create adaptive management scenarios for specific forest species in Living Labs (LLs). The methodology presented here includes the selection and monitoring of parameters and indicators, their linkage to management options and their integration into fire simulators and decision support systems to evaluate management alternatives. An example is given using forest management guidelines developed in Catalonia for the *P. halepensis* forest type. The methodology can be implemented in other LLs interested in its application within WP2.

Key words: stand's fire resistance, fire simulator, forest management, fire prevention

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1 Introduction

As part of FIRE-RES, deliverable *1.13 Recommendations and novel adaptative management scenarios to create resilient forest landscapes to EWE* consists of two deliverables. This document is the first deliverable (part I), prepared for month 18 to feed the IAs and subtasks of WP2, while the second deliverable submitted at the end of the project will focus on specific recommendations and novel adaptive management scenarios. Thus, in WP2, there is the need to parameterize forest management options to move towards resilient landscapes to EWE, based on general recommendations and concepts developed under WP1 and specific forest management guidelines/silvicultural models available for main forest species in LLs.For this purpose, a process has been developed to adapt their usability for stand-level planning processes and forest management decisions. This process involves selecting and monitoring parameters and indicators (e.g., stand density, forest cover, understory cover, etc.) that need to be (i) linked to management options and pre- and post-treatment conditions, and (ii) integrated into fire simulators and decision support systems (DSS) for cost-effective evaluation of novel management alternatives. In addition to prevention measures, forest management also considers the use of fire as a fuel management tool and silvopastoral models.

In *Section 2*, we present the general methodology to:

1) Define forest types, objectives, scenarios, and dasometric parameters of forest structures before and after the application of different treatments.

2) Create fire resistant stands.

3) Incorporate pre- and post-treatment conditions for different management options in fire simulators and DSS. Specially, we show how to convert dasometric parameters of defined pre- and post-treatment forest structures into fuel-related metrics needed in fire simulators.

Section 3 provides an example of how this guidance can be implemented. The example uses the forest management guidelines (FMG) developed in Catalonia, called ORGEST (Piqué et al., 2017)., which cover almost all conifer- and broadleaf-dominated forests in Catalonia (including pure and mixed forests), which together account for over 90% of the forest area (Piqué et al., 2014).More particularly, we show an example for the forest type of *P. halepensis*.In other words, we present the dasometric parameters before and after treatments for three theoretical stages of *P. halepensis* forest type, the conversion of such dasometric parameters into inputs for fire simulation programs, the potential fire behavior simulated in both cases, and the direct costs associated with the treatments.

The methodology has been developed within the Catalonia Living Lab (LL), yet it holds applicability for other LL interested in its implementation (e.g., Aquitaine, Bulgaria, Portugal and Sardinia). During the second year of the project, the guidelines presented herein will be used to estimate the potential fire behavior for all forest types and treatments defined in the Catalonia LL.

2 Methodology

2.1 Definition of forest types and objectives

2.1.1 Forest types

The aim is to define the main forest types in the LL and then to assign different management alternatives to each identified forest type.

In the case of LL Catalonia, the forest types are classified by conifers (60%), *Quercus* forests (30%) and other minority forests (10%). Although we have over 160 forest types based on species composition and including mixed forests (34 pure forest types, 128 mixed forest types, Piqué et al., 2014), most of our forests are dominated by *Pinus halepensis*, *P. sylvestris*, *P. nigra*, *P. uncinata*, *P. pinea*, *Quercus ilex*, *Q. pubescens*, *Q. suber* and *Q. faginea* (DGDRPF, 2016), which may be mixed with other species forming mixed forests.

To parameterize forest management alternatives, we suggest working with the main species in the LL and focus on the forest types dominated by these species. In the case of Catalonia, for example, these would be the forest types mentioned previously (DGDRPF, 2016): *Pinus halepensis* (409,000 ha), *P. sylvestris* (231,000), *P. nigra* (143,000 ha), *P. uncinata* (73,700), *P. pinea* (38,500), *Quercus ilex* (282,200 ha), *Q. pubescens* (115,100 ha), *Q. suber* (69,200 ha) and *Q. faginea* (28,100 ha), with a total forest area of 1,384,800 ha (87% of the forest area in Catalonia).

Given the need to link forest types to various forest management guidelines and treatments in order to reduce the vulnerability of forest landscapes to EWE, it is critical to also consider their management when identifying the main forest types, i.e. the silvicultural models and/or information on the most common silvicultural treatments used in these forest types, taking into account the possibility of linking models and management scenarios for most forest types, as might be the case for mountain pines (*P. nigra*, *P. sylvestris* and *P. uncinata*).

2.1.2 Management objectives

The general objective of management is always to lower fuel load and thus develop forests that are more resistant to EWE and high intensity fires. To attain this purpose, many management options/approaches are possible depending, among other things, on factors such as the conditions of the forest stand and the tools available to implement the management options. WP1 provides general recommendations for resilient landscapes, that serve as the foundation for designing management strategies. The following are the main management strategies currently being addressed in these guidelines to promote more resistant forest landscapes:

- Density management strategies, mainly through thinning

- Fuel load reduction (mechanical or through prescribed burning)
- Sylvopastorism

2.1.3 Pre- and post-treatment forest structures

The different management options include different silvicultural itineraries and the implementation of specific silvicultural treatments Different silvicultural itineraries, and the application of specific silvicultural treatments are among the various management alternatives, some of which are decided at the stand level depending on forest structures and characteristics prior to treatment. At the same time, forest treatments and measures implemented lead to specific forest structures after treatment.

Based on the general management approaches considered in this methodology (density management strategies, fuel reduction and sylvopastorism), each LL should define the forest parameters (before and after treatments) associated with the various forest management alternatives and silvicultural practices described. These forest metrics, which relate to forest stand development and stand density, are frequently used in silvicultural guidelines and itineraries. The parameters needed to describe the forest structure before and after treatments are: dominant tree height, canopy cover, stand density, mean diameter, basal area, shrub cover and height. All these parameters are required because the method proposed in this guideline turns these forest parameters into fuel variables required by fire simulators. For each forest type, we proposed defining pre- and post-treatment characteristics for those development stages when silvicultural treatments are most commonly applied in a specific forest type. For example, for the case of **Forest Type: *Pinus halepensis* and Forest Management Scenario:** tree density and fuel load reduction, for the LL Catalonia, based on the Sustainable Forest Management Guidelines for forest production and fire prevention developed in Catalonia, called ORGEST (Piqué et al., 2017), expert knowledge and literature review, we defined silvicultural treatments and pre- and post-treatment characteristics for three different development stages (where silvicultural treatments are most commonly applied) (Table 1).

Table 1. Pre- and post-treatment forest structure in three different development stages of P. halepensis forests. H: dominant tree height; CC: canopy cover; N: stand density; DBH: diameter at breast height; BA: basal area; SC: shrub cover; SH: shrub mean height

Development stages	Treatment	H (m)	CC (%)	N (tree ha^{-1})	DBH (cm)	BA (m^2 ha^{-1})	SC (%)	SH (m)
Regenerated-Young forest								
Pre-treatment		4-6	≈100	6000	6			
Post-treatment	Pre-commercial thinning	6	≈70	1800	8-10	20	<30	<1.3
Mid-age forest								

Pre-treatment		6-12	>70	1600	15-17	30-40	>50	>1.3
Post-treatment	Clearing + low thinning	12	≈70	850	20	20-30[1]	<30	<1.3
Adult forest								
Pre-treatment		>12	>70	750	28-30	>30	>50	>1.3
Post-treatment	Clearing + mixed thinning	>14	≈70	500	32	>20[1]	<30	<1.3

[1]The pre-treatment basal area has been reduced in 30%.

2.1.4 Fire resistant stands

The information presented within this section is derived from D1.11 (Valor et al., 2023) and serves as a resourcefor defining the treatments that will be used to create fire resistant stands and landscapes. Based on the literature review and survey results, a summary table (Table 2) was developed , outlining the key fuel factors (along with their relative importance), metrics, and thresholds that determine landscape resistance to EWE and high intensity fires. The factors identified as determinants of resistance to EWE are, in order of significance, fuel load, horizontal continuity, fuel connectivity, land use land cover (LULC) structure, and fuel composition. Regadless of the specific bioregion, the results of the questionnaire suggest that the order of the identified factors should maintain the same prioritization. While the effect of fuel composition on the spread of EWE is irrelevant, it may play a role in mitigating 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.Regarding high-intensity fires, thresholds aligning with both the literature review and experts' results are provided, and for such fires vertical continuity is included as it negatively influences resistance.

Table 2. 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		

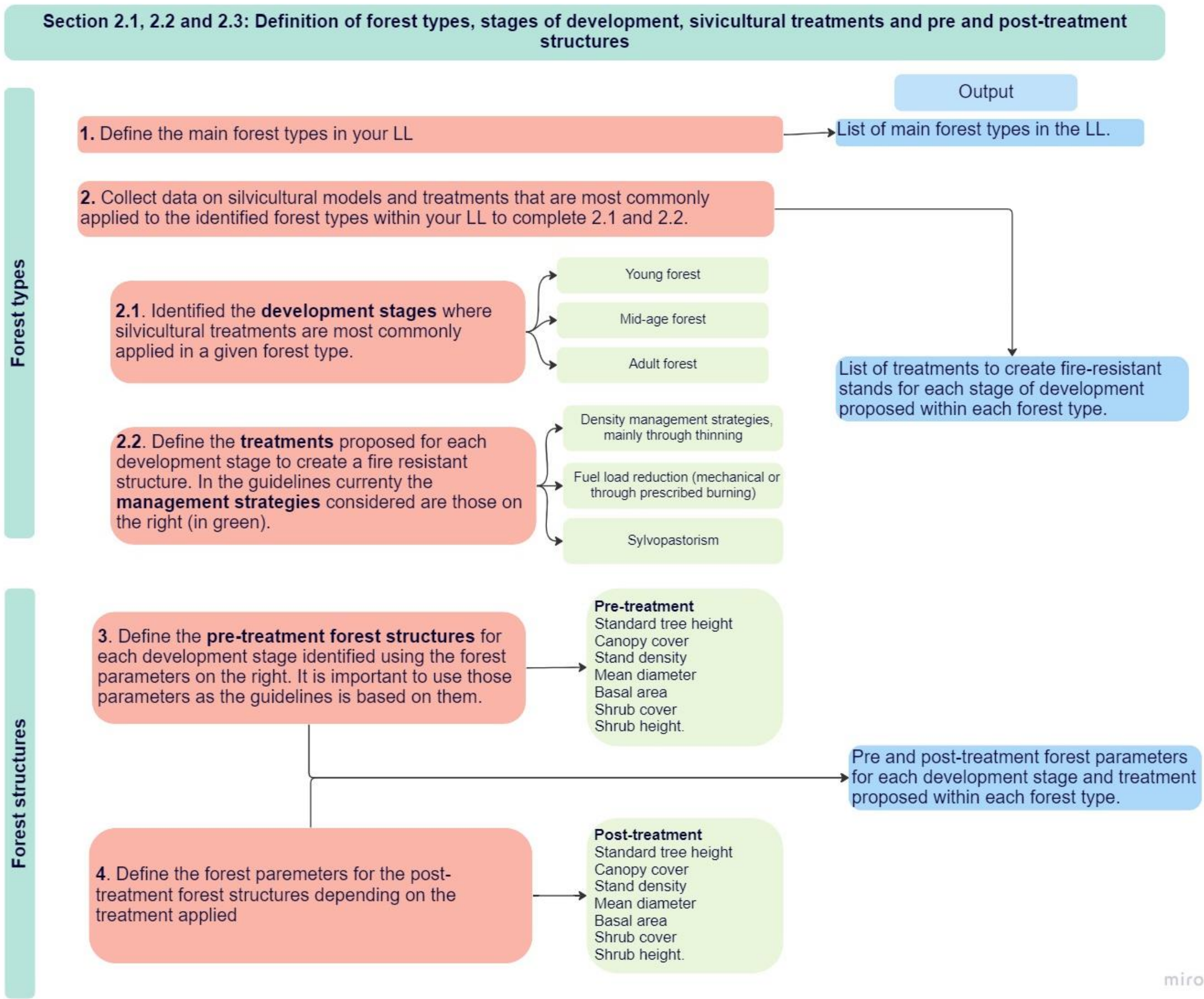
			Basal area (m^2 ha)	20		
			Understory cover (%)	30		
Stand	3: high intensity fires	Vertical continuity	Canopy base height (m)	7	Not appl.	
Landscape	4: high intensity fires 3: EWE	Fuel connectivity	Time since last fire (years)	9	Not avail.	Fire spread
			Landscape treated in strategic locations (%)	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)

2.1.5 Summary

The process described above, which is summarized in Figure 1 should be repeated for all forest types and management scenarios identified within each LLs, to obtain the pre- and post-treatments silvicultural parameters that later will be converted into fuel variables required by fire simulators (see sections 2.3 to 2.5).

Figure 1. Scheme with the main steps to apply the steps described in section 2.1, 2.2 and 2.3 to define forest types, stages of developments, silvicultural treatments and pre- and post-treatment forest structures.



2.2 Fire simulators software

The ultimate objective of the methodology is to provide the fuel metrics required for fire simulation software to assess the impact of various suggested treatments in terms of fire behaviour as well as direct costs. A static stand simulator can be employed to compare potential fire behavior in forest structures before and after treatment using tools such as BehavePlus or Nexus. The recommended simulator is Behave Plus 6.0. The latest version can be found at the following link: https://www.frames.gov/behaveplus/software-manuals. The user manual for the previous version (Heinsch & Andrews, 2010) is still valid and has not been updated. Behave Plus requires variables related to fuel (fuel model, canopy height, canopy base height, canopy bulk density), moisture (for different fuel size classes), weather (wind), and terrain (slope) to estimate crown fire behavior (Figure 2). This guideline provides some information on how to use BehavePlus but its purpose is not to demonstrate how to utilize the simulator.

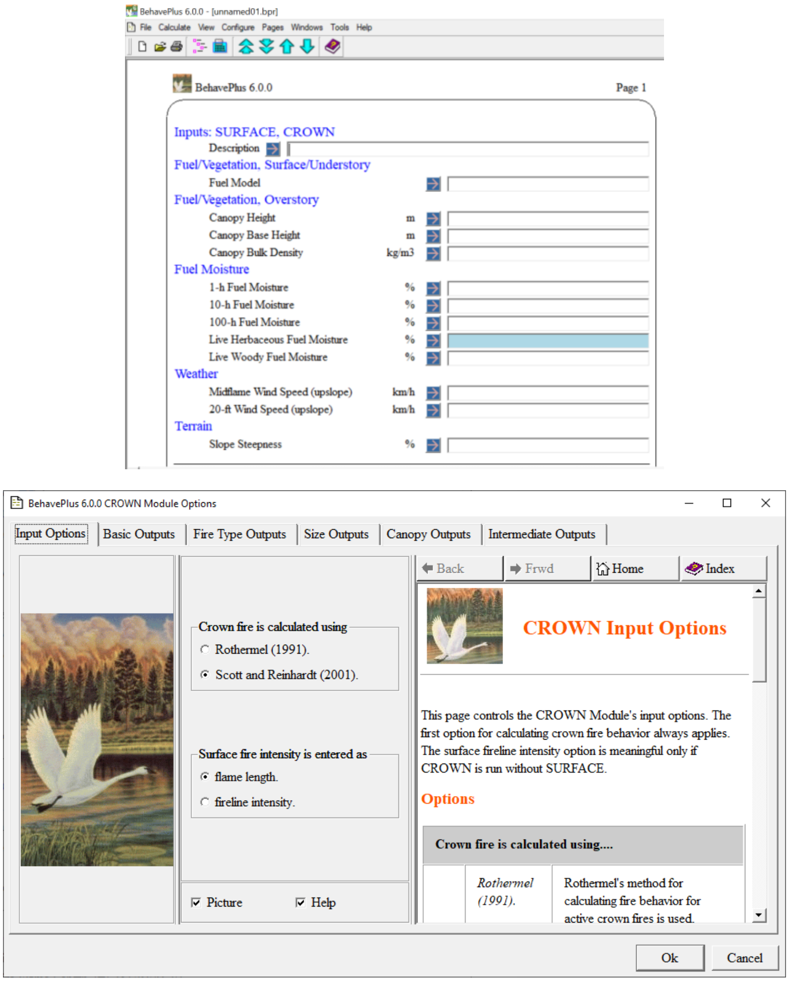


Figure 2. Screenshot of BehavePlus 6.0 showing the inputs needed to run a crown fire simulation (up). The scott and Reinhardt (2001) crown fire model should be selected to run the simulations (bottom).

Once the forest type and the forest structure are described using dasometric variables before and after treatment, the methodology presented below enables the conversion of the dasometric variables into the fuel inputs required by Behave plus (i.e., fuel model, canopy height, canopy base height, canopy bulk density). Additional variables associated with fuel moisture, weather and terrain characteristics are detailed in *Section 2.6 Setting Up Scenarios*.

2.3 Estimation of shrub layer metrics required in fire simulator software's

The shrub layer input variable required in all fire simulation software's is the surface fuel model.

2.3.1 Surface fuel model

The fuelbed features (i.e., surface fuel, shrub layer) in fire simulator systems are set by selecting a specific surface fuel model (hereinafter "fuel model"). The selected fuel model is then used by the fire simulator system to predict surface fire spread using Rothermel (1972) equation. Usually, each fuel model is represented by a set of fuelbed or surface layer properties (Box 1 and):

Box 1. Parameters that described a fuel model.

- Fuel load by size classes (fine, medium, and coarse) and condition (live and dead).
- Dead fuels by timelag categories (1, 10, 100 h) depending on their diameter (0-6, 6-25, 25-75). 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).
- Surface-area-to-volume (SAV) ratio by component and size class.
- Heat content by category.
- Fuelbed depth.
- Dead fuel moisture of extinction.

The first fuel models were developed in the United States by Rothermel (1972), who listed the parameters showed above for 11 fuel models Rothermel (1972), who specified the parameters shown above for 11 fuel models, developed the first fuel models in the United States. These fuel models can be used to predict surface fire spread using Rothermel (1972) equation Using the Rothermel (1972) equation, these fuel models can be used to estimate surface fire spread. Later, Albini (1976) refined these 11 fuel models and added two more, which were referred to as the original 13 fuel models for fire behavior. The original fuel models have been successful in predicting the rate and intensity of spread of active fires during the peak of the fire season, in part because dry conditions lead to a more uniform fuel complex, which is a fundamental assumption of the underlying model of fire spread. However, they are deemed unsuitable for alternative applications, such as prescribed fire, wildland fire use, simulating the effects of fuel treatments on potential fire behavior, and simulating the transition to crown fires using crown fire initiation models. Some of these caveats were overcome by Scott & Burgan (2005), who formulated 40 standard fuel models. These fuel models are categorized into the subsequent fuel classifications: Nonburnable (NB), Grass (GR), Grass-Shrub (GS), Shrub (SH), Timber-Understory (TU), Timber Litter (TL) and Slash-Blowdown (SB) and within each fuel type there are different fuel models specify using a number (e.g., SH7). With regard to each fuel type, the fuel models exhibit variations in terms of fuel bed properties or characteristics (see Box 1). Refer to Figure 3 for an illustration of the parameters associated with fuel model SH7, as developed by Scott & Burgan (2005).

Fuel Model sh7

Fuel Model Number	147	
Fuel Model Name	sh7	
Fuel Model Type	Static	
Description	Very high load, dry climate shrub (S)	
1-h Fuel Load	3.5 tons/ac	7.8 tonnes/ha
10-h Fuel Load	5.3 tons/ac	12 tonnes/ha
100-h Fuel Load	2.2 tons/ac	4.9 tonnes/ha
Live Herbaceous Fuel Load	0 tons/ac	0 tonnes/ha
Live Woody Fuel Load	3.4 tons/ac	7.6 tonnes/ha
1-h Surface Area/Vol Ratio	750 ft2/ft3	24.6063 cm2/cm3
Live Herbaceous Surface Area/Vol Ratio	1800 ft2/ft3	59.0551 cm2/cm3
Live Woody Surface Area/Vol Ratio	1600 ft2/ft3	52.4934 cm2/cm3
Fuel Bed Depth	6 feet	182.88 cm
Dead Fuel Moisture of Extinction	15 percent	15 percent
Dead Fuel Heat Content	8000 Btu/lb	18622.3 KJ/Kg
Live Fuel Heat Content	8000 Btu/lb	18622.3 KJ/Kg

Figure 3. Screenshot of BehavePlus showing the fuelbed properties of fuel model SH7 (Scott & Burgan, 2005) in english and metric units.

Outside the U.S., fuel models have also been developed at regional scales (see, e.g., Rodríguez y Silva & Molina-Martínez, (2012) for the Andalusia region of Spain, see Allgöwer et al., (1998) for Switzerland. As explained below, fuel models have been related to forest types or even forest structures within forest types, however there are few examples. In the next section we show how to connect a fuel model to the defined forest structures before and after treatment.

2.3.2 Pre-treatment forest structure: assigning a fuel model

Once pre-treatment forest structures have been defined for a certain forest type (Subsection 2.1 and 2.2), there are several options with varied degrees of complexity for assigning a fuel model to each pre-treatment structure (Table 3). Choosing one of the possibilities is determined by the availability of data in your region, as well as time and economic constraints. We outline how to proceed for each of the options in Table 3

Table 3. Tier list showing the different options for assigning a fuel model to a pre-treatment forest structure from simplest to most complex.

	Tier	List of options to assign a fuel model to a pre-treatment forest structure
Complexity	1	Use existing national or regional fuel models that are already tied to different forest structures within a forest type.
	2	Assign a standard, national or regional fuel models to forest structures within forest types.
	3	Tier 1 and 2 but adjusting fine fuel loads.
	4	Elaborate custom fuel models for forest structures within forest types.

Tier 1: Use existing national or regional fuel models tied to forest structure within forest types.

Tier 1 represents the simplest option; however, based on our current understanding, there is a limited availability of fuel models associated with different forest structures across a diverse range of forest types in Europe (Table 4). As an illustration, in Portugal, Fernandes (2009) defined 19 forest types, each comprising four structural types (closed and low stands, closed and high stands, open and low stands, open and high stands). For each structure type, the fuel model parameters are defined (e.g. fuel load by size class, see Box 1). These fuel models were created through destructive sampling and the use of allometries to characterise the properties of strata (e.g. load by size class and condition) in a range of forest structures within forest types.

Table 4 Reference list of fuel models tied to forest structures within forest developed in European areas at national and regional scale.

Country	Scale	Reference	Fuel models linked to...
Portugal	National	Fernandes (2009)	Forest type and structure
Austria	National	Neumann et al. (2022)	Forest type and structure

In Table 5 the step to follow tier 1 is provided, which basically consist of conducting a search for existing fuel models linked to forest structures within forest types in your region and match them to the defined pre-treatment forest structure.

Table 5. Tier 1: steps to assign a fuel model to a pre-treatment forest structure within a forest type.

Step	Tier 1: Use existing national or regional fuel models tied to forest structure within forest types
1	Look for existing fuel models that are linked to forest structures within forest types in your region or state. In Table 3 will find a list of some fuel models associated with forest structures within forest types developed for European countries or regions. If such models exist, consider using them. Match the fuel models to the pre-treatment forest structures, considering the forest parameters of the defined pre-treatment forest structure and the characteristics of the forest structures linked to the fuel models in your region. Then proceed to the section "Forest structure after treatment: Assigning a fuel model". Consider Tier 2, 3 and 4 if such fuel models do not exist or if fuel models exist in your region but are not linked to forest structure.

Tier 2: Assign a standard, national or regional fuel model to pre-treatment forest structures

In Tier 2, the standard fuel models developed by Scott & Burgan (2005) (as described at the beginning of the Surface Fuel Model section) or, if available, fuel models developed in your region can be used (regional or national fuel models linked or not to forest types) (Table 6). For instance, Ascoli et al. (2020) developed a set of fuel models for Italy that are connected to European forest types but not to forest structure within each forest type, unlike the approach taken by Fernandes et al. (2009) in Tier 1. Other fuel models such as those proposed by Rodríguez y Silva & Molina-Martínez, (2012) for the Andalusia region of Spain are not correlated to forest types. In Table 7 the steps to follow tier 2 are provided.

Table 6 Reference list of fuel models tied to forest structures within forest types or to forest types developed in European areas at national and regional scale.

Country	Scale	Reference	Fuel models linked to...
Greece	National	Dimitrakopoulos (2002)	Forest type
Italy	National	Ascoli et al. (2020)	Forest type
Italy	Regional (Apulia)	Elia et al. (2015)	Forest type

Table 7. Tier 2: steps to assign a fuel model to pre-treatment forest structure.

Step	Tier 2: Assign a standard, national or regional fuel model to forest structures within each forest type
1	Look for existing fuel models in your region or state. If fuel models exist (either tied to forest types or not) consider to use them. If there are none, you can use the 40 standard fuel models developed by Scott & Burgan (2005).
2	Regardless of which fuel model you choose, assign a fuel model to a pre-treatment forest structure. To do that, you can follow Krsnik et al., (2020) who developed a decision for each forest type, which can assign one of the 40 standard fuel models of Scott & Burgan (2005) to forest structure with varying levels of canopy and understory cover If the forest types in Catalonia are similar to those in your country, consider using the Krsnik et al., (2020) algorithm to assign a fuel model to pre-treatment forest structures depending on its canopy and understory cover. If forest types are not similar to those in Catalonia, you can replicate the method described in Krsnik et al., (2020) but considering your forest types (Box 2). An example of the algorithm developed by Krsnik et al., (2020) for *P. halepensis* can be found in Table 8.

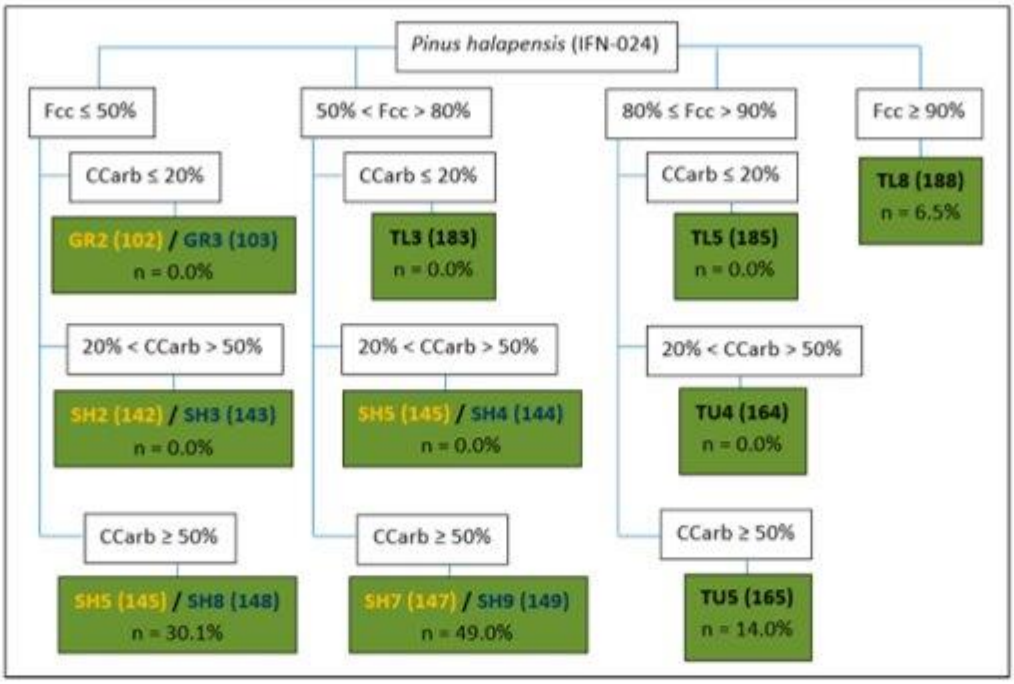
Box 2. Summary of the methodology used by Krsnik et al., (2020) to develop an algorithm to assign a fuel model to a forest structure within a forest type for the main species covering the Catalan forest.

The method presented in Krsink et al., (2020) consists of developing an algorithm based on expert knowledge highly dependent on tree species, average vegetation height, canopy cover, understory shrub cover, and climate zones. The algorithm was monitored and adapted by experts to match both the description of the fuel model of Scott & Burgan (2005) and the experience of the experts from the Forestry Action Group (GRAF, Fire Department of the Government of Catalonia) in terms of representability and observed fire behaviour. For each of the 11 forest types, a set of fuel models was assigned depending on f canopy and understory cover.

Table 8. Help table to designate a standard fuel models of Scott & Burgan (2005) according to the algorithm developed in Krsink et al., (2020) *that uses canopy cover and shrub cover for the P. halepensis forest type.*

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="10">Canopy Cover (CC, %)</th></tr>
<tr><th>0-10</th><th>10-20</th><th>20-30</th><th>30-40</th><th>40-50</th><th>50-60</th><th>60-70</th><th>70-80</th><th>80-90</th><th>90-100</th></tr>
<tr><th rowspan="10">Shrub Cover (SHC, %)</th><td>0-10</td><td colspan="5" rowspan="2">GR</td><td colspan="4" rowspan="2">GR, TL</td><td rowspan="5">TL</td></tr>
<tr><td>10-20</td></tr>
<tr><td>20-30</td><td colspan="5">GS</td><td colspan="4">GS, TU</td></tr>
<tr><td>30-40</td><td colspan="5" rowspan="3">GS, SH</td><td colspan="3" rowspan="3">GS, SH, TU</td><td rowspan="3">SH, TU</td></tr>
<tr><td>40-50</td></tr>
<tr><td>50-60</td><td rowspan="5">TL, TU</td></tr>
<tr><td>60-70</td><td colspan="5" rowspan="4">SH</td><td colspan="4" rowspan="4">SH, TU</td></tr>
<tr><td>70-80</td></tr>
<tr><td>80-90</td></tr>
<tr><td>90-100</td></tr>
</table>

GR (Grass): nearly pure grass and/or forb type; **GS (Grass-Shrub):** mixture of grass and shrub, up to about 50 percent shrub coverage; **SH (Shrub):** shrub cover at least 50 percent of the site; grass sparse to nonexistent; **TU (Timber-Understory):** grass or shrubs mixed with litter from forest canopy; **TL (Timber Litter):** dead and down woody fuel (litter) beneath a forest canopy.



Tier 3: Tier 1 or 2 but adjusting fine fuel loads

Following Tier 3 allows you to adjust the fine fuel load of the fuel models selected for each forest structure withinthe designated forest type. This step holds particular significance if you selected the standard fuel models of Scott & Burgan (2005) but it is not mandatory. Similarly, if you selected fuel models developed in your region or country, Tier 3 can still be followed. Adjusting the fine fuel loads of the standard fuel models of Scott & Burgan (2005), is advisable when applying them to represent European fuels, as standard fuel models were developed in the USA and may not be accurate enough to represent European fuels. Fine fuel, both in a living and dead state, contributes the most to fire spread since it dries more quickly and its moisture content changes dramatically depending on ambient conditions because it has a greater surface-to-volume ratio (Rothermel, 1972).Consequently, adjusting the fine fuel loading of Scott & Burgan (2005) models assigned to a pre-treatment forest structure should result in a more accurate prediction of fire behaviour. 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). De Cáceres et al., (2019), for example, developed equations to estimated biomass and fine fuel fraction of 26 Mediterranean shrub species using percent cover and average height of each species as predictors. These equations can be used for the purpose of modifying fuel loads as they estimate the live fine fuel load and set a proportion of the live fine fuel load as the dead fine fuel load. In Table 9 the sequential guidelines for implementing tier 3 arepresented. An example of how to apply Tier 3 can be found in the example provided within Section 3 and Annex 5.1.

Table 9. Tier 3: steps to assign a fuel model to a pre-treatment forest structure.

Step	Tier 3: Tier 2 but adjusting fine fuel loads
1	Search for existing allometric equations that estimate fine fuel loads for the major shrub species in your region (see De Cáceres et al., 2019). If such allometries exist, proceed to the next step. If none exist, you can not follow this tier.
2	In case of using De Cáceres et al., (2019) allometric equations, select all National Forest Inventory plots for each forest type. Then, select the shrub species that occur on more than 50% of the plots and determine their average cover and height. Using the shrub cover of the pre-treatment forest structure, determine the proportion of each shrub species according to the percent cover calculated using the National Forest Inventory. *Note:* If you select other allometric equations, verify that they estimate fine fuel loading.
3	Apply the allometric equations to estimate fine fuel loading. If using De Caceres' allometries, you can use the Medfuels R package (De Cáceres et al., 2019) to estimate live and dead woody fuel loads using cover and average height of different Mediterranean shrub species as independent variables.
4	Modify the fine fuel loads from the selected standard fuel models Scott & Burgan (2005) accordingly by creating a custome fuel model in BehavePlus (see Figure 4).

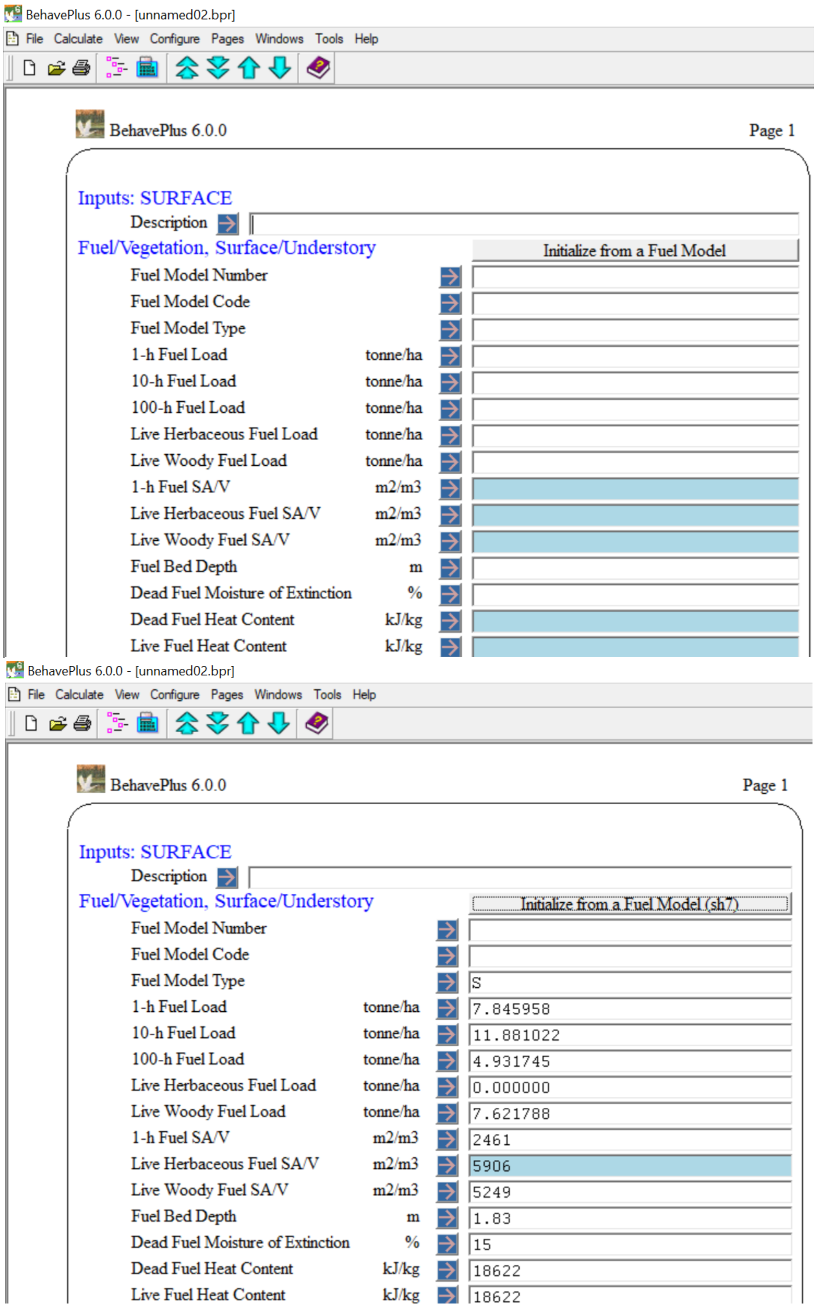


Figure 4. Screenshot of BehavePlus for creating custom fuel models. The user can create a custom fuel model with a blank template (top) or starting from a default fuel model (bottom), in this case SH7, where you can change the desired parameters. In case of adjusting fine fuel load modify 1-fuel load and live woody fuel load.

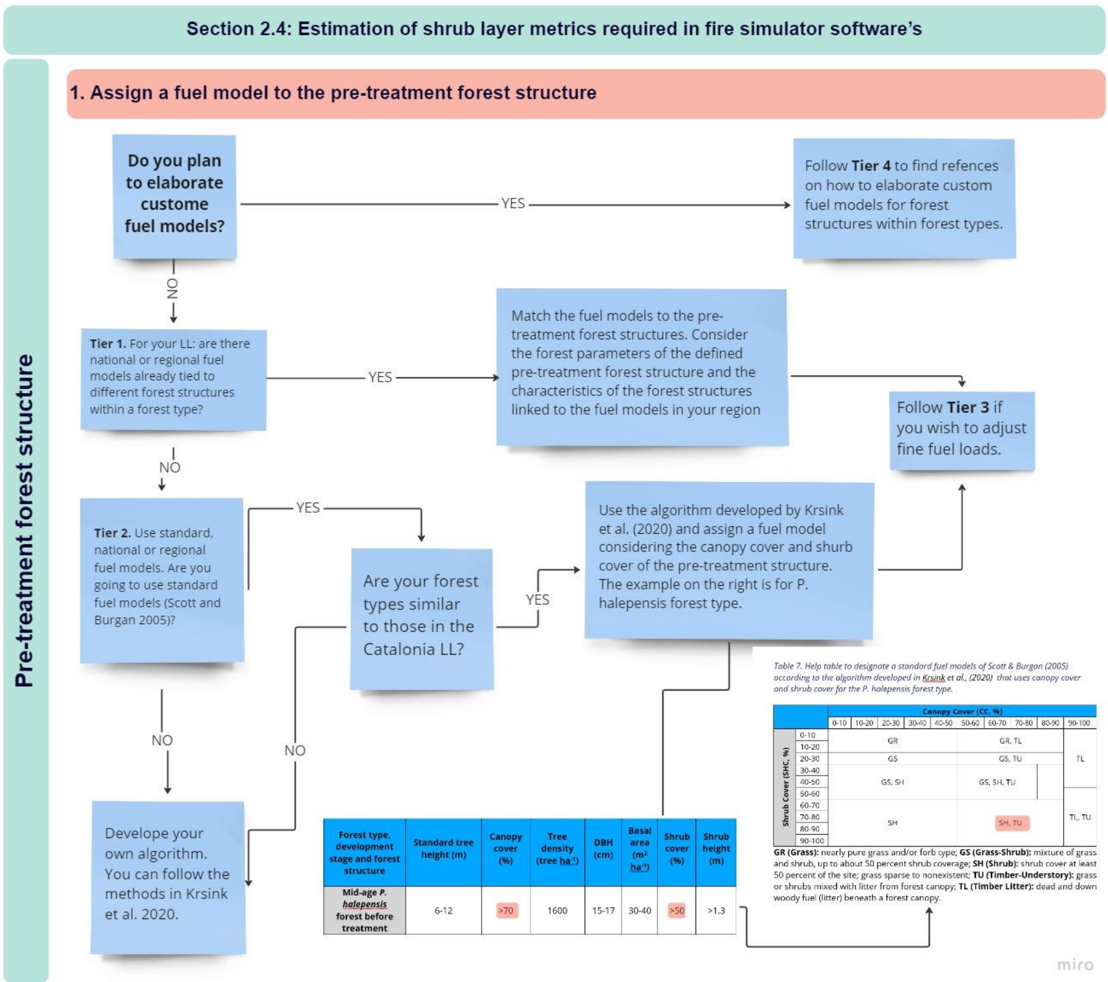
Tier 4: Elaborate custom fuel models for forest structures within forest types

If the available budget and timepermit, the best option is to create custom fuel models for the predefined forest structures within the forest types.Nonetheless, the creation of such custom fuel models require field work through destructive sampling to characterise the properties of the fuelbed (e.g loading by size class and condition). In the event that you decide to build your own fuel models, you may adopt the methodologies used in the studies listed in Table 6.

2.3.3 Summary

In Figure 5, the steps to follow to assign a fuel load to a forest structure are shown.

Figure 5. Scheme with the main steps to follow in order to assign a fuel model to a pre-treatment forest structure.



2.3.4 Post-treatment forest structure: assigning a fuel model

The assignment of a fuel model to a forest structure after treatment is dependent on the silvicultural treatment carried out (e.g. high or low thinning, harvesting system, slash treatment, prescribed burning, grazing). If you opt to utilize the decision algorithm developed by Krsnik et al. (2020) to assign a fuel model to the pre-treatment forest structure (Tier 2), note that this approach cannot be used for post-treatment structures, as it was developed for young and mature forests that have not undergone silvicultural treatment in recent years. There are several options with varying degrees of complexity for assigning a fuel model to a post-treatment structure (Table 10). The first option requires expert knowledge, while the second option involves applying a multiplication factor to the pre-treatment fuel model assign and therefore does not require expert knowledge. For each option listed, we describe how to proceed.

Table 10. Tier list showing the different options for assigning a fuel model to a post-treatment forest structure from simplest to most complex.

	Tier	Post-treatment structure: fuel models
Complexity	1	Assign a standard fuel model depending on the type of treatment using expert criteria.
	2	Apply a multiplying factor to the dead fuel load for each timelag, the degree of compactness of the fuel bed depth and the live woody load left to the fuel model assigned to the pre-treatment structure depending on the type of treatment.

Tier 1: Assign a standard fuel model to the post-treatment structure depending on the treatment type.

Make use of expert criteria to select a fuel model for the post- treatment structure, taking into account the fuel treatment applied. For example, one option is to employ the standard fuel models representing slash (SB) (Scott & Burgan, 2005). These models differ in terms of the dead fuel load for each timelag (1h, 10h, 100h), the total fuel load and the degree of compactness of the fuel bed depth. Depending on the silvicultural treatment, one of the slash models might be more suitable.

Tier 2: Apply a multiplication factor

Depending on the type treatment implemented, it is necessary to apply a multiplication factor to the dead fuel load for each timelag, the degree of compactness of the fuelbed depth and the live woody load remaining on the floor to the fuel model assigned to the pre-treatment structure (Table 11).Subsequently, a custom fuel model should be created using the obtained values after the multiplication factor has been applied (see Figure 4). Appendix 5.2 describes the methodology used to estimate the multiplication factor.

Table 11. Multiplication factor to apply to the assigned pre-treatment fuel model depending on the type of fuel treatment. These multiplying factors reflect the short-term (0-2 years) effect of fuel treatments on fuel loads.

Code	Fuel treatment	1-h fuel load[1]	10-h fuel load	100-h fuel load	Fuel bed depth[2]	Live woody[3]	Reference
	Slash out						
PB	Prescribed burning	0.25	0.25	0.75	0.5	0	Buckley & Corkish (1991)
HT_PB_Sout **LT_PB_Sout**	High or low thinning + prescribed burning + slash out						
G	Grazing	0.81	0.78	1	100 cm	SCpost/100	Tsiouvaras et al. (1989)
HT_G_Sout **LT_G_Sout**	High or low thinning + slash out + grazing						
C	Clearing+ slash out	0.2	0.2	0.2	0.6	SCpost/100	Expert opinion
CT_C_Sout	Pre-commercial + clearing+ slash out						
HT_C_Sout	High thinning + clearing+ slash out						
LT_C_Sout	Low thinning + clearing + slash out						
CT_Sout	Pre-commercial thinning + slash out	1	1	1	1	SCpost/100	Mitsopoulos & Dimitrakopoulos (2017)
HT_Sout	High thinning + slash out						
LT_Sout	Low thinning + slash out						
	Slash in						
CT_Sin	Pre-commercial thinning + slash in	1.4	5	11	50 cm	SCpost/100	Palmero-Iniesta et al. (2017) Piqué et al., (2022)
HT_Sin	High thinning + slash in[3]	1.8	3.3	11.3	0.2	SCpost/100	Piqué & Domènech (2018)
LT_Sin	Low thinning + slash in[3]	1.6	4.5	5	0.2	SCpost/100	
HT_PB_Sin	High thinning + prescribed burning + slash in[3]	0.6	0.4	8.8	0.3	0	Piqué & Domènech (2018)
LT_PB_Sin	Low thinning + prescribed burning + slash in[3]	0.5	0.7	4.6	0.1	0	
HT_G_Sin	High thinning + grazing + slash in[3]	1.3	2	11.3	100 cm	SCpost/100	

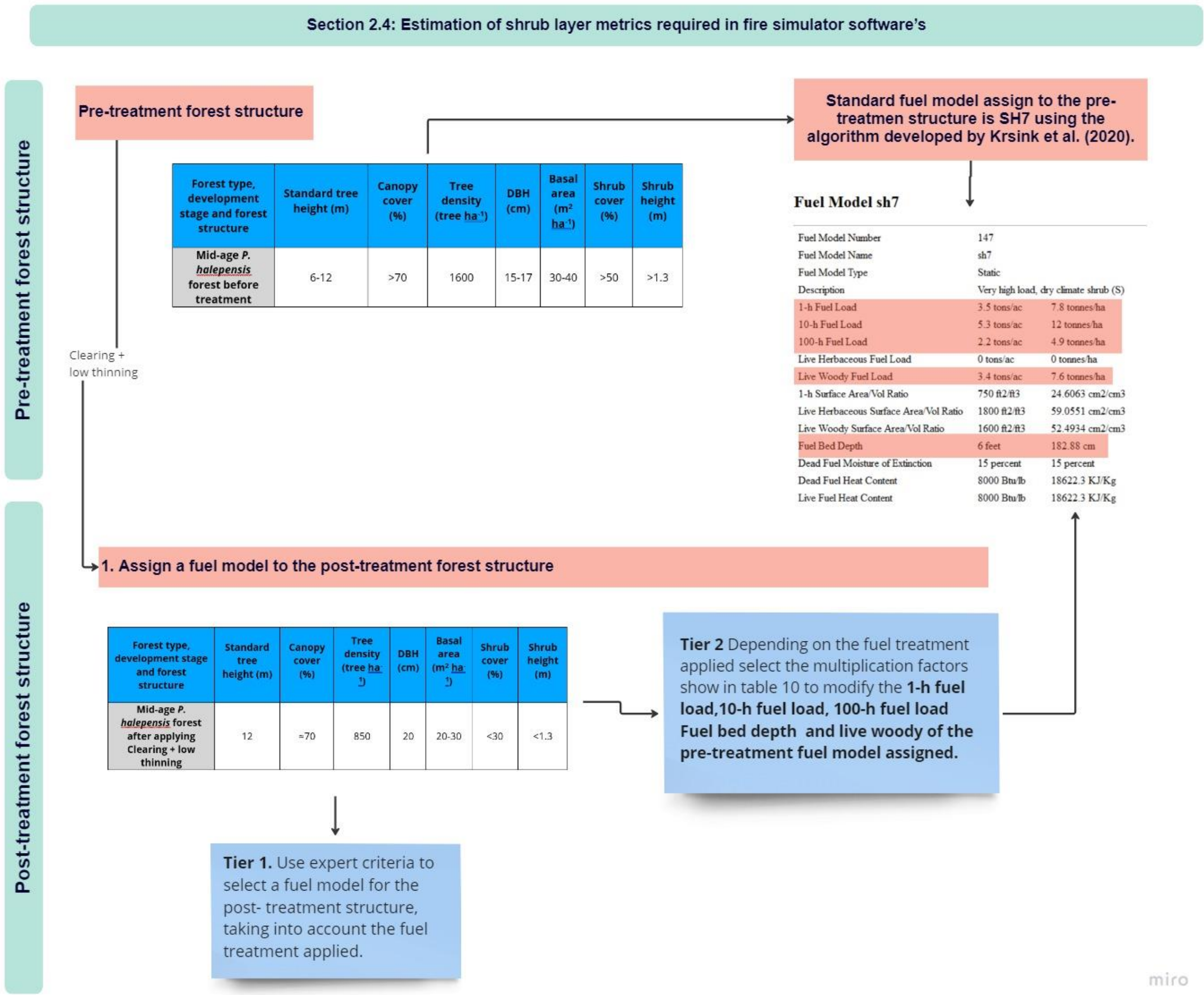
HT_G_Sin	Low thinning + grazing + slash in[3]	1.2	2.6	5	100 cm	SCpost/100	Mean of grazing and high or low thinning multiplying factors.
HT_C_Sin	High thinning + clearing + slash in[3]	1.8 + add live woody load removed	3.3	11.3	0.4	SCpost/100	Mean of clearing and high or low thinning multiplying factors.
LT_C_Sin	Low thinning + clearing+ slash in[3]	1.6 + add live woody load removed	4.5	5	0.4	SCpost/100	

[1] For the clearing treatment, no multiplying factor is provided, the pre-treatment live woody fuel load removed should be added.
[2] For the grazing treatment, instead of a multiplying factor, fuel bed depth is fixed to 100 cm.
[3]The multiplying factor will depend on the post-treatment shrub cover (SC) established.

2.3.5 Summary

In Figure 6, the steps to follow to assign a fuel load to a post-treatment forest structure.

Figure 6. Scheme with the main steps to follow in order to assign a fuel model to a post-treatment forest structure.



2.4 Estimation of canopy layer metrics required in fire simulator software's

The canopy layer input variables in fire simulation software include canopy base height, canopy fuel load and canopy bulk density.

2.4.1 Canopy base height

Pre-treatment

Canopy base height (CBH) serves as a measurable parameter that indicates the vertical fuel continuity and refers to the lowest height above the ground at which there is sufficient fuel in the canopy to spread a fire vertically (Scott & Reinhardt, 2001). CBH can be estimated using instrument-based optical techniques, inventory-based techniques, or the utilization of allometric equations that establish a relationship between canopy base height and easily measured variables. Several options with varying degrees of complexity are available for estimating canopy base height based on the forest parameters that characterize the pre-treatment forest structures (Table 12).

Table 12. Tier list showing the different options for estimating canopy base height.

	Tier	List of options to estimate canopy base height
Complexity	1	Use existing allometric equations to predict canopy base height. The predictors of the equations need to be any of those used to define the pre-treatment forest structure.
	2	Calculate canopy base height: dominant height minus canopy depth-

Tier 1: Use existing allometric equations

CBH can be determined using allometric equations if 1) equations exist for key species or functional groups in the study area or in areas with similar characteristics and 2) the variables used as predictors in the equations are within those forest parameters used to defined the pre- and post-treatment forest structure. Table 13 presents a detailed outline of the steps to follow for tier 1 estimation.

Table 13. Tier 1: steps to use existing allometric equations to estimate canopy base height.

Step	Tier 1: Use existing allometric equations to estimate canopy base height
1	Search for existing allometric equations that estimate canopy base height using the stand or tree variables that have been used to define the pre-forest structure for the key species of the given forest type. It is advisable that this allometric equation have been developed in your region or in areas with similar vegetation characteristics. If such allometrics exist, proceed to the next step. If none exist, follow tier 2.
2	Make sure that the tree or stand variables used to create the allometric equations cover the range of values of the tree or stand variables of the

	define the pre- treatment forest structures. For example, you cannot use allometric equations based on standard tree heights of 10-14 m if the average standard tree height defined for your pre- treatment forest structure is between 6-8 m.
3	Apply the allometric equations to estimate canopy base height for the pre-treatment forest structure

Tier 2: Calculate canopy base height using canopy depth and dominant tree height

The CBH for any species can be determined by the following formula:

$$CBH = STH - CD$$

Where, *STH* is standard tree height and *CD* is the mean canopy depth. Pre-treatment forest types use standard tree height as a stand descriptor. Therefore, to estimate CBH, canopy depth (CD) data is needed. Using data from the 4th National Forest Inventory (DGDRPF, 2017), in which CD was recorded for all species in Catalonia, Krsnik et al., (2020) developed the following two models:

- $if\ STH > 5\,m\ //\ CD = \beta 0 + (\beta 1 * STH)$
- $if\ STH \leq 5\,m\ //\ CD = \beta 1 * STH$

The values for β0 and β1 were constant and varied depending on the dominant tree species. These equations can be found in Appendix A, of Krsnik et al., (2020). Once CD is known, CBH is calculated by sustraction from CD to the STH of the pre-treatment forest structure. This method can be replicate for different forest types if CD is available.

Post-treatment

The post-treatment CBH changes if a pruning treatment is applied. Therefore, CBH will be modify when:

- Pruning height is > post-treatment canopy base height value, then use the value of the pruning height.
- Pruning height is < post-treatment canopy base height value, then use the pre-treatment value, as this means that the pruning was applied to dead branches.

Also, CBH can change if a low thinning is applied.

2.4.2 Canopy fuel load

Canopy fuel load (CFL) denotes the quantity of fuels present within the that would be consumed during the propagation of an actively burning crown fire. Typically, it is assumed that all the foliage and some portion of live and dead branch wood with a diameter less than 6 mm will be consumed within the flaming front (Scott & Reinhardt, 2001).

Pre-treatment

There are several options with varying degrees of complexity for estimating CFL (Table 14).

Table 14. Tier list showing the different options for estimating canopy fuel load.

	Tier	List of options to estimate canopy fuel load
Complexity	1	Use existing allometric equations to predict canopy fuel load using easily measured stand or tree level variables that have been used as forest parameters to characterize the pre-treatment forest structures.
	2	Develop allometric equations for predicting canopy fuel load using easily measured stand or tree level variables.

Tier 1: Use existing allometric equations

Allometric equations derived from destructive sampling, which establish relationships between species-specific tree or stand variables and CFL, are increasingly available for a wide number of species. For instance, crown fuel load can be estimated for *P. pinea* utilizing DBH and crown projection area as predictors (Molina et al., 2011). Similarly, for *P. pinaster* and *P. radiate,* DBH can be used as a predictor(Gómez-Vázquez et al., 2013), while for the main softwood and hardwood species in Spain (Ruiz-Peinado et al., 2012; Ruiz-Peinado et al., 2011) DBH and standard tree height are employed. In the case of *P. brutia* and *P. halepensis*, canopy features can be estimated by stand variables such as basal area, dominant height or SDI (Mitsopoulos & Xanthopoulos, 2016).The steps to be followed for tier 1 are provided in Table 15.

Table 15. Tier 1: steps to use existing allometric equations to estimate canopy fuel load.

Step	Tier 1: Use existing allometric equations to estimate canopy fuel load
1	Search for existing allometric equations that estimate canopy or crown fuel load using stand or tree data for key species or functional groups in your region or in areas with similar vegetation characteristics. These allometric equation need to use as predictors variables those forest parameters that have been used to characterize the pre-treatment forest structures. If such allometrics exist, proceed to the next step. If none exist, follow tier 2.
2	Make sure the allometric equation estimates canopy or crown fuel load less than 6 mm in size. For example, the equation for softwood in Ruiz-Peinado et al., (2011) and for hardwood in Ruiz-Peinado et al., (2012) considers not only foliage (ø < 6 mm) but also thin branches (ø < 2 cm), which may result in an overestimation of fire behavior because branches between 0.6 and 2 cm are included. In such cases, the application of a correction factor would be recommended (e.g., expert comment suggest for this case 1/3 of the fuel load obtained).

3	Make sure that the tree or stand variables used to create the allometric equations cover the range of values of the tree or stand variables descriptors that described the pre-treatment forest structures. For example, you cannot use allometric equations created with trees whose DBH is between 20-25 cm if the DBH of the forest structure before treatment is 10 cm.
4	Apply the allometric equations to estimate canopy or crown fuel load of the pre-treatment forest structure.
5	If the equations estimate crown fuel load (individual tree level), pre-treatment tree density is required to convert crown fuel load (kg tree^{-1}) to stand canopy fuel load (t ha^{-1}).

Tier 2: Developing allometric equations

The development of allometric equations for estimating CFL depends on time and economic constraints due to the requirement of employing destructive sampling techniques on the tree's canopy to formulate such allometries. While no tiers are delineated here, you may refer to any of the aforementioned references to learn how to create allometries for CFL.

Post-treatment

Post-treatment CFL will not change after treatment unless pruning and/or thinning is done:

- If the pruning height is > pre-treatment CBH, the pre-treatment CFL must be lower because pruning reduces foliage and thin branch loads. In such case, assume that the percent reduction in CFL is equal to the reduction in canopy depth due to pruning, even if the CFL is not evenly distributed throughout the canopy depth.
- If thinning has been applied, calculate post-treatment CFL by multiplying post-treatment tree density in case of tree-level allometries.

2.4.3 Canopy bulk density

Canopy bulk density (CBD) is the CFL available in each unit of canopy volume (Scott & Reinhardt, 2001).

Pre-treatment

CBD represents available canopy fuel load per unit of surface area. To estimate CBD, CFL must be divided by CD to convert to volume (Kg m^{-3}) (Cruz & Alexander, 2014).

Post-treatment

The post-treatment CBD depends on the post-treatment CFL and, therefore, also on the CBH after treatment.

2.5 Setting up scenarios

Once fuel related metrics have been introduced in BehavePlus, parameters related with terrain and weather and fuel moisture need to be entered (Figure 7).

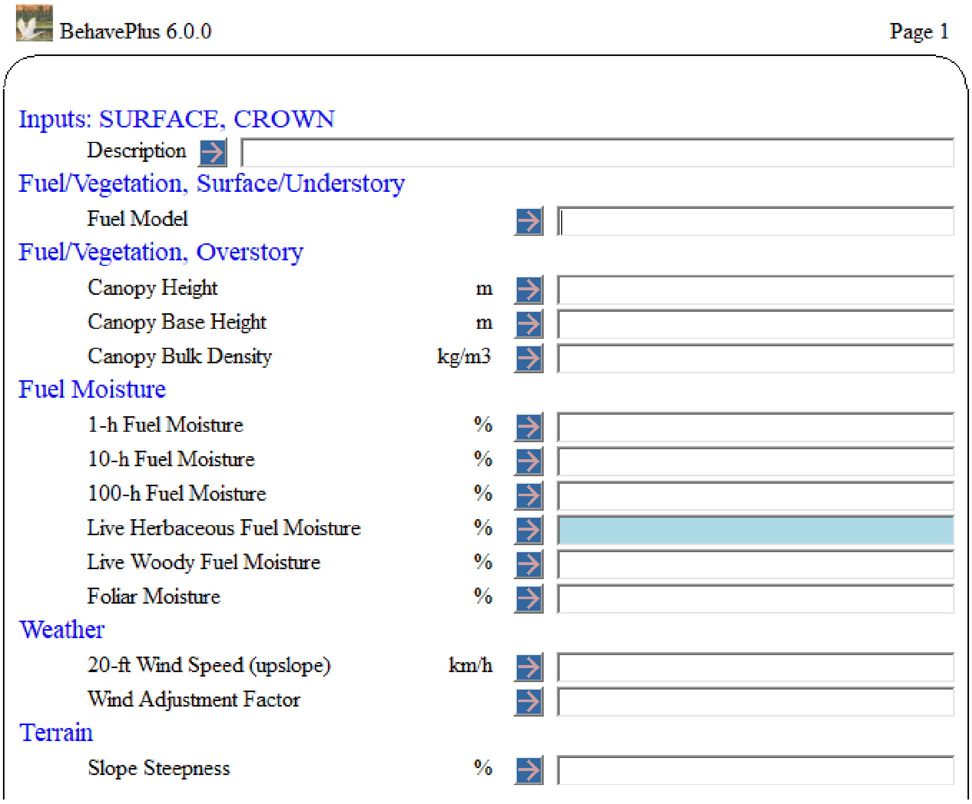


Figure 7. Screenshot of BehavePlus 6.0 showing the inputs to run a simulation.

Usually more than one wildfire scenarios are simulated. In this particular instance, our proposition entails the simulation of wildfire behaviour under two distinc scenarios: extreme and mild. Several options, each with varying degrees of complexity, are available for configuring wildfire scenarios (Table 16). For each option listed, we describe how to proceed.

Table 16. Tier list showing the different options for setting a wildfire scenario.

	Tier	Wildfire scenarios
Complexity	1	Use the 30-30-30-30 rule of thumb.
	2	Use historical climatic data of your region.

Tier 1: Use the 30-30-30-30 rule of thumb

Usually, the extreme wildfire scenario represents a summer day with wind speeds above 30 km h^{-1} (see Box 3), relative humidity below 30%, and air temperature above

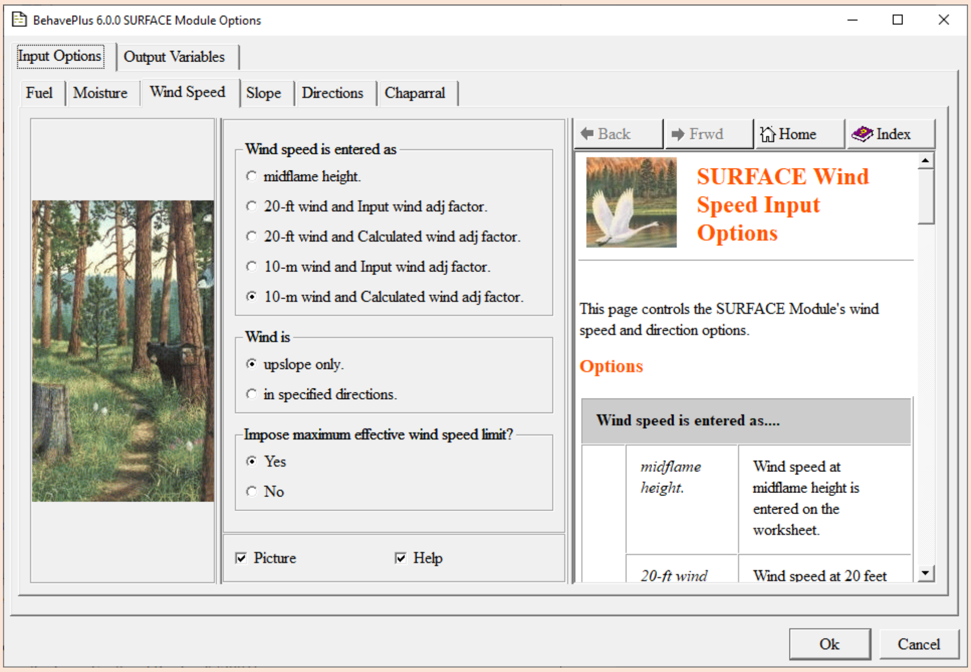
30º C. As a mild scenario, it is suggested to set wind speed at 15 km h^{-1}, relative humidity at 15% and air temperature at 15º C.

Box 3. Entering wind speed in stand static fire simulator software's.

Wind speed

Normally, wind is measured at 20-feet above vegetation in the U.S. and at 10 m in Europe. However, the wind that affects the surface fire, called midflame wind, can be as low as 10% of the wind speed predicted by weather services. In addition, forest cover also changes wind speed. In Behave Plus, the wind speed at a height of 10-m or 20-feet can be entered along with the value of the forest cover. This information is then used to calculate a wind adjustment factor, which converts wind speed into midflame wind speed, considering the forest cover (Figure 8).

Figure 8. Wind speed configuration to calculate midflame wind speed.



The slope of the stand influences fire behaviour but also whether the proposed treatments can be fully mechanized. We defined a slope of 30% as the limit for the mechanized treatments to be applied and, therefore, for both, the extreme and the mild scenario, a slope of 30 % should be considered.

Tier 2: Use historical climatic data

For each forest type, select a reference fire that occurred in the past in the study region and identify the nearest meteorological station. use the historical climate dataset (at least 20 years) to calculate the 50th and 90th percentiles of relative humidity, temperature and wind speed during the summer period (June-August) to create the mild and extreme forest fire scenarios. As in tier 1, a slope of 30% should be considered for both the extreme and mild scenarios.

Fuel moisture

Fuel moisture values depend on terrain and weather conditions. Regardless of the tier selected, the moisture content of the various fuels can be calculated based on the terrain and weather values set for each scenario. Fuel moisture must be entered for 1-h, 10-h, and 100-h dead fuels, live shrub woody and herbs fuels and crown foliage fuels.

- **Dead fuel** moisture can be estimated using Rothermel's (1983) tables, which require solar radiation, air temperature, and relative humidity. Behave Plus provides a calculator based on Rothermel's (1983) tables to calculate 1-h dead fuel moisture (Tools > Fine Dead Fuel Moisture Tool). Adding 1% to the calculated 1-h fuel moisture gives the moisture content of 10-h dead fuel, while adding 2% to the calculated fine dead fuel load gives the 100-h fuel moisture.
- **Live fuel** moisture can be adjusted using the live fuel moisture scenarios defined in Scott and Burgan (2005). For the extreme scenario, we recommend using the very low scenario and for the mild scenario, we recommend using the moderate scenario (Table 17). However, it is best to use data from the specific region. For example, in Catalonia, the forest fire reports provide the live fuel moisture as a function of different scenarios.

Table 17. Live fuel moisture content values (%) for the very low and moderate scenarios defined by Scott and Burgan (2005).

	L1 fully cured Very low	L3 one-third cured Moderate
Live herbaceous	30	90
Live woody	60	120

3 Forest management guidelines of Catalonia: example for *P. halepensis* forest types

The Forest Management Guidelines (FMG), named ORGEST, cover almost all conifer- and broadleaf-dominated forests in Catalonia (including pure and mixed forests), These forests collectively account for over 90 % of Catalonia's forested area (Piqué et al., 2017) (see http://ags.ctfc.cat/?p=649 for all those). For each species-dominated forest considered, ORGEST offers site quality charts and different guidelines for various management scenarios. These guidelines were built considering 2-3 site quality classes (depending on tree species), the presence of high or low risk of large wildfires in the area, even- or multi-aged forest structure, and different objectives such as timber production, non-wood forest products, wildfire prevention, or enhancing forest vitality and resilience.

For each forest type, the final outcome will comprise a detailed description of the pre- and post-treatment structure defined in the FMG, the potential fire behavior simulated in both cases and the direct costs associated with the treatments. In this context, we present an example showcasing 3 theoretical stages (i.e., 3 pre-treatment forest structures) for *P. halepensis* forest types. The ultimate aim of this final product is to be a useful tool for managers to better evaluate the impact of the different treatment proposals in terms of fire behavior and direct costs.

3.1 Forest type, objective and pre and post treatment forest structures

Management scenario: density and fuel reduction

For the *P. halepensis* forest type, we have established specific forest treatments and pre- and post- treatment forest structures, based on three distinct silvicultural models for the specie (named in the ORGEST FMG as Ph01, Ph04, Ph05, Beltrán et al., 2011). These models were developed considering expert knowledge and forest characteristics at three stages of development where is most common to implement silvicultural treatments. Table 18 shows the dasometric characteristics of each theoretical stage before and after treatments. The treatment assigned was thinning, clearing and slash out, as some reports have highlighted that neglecting slash reduction can render the treatment useless or even increase fire behavior (GRAF, 2005; Prichard et al., 2020).

Table 18. Dasometric characteristics of the pre- and post-treatment theoretical stages of P. halepensis. H: tree height; CC: canopy cover; N: stand density; DBH: diameter at breast height; BA: basal area; Si: shrub cover; SH: shrub mean height

Development stages	Treatment	H (m)	CC (%)	N (tree ha^{-1})	DBH (cm)	BA (m^2 ha^{-1})	SC (%)	SH (m)
Regenerated-Young forest								
Pre-treatment		4-6	≈100	6000	6			
Post-treatment	Pre-commercial thinning	6	≈70	1800	8-10	20	<30	<1.3
Mid-age forest								
Pre-treatment		6-12	>70	1600	15-17	30-40	>50	>1.3
Post-treatment	Clearing + low thinning	12	≈70	850	20	20-30[1]	<30	<1.3
Adult forest								
Pre-treatment		>12	>70	750	28-30	>30	>50	>1.3
Post-treatment	Clearing + mixed thinning	>14	≈70	500	32	>20[1]	<30	<1.3

[1]The pre-treatment basal area has been reduced in 30%.

3.2 Selected options to convert dasometric values to fire simulator inputs

The methodology explained in Section 2 was applied to convert the dasometric variables showed in Table 18 into fire simulator variables. A summary overview of the selected tiers is provided in Table 19. It is important to note that for pre- and post- treatment fuel model assignment multiple options have been selected to provide to the user of this guideline with more than one example.

Table 19. Options selected to transform dasometric variables to inputs for fire simulation systems.

Inputs		Treatment	Selected options
	Fuel model	Pre	Tier 2: Assign a standard, national or regional fuel model to pre-treatment forest structure A standard fuel model (Scott & Burgan, 2005) has been assigned to each theoretical stage using Krsnik et al., (2020) algorithm for *P. halepensis* that depends on shrub cover and canopy cover. In the case of regenerated crops, the algorithm would have assigned a model of the timber litter group. However, even if no understory can develop due to the high tree density, *P. halepensis* does not have self-pruning, so the low branches, which are usually dead, can act as a fuel model with very high fuel loads. Based on expert criteria, the model 7 of the shrub group with very high fuel load is most appropriate. Tier 3: Tier 2 but adjusting fine fuel loads We have also considered for this example Tier 3 to test for differences in fire potential between Tier 2 and 3. De Cáceres et al., (2019) allometries were used to estimate live and dead woody fuels at the stand level (t ha^{-1}), using cover and average height of the different Mediterranean shrub species as independent variables. Then, the fuel loads of the pre-treatment fuel model have been adjusted considering the estimated fine fuel loads using the allometries. See Annex 5.1 for the methodology used to adjust fuel loads.
		Post	Tier 1: Assign a standard fuel model to the post-treatment structure depending on the treatment type Using expert criteria, as the decision algorithm cannot be used, the standard fuel model of the understory group (TU) with a low fuel load was selected, as clearing respected part of shrub cover (shrub cover < 30% + shrub height < 1.3m). For regenerated stands that do not have shrub or herbaceous fuel due to high pre-treatment tree density, the standard fuel model of the litter group (TL) was selected to represent the fallen needles and smallest remnants of the treatment. Tier 2: Apply a multiplication factor to the pre-treatment structure The multiplying factor provided in Table 11 has been applied to the assigned pre-treatment standard fuel load depending on treatment type.
Canopy layer	Canopy base height	Pre	Tier 2: Tier 2: Calculate canopy base height using canopy depth and dominant tree height The Krsnik et al., (2020) models that estimate canopy depth has been used. Then, canopy base height has been calculated as the difference between the standard tree height defined in the pre-treatment forest structure and canopy depth.
		Post	Post-treatment canopy base height is the same as pre-treatment, as pruning has not been considered as a treatment.
	Canopy fuel load	Pre	Tier 1: Use existing allometric equations to estimate canopy fuel load The equation for *P. halepensis* in Ruiz-Peinado et al., (2012) has been selected but as it considers also thin branches (ø < 2 cm) a correction factor of 0.3 to the estimated canopy fine fuel load has been applied. Pre-treatment tree density has been used to estimate canopy fuel load at the stand level.
		Post	Canopy fuel load has been re-calculated depending on post-treatment tree density when thinning has been considered as a treatment.
	Canopy bulk	Pre	Pre-treatment canopy fuel load has been divided by the canopy depth obtained using Krsnik et al., (2020) equation.
		Post	Post-treatment canopy fuel load has been divided by the canopy depth obtained using Krsnik et al., (2020) equation.

3.3 Fire simulation inputs for pre- and post-treatment *P. halepensis* forest structures

The key inputs required to execute fire simulations for the defined forest structures before and after treatment are listed at Table 20. For the pre-treatment forest structures, two fuel model assignment were considered: using Krsnik et al., (2020) algorithm and adjusting fine fuel loads.

Table 20. Inputs needed for simulating fire behaviour before and after treatment in 3 theoretical stages of P. halepensis. For fuel model, we show two different options for the assignment of a fuel model to the pre-treatment forest structure (see table footnotes 1 and 2) and three options for the assignment of a fuel model to a post-treatment forest structures (see table footnotes 3, 4 and 5). SH, shrub; TL, timber litter, TU, understory; CT_C_Sout, pre-commercial thinning +clearing+ slash out; LT_C_Sout, low thinning+ clearing+ slash out; MT_C_Sout, mixed thinning + clearing+ slash out

		Shrub layer				Canopy layer		
	Treat.	SC (%)	Fuel model (Tier 2)	Fuel model (Tier 3)	Fuel model (Tier 2)	CBH (m) (Tier 1)	CFL (kg m^2)	CBD (kg m^3)
Regenerated crop								
Pre-treatment			SH7[1]	SH7adj[2]		2.3	1.03-1.06	0.60-0.28
Post-treatment	Pre-commercial thinning + clearing + slash out	<30	TL3[3]		SH7x CT_C_Sout[4] SH7adjx CT_C_Sout[5]	2.3	0.35-0.41	0.09 - 0.11
Young forest								
Pre-treatment		>50	SH7[1]	SH7adj[2]		2.3-5.8	0.60-0.18	0.16-0.18
Post-treatment	Low thinning + clearing + slash out	<30	TU1[3]		SH7x LT_C_Sout[4] SH7adjx LT_C_Sout[5]	5.8	0.87	0.14
Adult forest								
Pre-treatment		>50	SH7[1]	SH7adj[2]		>5.8	1.60-1.84	0.25-0.29
Post-treatment	Mixed thinning + clearing + slash out	<30	TU1[3]		SH7x MT_C_Sout[4] SH7adjx MT_C_Sout[5]	>7	1.63	0.23

Two pre-treatment options:

[1]A standard fuel model (Scott & Burgan, 2005) has been assigned to each theoretical stage using Krsnik et al., (2020) algorithm for *P. halepensis*.

[2] Fuel model assigned using the algorithm for *P. halepensis* but adjusting live and dead woody fuel using (De Cáceres et al., 2019) (see Table 21).

Three post-treatment options

[3] A standard fuel model for the post-treatment structure has been assigned using expert knowledge.
[4] A fuel model for the post-treatment structure has been assigned. It is based on the pre-treatment fuel model assigned using the algorithm for *P. halepensis*, but with the treatment type multiplication factor applied to fuel loads, fuelbed depth and live woody. SH7_147xCLT: SH7_147 refers to the pre-treatment fuel model; x, multiply; CLT, clearing + low thinning.
[5] A fuel model for the post-treatment structure has been assigned. c, but with the treatment type multiplication factor applied to fuel loads, fuelbed depth and live woody.

Table 21presents the fuel loads for both alternatives. It is noteworthy that fine fuel load remains relatively consistent regardless of the chosen option. The adjusted fuel loads were calculated considering a shrub cover value of 90% . However, it is important to mention that if a lower shrub cover had been considered, the disparities in fine fuel loads between both options would have been greater.

Table 21. Comparison of the pre-treatment fuel loads of the SH7 fuel model (Scott & Burgan, 2005) and the SH7adj fuel model with adjusted 1-fuel load, live woody fuel load and fuel bed depth using De Cáceres et al., (2019) allometries. See Annex 5.1 for the methodology used to calculate adjusted fine fuel loads.

	SH7	SH7adj
1-h fuel load (tonne ha^{-1})	7.8	7.7
10-h fuel load (tonne ha^{-1})	12	12
100-h fuel load (tonne ha^{-1})	4.9	4.9
Fuel bed depth (cm)	182.9	104.7
Live herb fuel load (tonne ha^{-1})	0	0
Live woody fuel load (tonne ha^{-1})	7.6	5.1

For the post-treatment structures, three ways of fuel model assignment were considered: expert opinion, application of the multiplication factor to the assigned pre-treatment fuel model, and fuel model with adjusted fine fuel loads (see Table 22 for fuel loads comparison). Note that the multiplication factors are the same for all three treatments considered, so the differences between the fuel loads are due to the assigned pre-treatment fuel loads.

Table 22. Fuelbed characteristics for the three different options tested for the post-treatment fuel models assigned.

Forest structure and fuelbed characteristics	Post-treatment fuel models			Treatment type
Regenerated crop	TL3	SH7xPC_C_Sout	SH7xPC_C_Sout	Pre-commercial thinning + clearing + slash out
1-h fuel load (tonne ha^{-1})	1.1	1.56	1.54	
10-h fuel load (tonne ha^{-1})	4.9	2.4	2.4	
100-h fuel load (tonne ha^{-1})	6.3	0.98	0.98	
Fuel bed depth (cm)	9.144	109.74	62.82	
Live woody fuel load (tonne ha^{-1})	0	1.52	1.02	
Young forest	TU1	SH7x LT_C_Sout	SH7adjx LT_C_Sout	Low thinning + clearing + slash out
1-h fuel load (tonne ha^{-1})	0.45	1.56	1.54	
10-h fuel load (tonne ha^{-1})	2	2.4	2.4	
100-h fuel load (tonne ha^{-1})	3.4	0.98	0.98	
Fuel bed depth (cm)	18.23	109.74	62.82	
Live woody fuel load (tonne ha^{-1})	2	1.52	1.02	
Adult forest	TU1	SH7x MT_C_Sout	SH7adjx MT_C_Sout	Mixed thinning + clearing + slash out
1-h fuel load (tonne ha^{-1})	0.45	1.56	1.54	
10-h fuel load (tonne ha^{-1})	2	2.4	2.4	
100-h fuel load (tonne ha^{-1})	3.4	0.98	0.98	
Fuel bed depth (cm)	18.23	109.74	62.82	
Live woody fuel load (tonne ha^{-1})	2	1.52	1.02	

3.4 Setting up scenarios

Using data recorded at the meteorological reference station for the study region during the summer period (June-August) from 1999 to 2015, the 50th and 90th percentiles of the following variables were determined: temperature, relative humidity, and wind speed (Table 23). Additionally, the moisture content of dead fuel was determined using the tables in Rothermel (1983). Moisture content of live and crown foliage fuel was obtained from data supplied by the Department of Climate Action, Food and Rural Agenda of the Generalitat of Catalonia. It is important to note that the slope of the stand was set at 30%.

Table 23. Values of terrain, weather, and fuel moisture conditions in the two scenarios studied.

	Variables	Extreme scenario	Mild scenario
Weather	Wind adjustment factor	0.1	0.1
	10 m wind speed (km h^{-1})	40	20
	Air temperature (ºC)	35	25
Fuel moisture	1-h fuel moisture (%)	5	8
	10-h fuel moisture (%)	6	9
	100-h fuel moisture (%)	7	10
	Live herbaceous fuel moisture (%)	30	60
	Live woody fuel moisture (%)	70	95
	Foliar moisture	100	120
Terrain	Slope (%)	30	30

3.5 Fire simulation outputs in pre- and post-treatment forest structures

Extreme scenario

Prior to the treatment, crown fires were the predominant type of fire expected across all theoretical stages, with the exception of adult forest with the adjusted fine fuel load, where conditional fire would occur (Table 24). In regenerated crops, the occurrence of surface fires become more probable following pre-commercial thinning + clearing + slash out (e.g., flame length, fire intensity, and rate of spread are significantly reduced compared to pre-treatment conditions), regardless of the fuel model used. In young and mature forests, after low or mixed thinning + clearing + slash out resulted in conditional crowing regardless of the fuel model chosen. However, the flame length, fire intensity, and spread rate exhibit distinct values in each scenario (Table 24).

Table 24. Output of the fire simulation exercise for the different pre- and post-treatment forest structures under the extreme wildfire scenario. Cond. Crowing, conditional crowing:

	Fuel model	Flame length (m)	Fire intensity (Kw m^{-1})	Rate of spread	Crown Fire Type	Scorch Height (m)	Crowing index (m min^{-1})
Regenerated crop							m/min
Pre	SH7_147	20.2	20970	26.0	Crowing	50.1	202.4
	SH7_147adj	20.4	21268	26.0	Crowing	34.7	202.4
Post	TL3_183	0.3	18	0.5	Surface	0.5	643.9
	SH7_147xCLT	1.2	371	6.5	Surface	8.6	643.9
	SH7_147adjxCLT	0.9	227	3.7	Surface	5.8	643.9
Young forest							
Pre	SH7_147	19.2	19398	26.0	Crowing	46.6	435.6
	SH7_147adj	19.4	19696	26.0	Crowing	32.5	435.6
Post	TU1_161	0.5	69	0.9	Conditional Crowing	2.1	503.2
	SH7_147xCLT	1.2	357	6.3	Conditional Crowing	8.4	503.2
	SH7_147adjxCLT	0.9	219	3.6	Conditional Crowing	5.7	503.2
Adult forest							
Pre	SH7_147	23.6	26412	26.0	Crowing	47.3	306.1
	SH7_147adj	2.8	2385	5.4	Conditional Crowing	32.9	306.1
Post	TU1_161	0.5	67	0.8	Conditional Crowing	2.1	346.5
	SH7_147xCLT	1.1	343	6.0	Conditional Crowing	8.3	346.5
	SH7_147adjxCLT	0.9	211	3.5	Conditional Crowing	5.7	346.5

Mild scenario

Under a mild scenario, crowing occurred in regenerated crops before treatment. In all other situations before and after the treatments surface fire was more likely to occur (Table 25).

Table 25. Output of the fire simulation exercise for the different pre- and post-treatment forest structures under the mild wildfire scenario.

	Fuel model	Flame length (m)	Fire intensity (Kw m^{-1})	Rate of spread	Crown Fire Type	Scorch Height (m)	Crowing index (m min^{-1})
Regenerated crop							m/min
Pre	SH7_147	8.6	5762	7.5	Crowing	18.9	263.1
	SH7_147adj	8.6	5800	7.5	Crowing	13.2	263.1
Post	TL3_183	0.2	8	0.2	Surface	0.3	811.1
	SH7_147xCLT	0.7	133	2.6	Surface	3.3	811.1
	SH7_147adjxCLT	0.6	82	1.5	Surface	2.4	811.1
Young forest							
Pre	SH7_147	2.3	1571	4	Surface	18	551.8
	SH7_147adj	1.8	925	2.4	Surface	12.6	551.8
Post	TU1_161	0.3	19	0.3	Surface	0.8	635.9
	SH7_147xCLT	0.7	129	2.5	Surface	3.3	635.9
	SH7_147adjxCLT	0.6	80	1.5	Surface	2.3	635.9
Adult forest							
Pre	SH7_147	2.3	1597	4.1	Surface	18.1	391.1
	SH7_147adj	1.8	940	2.4	Surface	12.7	391.1
Post	TU1_161	0.3	19	0.3	Surface	0.8	441.2
	SH7_147xCLT	0.7	125	2.4	Surface	3.2	441.2
	SH7_147adjxCLT	0.6	78	1.4	Surface	2.3	441.2

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5 Annexes

5.1 Adjusting the fine fuel loads of fuel models

The SH7 standard fuel model was assigned to the pre-treatment forest structures of regenerated crops, young and adult *P. halepensis* forests by using Krsnik et al., (2020). In this context, we present a methodology for adjusting the fine fuel loads of the SH7 model using the allometric equations developed by De Cáceres et al., (2019). It should be noted that this methodology can be applied to any other fuel model.

Species shrub cover and height are utilized as predictors in the allometric equations, but the shrub cover and height defined in the pre-treatment forest structures are not specific to particular species. By employing exclusively pure *P. halepensis* plots from the national forest inventory for the Catalonia region, we selected shrub species that occurred in at least 50% of the plots and determined the average cover and height of the selected shrub species. Subsequently, we calculated the corresponding cover of each shrub species as a function of the cover established in the pretreatment structure and taking into account the proportion of each shrub species calculated from the national inventory data. The overall shrub cover in young and adult pretreatment structures is described as > 50% and an average shrub height > 1.30 m. For shrub cover, we set a value of 90%. For shrub height, we used the maximum height of the shrub species sampled by De Cáceres et al., (2019) to create the allometries, since the National Forest Inventory gives the average height of shrubs and it is not higher than 1.30 m. In the case of regenerated crops, where the assumption is that understory is inhibited due to the high tree density, we pressumed the same cover and height as young and mature forests, owing to the presence of dead branches. Once shrub species and height were established (see Pre-treatment structures in Table 26), we used the Medfuel package by De Cáceres et al., (2019) to estimate fine fuel loads.

Table 26. Shrub species found in more than 50% of pure P. halepensis plots of the national forest inventory (NFI). Mean species shrub cover and height using selected plots of the NFI. Species shrub cover extrapolated for a total shrub cover of 90%, which is established in the pre-treatment structures. Maximum height of the species surveyed in the De Cáceres et al., (2019) *as the mean height of shrubs in the pre-treatment structures is greater than 1.30 the mean height of the forest inventory data cannot be used.*

	National forest inventory			Pre-treatment structures	
Species	**Plots (%)**	**Mean shrub cover (%)**	**Mean height**	**Mean shrub cover for a total cover of 90%**	**Maximum height (cm)**
Rosmarinus officinalis	89.3	21.9	8.6	26.6	195
Quercus coccifera	86.2	16.7	9.9	20.2	200
Pistacia lentiscus	79.5	12.7	12.6	15.4	266
Thymus	77.2	5.5	2.0	6.7	48
Erica multiflora	58.2	12.1	10.1	14.6	173
Genista scorpius	52.8	5.2	6.9	6.3	310

5.2 Estimation of the multiplying factor

The multiplication factor was determined from studies that examined the effects of varying fuel treatment effectiveness in fuel loading and potential fire behaviour (Table 27). This information, along with the simulator study developed Mitsopoulos & Dimitrakopoulos (2017) and cited there, made it possible to determine the multiplication factor for various management alternatives.

Table 27. 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.

		Stand structure			Surface layer										
Fuel treatment	**TST (yrs)**	**Dominant spp.**	**DBH (cm)**	**Density (trees ha-1)**	**TFL (t ha-1)**	**TFL variation respect to pre or control (%)**	**1h FL (t ha-1)**	**1h FL variation respect to pre or control (‰)**	**10h FL (t ha-1)**	**10h FL variation respect to pre or control (‰)**	**100h FL (t ha-1)**	**100h FL variation respect to pre or control ‰**	**FBD (cm)**	**FBD FL variation respect to pre or control (%)**	**Reference**
Unmanaged	NA	*P. nigra*	17.8	1592	40.41		17.64		3.25		2.52		152.9		Piqué & Domènech (2018)
Low thinning	2	*P. nigra*	17.5	1411	56.68	1.4	28.06	1.6	14.79	4.5	12.43	5	35.50	0.2	
Low thinning + PB	2	*P. nigra*	17.5	1411	22.95	0.5	8.86	0.5	2.39	0.7	11.71	4.6	15.00	0.09	
High thinning	2	*P. nigra*	20.6	690	72.41	1.8	32.46	1.8	10.73	3.3	28.51	11.3	42.00	0.2	
High thinning + PB	2	*P. nigra*	20.6	690	34.12	0.8	10.41	0.6	1.5	0.4	22.19	8.8	20.00	0.1	
Unmanaged	NA	*P. halepensis*	4.2	11579	29.6		11.7		6.1		2.2		180		Palmero-Iniesta et al. (2017)
Thinning	0	*P. halepensis*	6.0	1100	52.39	1.7	15.6	1.3	14.9	2.4	21.9	9.9	35	0.2	
Thinning	1	*P. halepensis*	6.0	1100	46.0	1.5	12.7	1.1	12.6	2.0	20.7	9.4	27	0.1	
Unmanaged	NA	*P. halepensis*	4.9	12117	40.1		33.8		3.0		0.2		100.7		Piqué et al. 2022
Pre-com. thinning	0.5	*P. halepensis*	10.5	1293	107.6	2.7	50.8	1.5	22.68	7.5	24.7	12.3	64.3	0.6	
Pre-com. thinning	2	*P. halepensis*	12.2	1119	66.2	1.6	37.8	1.1	14.7	4.9	11.1	5.5	55.3	0.5	
Pre-com. thinning	4	*P. halepensis*	10.5	1097	59.1	1.5	31.2	0.9	10.1	3.3	6.3	3.1	96.4	0.9	

Pre-com. thinning	10	*P. halepensis*	11.9	1401	56.2	1.4	27.2	0.8	6.1	2.3	5.6	2.8	109.0	1.1	
Unmanaged	NA	*P. pinaster*	12.4	2192	NA		45.46						52		Fernandes et al. (2004)
PB	13	*P. pinaster*	12.4	1480	NA		36.41	0.8					50	0.9	
PB	3	*P. pinaster*	13.4	1856	NA		12.07	0.2					31	0.6	
PB	2	*P. pinaster*	12.3	1760	NA		11.23	0.2					30	0.6	
Unmanaged		*P. pinaster*	NA	NA	16.2		7.91		1.89		0.99		35		Fernandes (2009b)
Before PB		*P. pinaster*	NA	NA	12.4		4.75		0.83		0.07		54		
Post PB	10	*P. pinaster*	NA	NA	12.9	0.8	6.77	0.8	1.36	0.7	0.51	0.7	31	0.9	

FIRE-RES