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Wildland Fire Fuels Database for Corsican - Mediterranean Forest stand types

Pérez-Ramirez, Y., Ferrat, L., Filippi, J.B.

1. Introduction

Wildfires represent a major concern for the forests in Mediterranean basin regions since global climate change enhances the frequency and the severity of this natural ecological disturbance agent (Thom and Seidel, 2016; McLauchlan et al., 2020). Wildfires result from the complex interactions between weather conditions, vegetation, topography and fire itself. Computational wildfire models take into account all these factors and can be of valuable help for fire risk assessment as well as for planning mitigation actions. These actions concern vegetation, since this is the one factor that can be modified by management activities (i) to modulate wildfires by reducing its intensity and severity but also (ii) to protect dwellings and lives and (iii) to restore ecosystems (Keane, 2013). On the other hand, vegetation modifications can affect some local weather conditions; vegetation is thus a key element for fire and forest management.

The way vegetation is characterized, this is the set of categories, components and variables used for describing it, depends on the intended application (i.e., forest management, fire management, fire behavior, fire ecology, etc.), the spatial and temporal resolution scale (Moritz et al., 2005) and the available resources (i.e., data, technology, fuel sampling techniques). In wildfires research, vegetation, this is dead and live biomass, is often considered as being “fuel” due to its role on fire combustion processes. Wildland fuels form extremely complex structures which are highly variable over space and time. This complexity makes it difficult to accurately describe, classify, sample and map them. To overcome these difficulties, traditionally, similar fuels in terms of structural characteristics that are significant for fire behavior and management at a particular scale have been grouped constituting fuel description or classification systems which in turn have different categories often referred as fuel types or fuel beds (Keane, 2013). Grouping fuels is useful to simplify data collection as fuel sampling, and data input into wildfire models and the associated numerical simulation tools. For each fuel type, associated fuel attributes are defined. Fuel attributes have been traditionally described to match input variables of a particular wildfire model, with different models requiring different fuel input variables. For instance, fire behavior semi-physical models generally use mean input values of forest stand descriptors, whereas fire behavior physics-based models need detailed information of each vegetation element (i.e., tree, shrub, herbs). Thus, fuel description/classification systems have been usually developed to be linked to a particular wildfire model (Ottmar et al., 2007; Lutes et al., 2009 and Hollis et al., 2015). In these cases, the term fuel model or fire behavior fuel model is often used to denote the set of input parameters characterizing a fuel type as required by a particular wildfire model (Arroyo et al., 2008).

Advances in the knowledge on wildfires and its modeling, on the improvement of available spatial fuel-related data, as well as progresses in computing capabilities and simulation techniques have opened up new possibilities for modeling wildfires and fuels at finer scales (Parsons et al., 2018; Calvo et al., 2023; Chuvieco et al., 2023). And thus, for improving wildfire forecasts since fuel data has been identified as a major source of uncertainty (Benali et al., 2016). Nevertheless, despite of the efforts to develop methods for generating global fuel data sets (Pettinari et al., 2016; Aragoneses et al., 2023), there is a lack of fine resolution regional scale fuel data sets for the Mediterranean basin. In this regard, major efforts are dedicated to improve fuel classification and mapping, as well as determining particular fuel attributes (e.g., above ground fuel load). So, either there is a lack of fuel attributes necessary for modelers or, and so often, fire behavior fuel models (Scott & Burgan, 2005) are associated to fuel types for fire modeling purposes. However, these fuel models, which have been developed for the fuel

types typical of the United States, are quite simple to cope the specificities of well-aerated and heterogeneous Mediterranean fuel types (Fernandes, 2009). Moreover, these data sets are only suitable for a specific wildfire model.

In this particular framework, where there is a variety of fuel description/classification systems depending on the different wildfire models and applications (i.e., fire behavior, fire management, forest management, fire ecology, etc.) and where there is more and more available fuel-related data at finer scales, there is a need on producing detailed fuel data that integrates the available data sources while being easily customized to the current and forthcoming wildfire's models. The challenge being to find a balance between the level of detail of the fuel data and the need for generalized fuel data sets at the scales which are significant for fire management and risk assessment. Moreover, it is important to avoid duplication efforts and to increase interoperability between fire and forest management actors as well as all related research communities.

The aim of this work is to build a fuel data set based on existing data sources to provide researchers and fire/forest management actors with useful data for fire risk assessment purposes. So, this paper presents a database (building methods and data) of wildland fuels for Mediterranean basin vegetation stands types and in particular for those in Corsica, which gathers together most common input parameters needed by wildfire's models at several scales (i.e., stand, element, particle). This work has been carried out in the framework of the FireCaster project which was focused on developing a new generation national (French) scale Wildfire Decision Support System to provide operational agencies more efficient ways to forecast fire danger and handle ongoing crisis (Filippi et al., 2022).

This article firstly presents the database background, its structure and the fuel attributes considered. Next, the methods to gather together the data and the different data sources used are detailed. Then an example of application and the linkage to a wildfire model are detailed. Finally, conclusions and prospects of improvement are discussed.

2. Database description

2.1. Background

As already mentioned, this database was developed in the framework of the FireCaster project whose goal was to develop a prototype of coupled fire-weather decision support system in order to provide operational agencies new tools, based on ensemble simulations (Allaire et al., 2020; Allaire et al., 2021a) and probabilistic risk (Allaire et al., 2021b; Allaire et al., 2022), to forecast fire danger at regional scale. This system is based on the numerical solver ForeFire (Filippi et al., 2010; Filippi & Grandi, 2014) that can be coupled with the Meso-NH/SURFEX atmospheric model (Lafore et al., 2010; Masson et al., 2013). In order to respond to the needs of fuel data, as necessary inputs to the fire models used, it was necessary to conceive a data structure to categorize, store, manage, and to integrate fuel data. To this purpose the FireCaster Fuel Description System was implemented (Figure 1; Pérez-Ramirez et al., 2018). The database presented in this paper is issued from the parametrization of the FireCaster Fuel Description System and thus keeps the same structure and considers the same parameters, which have been defined to be meaningful at regional/landscape scales.

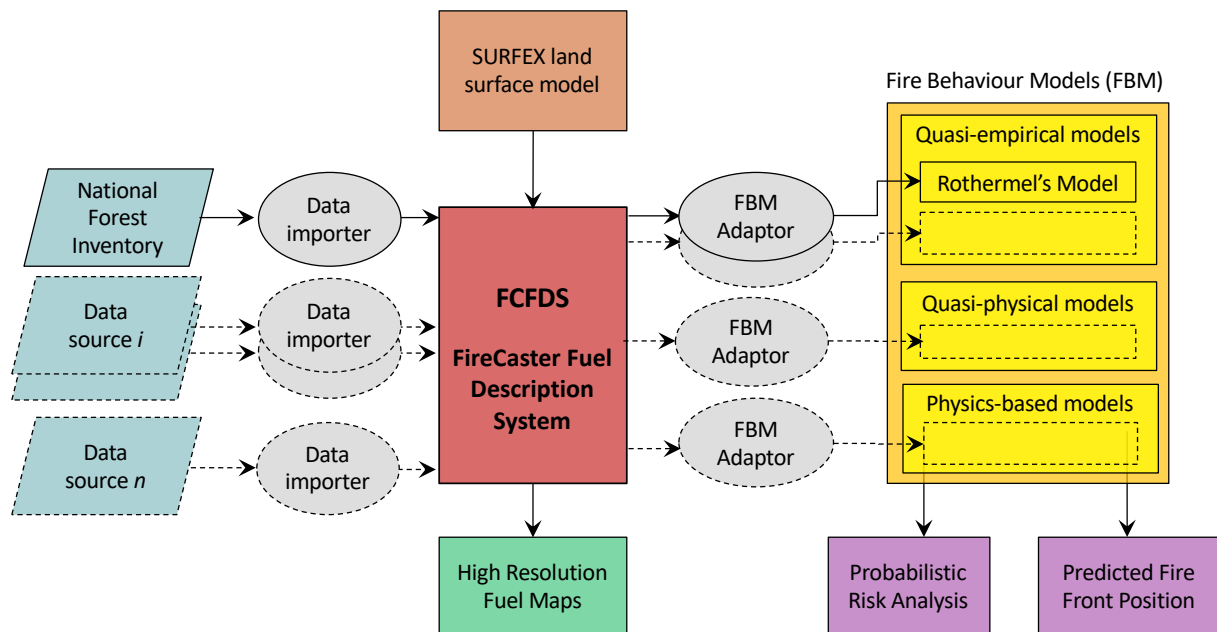


Figure 1 - Overall view of the FireCaster Fuel Description System and its interactions to other elements of the FireCaster Decision Support System (FCDSS). FBM: Fire Behaviour Model.

2.2. Database structure

As the FireCaster Fuel Description System, the Wildland Fire Fuels Database has been conceived by using a layering approach, this is, assuming that a vegetation stand type is constituted by one or more structurally distinct pseudo-homogenous layers of vegetation (Figure 2). This approach has often been used when describing vegetation for wildland fire modeling purposes (Ottmar et al., 2007; Pimont et al., 2016; Cruz et al., 2018), since distinct strata or layers have a different contribution to fire behavior that can be related to different fire attributes such as flame height, flame depth, smoldering combustion (Sullivan et al., 2012). Each layer is composed by fuel elements (e.g., trees, shrubs) or fuel particle arrangements (e.g., herb patch) sharing the same structural, physical and chemical characteristics. It should be pointed out that a fuel layer does not necessarily corresponds to a vegetation stratum, and that a vegetation stratum can be described by several fuel layers. Fuel elements are in turn composed by fuel particles. This approach allows different levels of detail, and thus data can be used by different types of fire models from semi-physical models (e.g., Rothermel's model; Rothermel, 1972; Andrews, 2018), to physics-based models (e.g., Wildland Urban Interface Fire Dynamics Simulator – WFDS; Mell et al., 2009). It is worth noting that to use the database as input fuel data for a particular fire behavior model a linkage between them is necessary (see section 4 for an example).

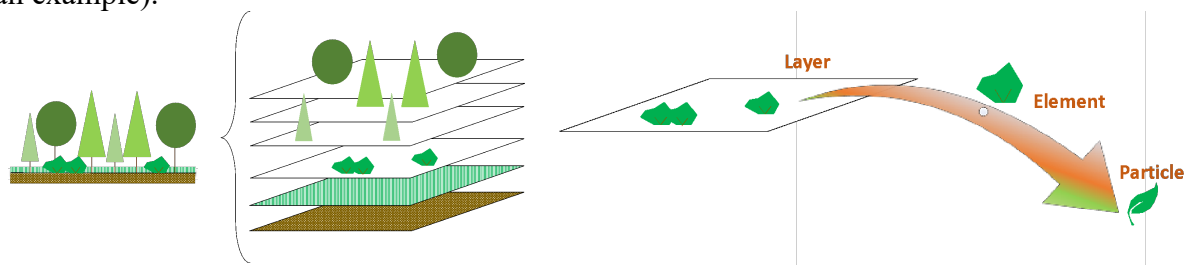


Figure 2 – Scheme of the Layering approach used for describing a vegetation stand.

2.3. Fuel attributes

A set of fuel layer attributes has been defined to describe the structure and the arrangement of fuels in the layer (Table 1). Correspondingly, a set of fuel elements and fuel particles attributes

has been defined (Table 2 and Table 3 respectively). Fuel attributes do not depend on the characteristics of the fuel layer or the element. Fuel attributes have been chosen and defined based on most common fuel input parameters of the current fire behavior models (Sullivan, 2009ab), but they do not constitute a complete set of the parameters needed by all the existing models. As already stated, linkages will be needed depending on the fire model used. However, certain attributes can be derived from the ones specified. For instance, for surface layers, the bulk density of a fuel layer can be estimated from total fine fuel load (i.e., the live fine fuel load plus the dead fine fuel load) and the layer height (i.e., the difference the layer top height and the layer base height). Moreover, the analysis of the different layers data can give information of the whole forest stand characteristics. As an example, the analysis of the vertical distribution of the different fuel layers, can give an insight on the likelihood that a surface fire transitions to a crown fire, since overlapping fuel layers can act as a ladder for fire to climb into the overstorey canopy.

Table 1 – Fuel Layer attributes

Layer attribute [units]	Definition
Surface cover fraction [%]	Ground surface covered by vegetation in percentage for surface fuels. For near-surface, elevated and canopy fuels the projected ground surface of the outermost canopy perimeter
Layer top height [m]	Vertical distance between the ground and the top of the fuel layer
Layer base height [m]	Vertical distance between the ground and the base of the fuel layer
Fine* live fuel load [kg/m ²]	Dry weight of fine live fuel per unit area
Fine* dead fuel load [kg/m ²]	Dry weight of fine dead fuel per unit area
Density of population [stems/ha]	Number of elements (e.g. tree, shrub, herb patch, litter patch) per unit area
Species	Name of the vegetation species
Stratum	Vegetation stratum (e.g. Canopy, understory, high shrub, low shrub, herbaceous, litter).

*Fine fuels: fuel particles with a characteristic size < 6 mm

Table 2 – Fuel element attributes

Fuel element attributes [units]	Definition
Crown projection area [m ²]	Surface area of the vertical projection of the outermost perimeter of the fuel element
Crown characteristic dimension [m]	Characteristic dimension of the vertical projection of the outermost perimeter of the fuel element (e.g., crown diameter)
Total fine* fuel mass [kg dry basis/element]	Total amount of dry weight of fine fuel per fuel element
Proportion of fine dead fuel [% kg fine dead fuel / kg total dry fuel]	Relation of the amount of fine dead fuel to the total amount of fine dry fuel

**Fine fuels: fuel particles with a characteristic size < 6 mm*

Table 3 – Fuel particle attributes

Fuel particle attributes [units]	Definition
Surface to volume ratio [m ⁻¹] (live/dead)	Relation of the particle cross surface area to the particle volume
Particle density [kg/m ³] (live/dead)	Relation of the particle dry mass to its volume
Low heat content [kJ/kg] (live/dead)	The energy released when fuel particles undergo complete combustion under standard conditions corrected for the heat loss arising from the water release during the combustion reaction

A key fuel attribute when modeling forest fires is the fuel moisture content of dead and live fine vegetation. The moisture content in live fuels is determined by the balance between water supply from the roots and water loss by transpiration. These processes mainly depend on plant species, the age of the plant, the time of the year, soil properties and the drought conditions. In the case of dead fuels, moisture content is controlled by humidity, precipitation, sunlight, wind and the size and shape of particles. Thus, fuel moisture content presents a very-short to short-term dynamic behavior, that is why it has not been included in the database. In the framework of the FireCaster project, dead fuel moisture content has been derived from the *Fine Fuel Moisture Code* in the *Forest Fire Weather Index System* (Van Wagner, 1987). Other models for assessing fuel moisture content can be found at Sharples et al. (2009). Live fuel moisture content has been estimated from the land surface model SURFEX (Masson et al., 2013), based on the available data from the “*Reseau hydrique*” on life fuel moisture content obtained from weekly summer measurements in fire-prone French Mediterranean regions (Martin-StPaul et al., 2018).

3. Database parametrization

This section describes stepwise the methodologies used for the parametrization of the database (Figure 3). It is important to note that forest stands characteristics evolve over time, and some fuel types change significantly over monthly or seasonal periods such as canopy fuels including deciduous tree species which undergo changes from a leafless stage in the spring to a green stage in the summer to a leafless stage once again in the fall. In this regard the data included in the database correspond to summer time characteristic values especially concerning the fuel biomass of deciduous species and the amount of dead fuel.

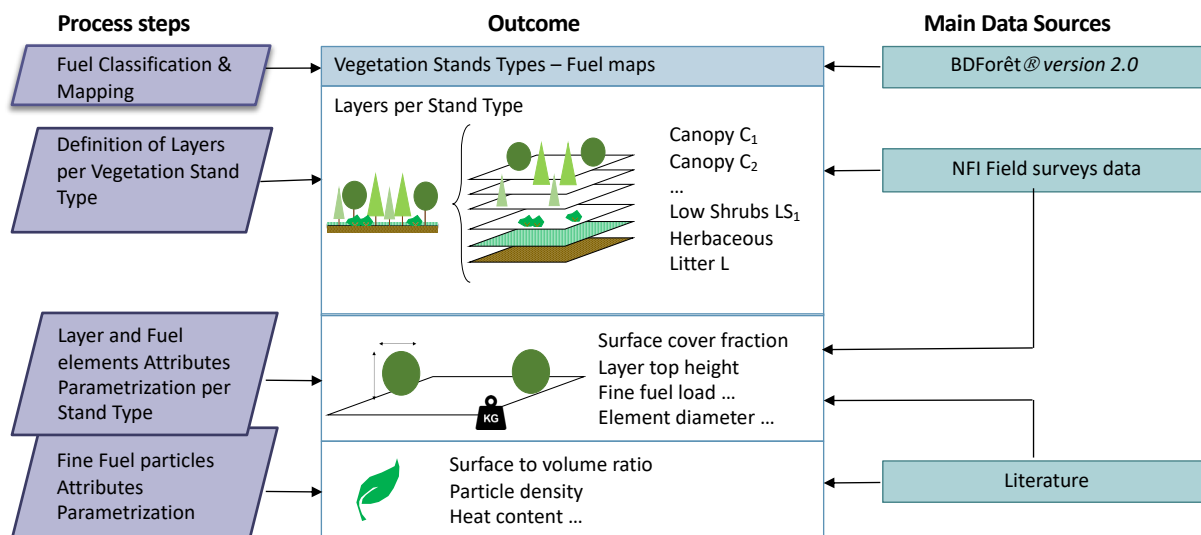


Figure 3 – Scheme of the database parametrization process

3.1. *Fuel Classification & Mapping - Fuel types and the corresponding georeferenced data*
 The *BDForêt® version 2.0 - Corsica* has been used as the georeferenced basis for defining and mapping the vegetation stand types to be considered. The *BDForêt® version 2.0* is the French reference GIS vector database mainly developed by photo-interpretation of near-infrared images (50 cm resolution). It describes the spatial distribution of forest and natural vegetation stands using a soil cover approach reflecting a description of the stand cover density, its composition and the dominant species following a national nomenclature, for vegetation patches covering at least a surface of 0.5 hectares. This database constitutes a national reference tool for the actors involved in forest/wood exploitation, land use planning, environment and sustainable development (e.g. management, fire, resources, supply, certification, etc.). *BDForêt® version 2.0 – Corsica* shares the common framework and structure of the regional version but with a more detailed description of vegetation stands in terms of identification of dominant species (level IV in Table 4).

Level I Soil Cover	Level II Stand Cover density	Level III General Stand Composition	Level IV Dominant Species
Forests	Closed Forest Tree surface cover: ≥ 40%	Deciduous	<i>Quercus ilex</i> <i>Quercus suber</i> <i>Fagus sylvatica</i> ...
		Coniferous	<i>Pinus pinaster</i> <i>Pinus nigra</i> <i>Juniperus oxycedrus</i> ...
		Mixed	
	Open Forest Tree surface cover: 10% - 40%	Young stand / Incident	
		Deciduous	<i>Quercus ilex</i> <i>Quercus suber</i> <i>Fagus sylvatica</i> ...

		Coniferous	<i>Pinus pinaster</i> <i>Pinus nigra</i> <i>Juniperus oxycedrus</i> ...
		Mixed	
	Poplar tree plantation		
Other stands	Shrublands	Shrubland	
		Grasslands	
	Tree plantations / Orchards		

Table 4 Scheme of the structure of the *BDForêt® Version 2.0*

The *BDForêt® version 2.0 - Corsica* accounts for 58 vegetation stands types, 32 from the National nomenclature and 26 specifics to Corsica, even though only 53 types have been mapped in Corsica. From these 58 types, 24 correspond to general stand types with no detailed information concerning the specific dominant species (level III, Figure 4; e.g. *Pure deciduous closed forest.*), 28 correspond to detailed stand types (level IV, Figure 4, e.g. *Pure cork oak closed forest*), 3 correspond to tree plantations or orchards (e.g. *Olive plantation*), 2 to shrublands and 1 to grasslands. For the purpose of this study the types of forest stands included in the *BDForêt® version 2.0 - Corsica* have been reviewed. A surface area distribution analysis has been carried out taking into account the fire hazard in order to identify the most common and relevant stand types. Moreover, general stand types have been associated to the closest and more relevant detailed stand type. For instance, the stand type '*Pure coniferous open forest*' has been merged to the stand type '*Pure Pinus pinaster open forest*'. In addition, the particular stand type '*Shrubland*' has been split in 3 different types, since shrublands are very fire prone fuel stand types that present highly variable characteristics. Moreover, '*Shrublands*' are the vegetation type covering the largest surface area in Corsica, this is more than 17 % of the vegetation land cover according to the *BDForêt® version 2.0 - Corsica* data. So, three different types have been considered depending on the bioclimatic stages, i.e., meso-Mediterranean, supra-Mediterranean/Montane and subalpine. As a result, the database accounts for 47 fuel stand types.

3.2. Stand structure modelling - Definition of layers

As already stated, the Wildland Fire Fuels Database has been conceived assuming that a vegetation stand type is constituted by one or more structurally distinct pseudo-homogenous layers of vegetation. Thus, for each of the stand types identified, its structure and composition have been modeled by different layers. To this purpose, the data collected by the National (French) Forest Inventory (henceforth NFI) have been mainly used. However, since NFI is focused on forest, the following stand types: orchards, shrublands, grasslands or forest stands which have undergone anthropogenic or natural disturbance and might present different stages of regeneration; were characterized using other data sources (mainly literature and field assessments).

French NFI field surveys aim to assess the state of forests in terms of wood resources, as well as botanical and ecological components. The French NFI is continuous over space and time. The whole metropolitan territory is covered by a systematic grid of rectangular cells of 2 x 1 km resolution. Each cell corresponds to a year of inventory from year t to year $t+5$, since sampling points are revisited every 5 years. Each rectangular cell of the grid is divided in two 1 km² squares, one square area is used for the annual inventory at year t , while the other square contains the sampling plots inventoried at year $t-5$ to be re-assessed at year t . The sampling points of the annual inventory, which are randomly located in the grid, consist in a system of

four nested circular plots with radii of 6, 9, 15 and 25 m. The larger plot with a surface area of approximately 20 ares is used to assess land cover, land use and stand-specific variables, whereas smaller plots (i.e., 6, 9 and 15 m plots) are used for tree-specific variables and the floristic inventory. Further details on the NFI sampling scheme and field measurements are provided in Hervé (2016).

To determine the layers characterizing the structure and composition of each forest stand type previously identified, several steps were required. First of all, it was necessary to link the NFI sampling points to the corresponding vegetation stand types. In order to be consistent with the data used for the identification of the fuel stand types, only NFI field surveys from sampling points in Corsica between 2013 and 2018 were taken into account.

Available NFI data include the position of the center of the corresponding grid cell and the maximum distance between this point and the sampling plots center, but not the exact position of the sampling plot center. For this reason, a methodology was developed to assign to each NFI plot the corresponding stand type based on the cover density (i.e., open or closed forest), the main tree species and the tree canopy surface cover. A verification procedure was implemented to assure that the stand type identified for the corresponding point was present nearby the NFI grid cell center. A buffer area corresponding to the maximum distance between the NFI grid center and the sampling points around each NFI grid point was created and overlapped to the the *BDForêt® version 2.0 – Corsica* vegetation stand types maps.

After that, the variability between IFN sampling points associated to the same stand type was assessed. Even though differences are observed over the territory for a particular stand type depending on the soil characteristics, the altitude, the slope of the terrain and the aspect and/or the age of the stand, a general profile for each stand type associated to the worst-case scenario in terms of fire risk was identified. Take into account the differences of a certain stand type due to all the factors afore mentioned would require a considerably larger data set. In addition, since the NFI data do not specify the statistical weight of each sampling plot it was not possible to perform a more detailed and complete analysis. When not enough plots were available to produce consistent estimates, other sources were considered as well as some field observations.

Thus, for each stand type basic statistical estimates (i.e., mean, median, standard deviation) were computed for the surface cover per strata. The NFI field surveys consider the following vegetation strata: moss, herbaceous, low ligneous (i.e., shrubs lower than 2 m high) and high ligneous (i.e., shrubs/trees taller than 2 m high). Additionally, statistic estimates for the tree surface cover and the modified Braun-Blanquet cover scale (Braun-Blanquet, 1965) were also computed. The modified Braun-Blanquet cover scale is an abundance-dominance scale that denotes the surface area covered by a particular species by using a scale ranging from 1 to 5.

Based on these estimates and the corresponding description of the fuel stand types as defined in the *BDForêt® version 2.0 – Corsica*, fuel layers describing the structure and composition of the stand were determined as well as the surface cover per layer. To that end several general hypotheses were taken into account. The vegetation strata considered in the database were: litter, herbaceous, low shrubs (i.e. height < 2 m), high shrubs (i.e. height > 2 m) and intermediate and overstorey canopy trees. Duff and coarse woody debris were not considered due to the lack of data. However, loadings of coarse woody debris are usually reduced in Mediterranean forests (Fernandes, 2009).

Only strata covering at least 10 % of the surface and/or species with a modified Braun-Blanquet cover scale at least equal to 2 (i.e., surface cover < 25 %, mean surface cover around 12 %) were taken into account. It was assumed that surface fuels (i.e., litter and herbaceous) formed a unique layer per strata. The diversity of herbaceous species was represented by only one species. For raised fuels (i.e., shrubs and trees), layers were associated to vegetation species, so that a fuel layer was only composed by one vegetation species. It was also assumed that the elements constituting a layer had the same characteristics. The maximum number of species and thus layers per strata considered for raised vegetation was limited to three.

All the species sampled in the NFI plots considered were classified according to the strata where they can develop. So, each species was associated to one or more strata depending on their characteristics. For instance, rockrose (*Cistus monspeliensis*) plants were associated to the low shrub strata, whereas tree heath plants (*Erica arborea*) were associated to the low shrub strata, the high shrub strata, and the intermediate canopy strata. Tree species were considered to be present only at the mature stage and thus to be part either of the overstorey or the intermediate canopy strata, with the exception of the fuel types corresponding to forest stands which have undergone anthropogenic or natural disturbance

Following this classification, species identified as trees were sorted based on statistic estimates for the tree surface cover and the Braun-Blanquet cover scale and ranked by the number of observations, this is, the number of IFN sampling points where the species is present. According to the definition of the fuel stand (open/closed canopy and pure or mixed stand), species and thus layers constituting the overstorey and intermediate canopy strata were defined. As already stated, the maximum number of layers considered by strata was three. Subsequently, the high-shrubs layers were determined in a similar manner taking into account that the surface cover of the canopy layers and the high-shrubs layers corresponds to the IFN surface cover for high ligneous plants. The same procedure was applied for the species that might develop as low-shrubs, considering that the total surface cover of low-shrubs layers should be consistent with the IFN surface cover of low ligneous (Figure 5)

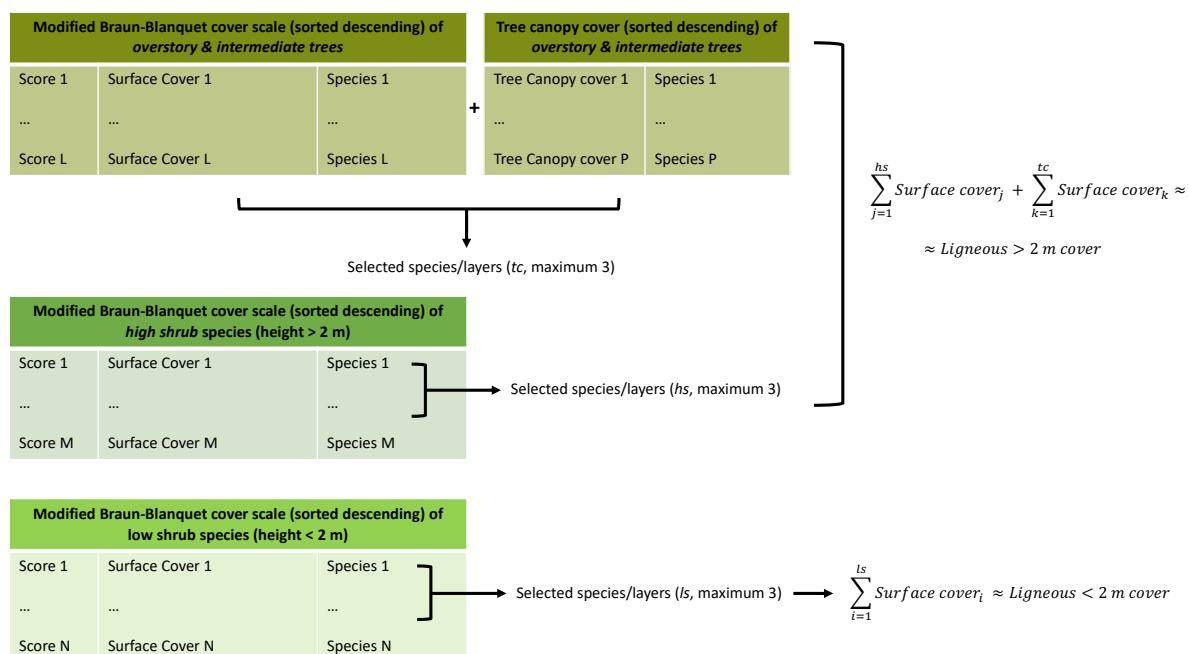


Figure 5 Scheme of the methodology for the definition of raised vegetation layers

For the herbaceous layer, as already stated, only one layer was considered. The species associated to this layer was mostly *Brachypodium retusum* when present, since there is available data on the literature concerning their particles attributes. These attributes are required input parameters for most of the fire behavior models. Finally, a litter layer was considered mainly based on literature, field observations and the consensus of the authors based on their expertise.

This step also allowed to determine the *species* and *stratum* attributes for each defined layer as well as their corresponding surface cover fraction. An example is presented in next section.

Example: Closed Forest of *Quercus ilex*

To illustrate the methodology this section details the different steps required for the determination of the layers characterizing a particular forest stand, the ‘Pure Closed *Quercus ilex* forest’. According to the *BDForêt® version 2.0 – Corsica*, a ‘Pure Closed *Quercus ilex* forest’ is defined as a closed forest (i.e., canopy cover higher than 40 %) with an overstorey composed by *Quercus ilex* covering more than 75 % of the total canopy cover (i.e., overstorey and intermediate canopy strata). This stand type constitutes more than 10 % of the total surface area covered by vegetation according to the *BDForêt® version 2.0 – Corsica*, and is the third more important vegetation stand type in terms of surface cover in Corsica. Consequently, there is a significant number of NFI sampling points associated to this vegetation stand type. Figure 6a) shows on green, the zones identified as ‘Pure Closed *Quercus ilex* forest’ stand type and red dots correspond to the NFI grid points that have been associated to this vegetation type (i.e., 55 sampling points). Figure 6b) illustrates the surface cover distribution per vegetation strata considered in the NFI (i.e.: herbaceous, ligneous lower than 2 m and ligneous higher than 2 m).

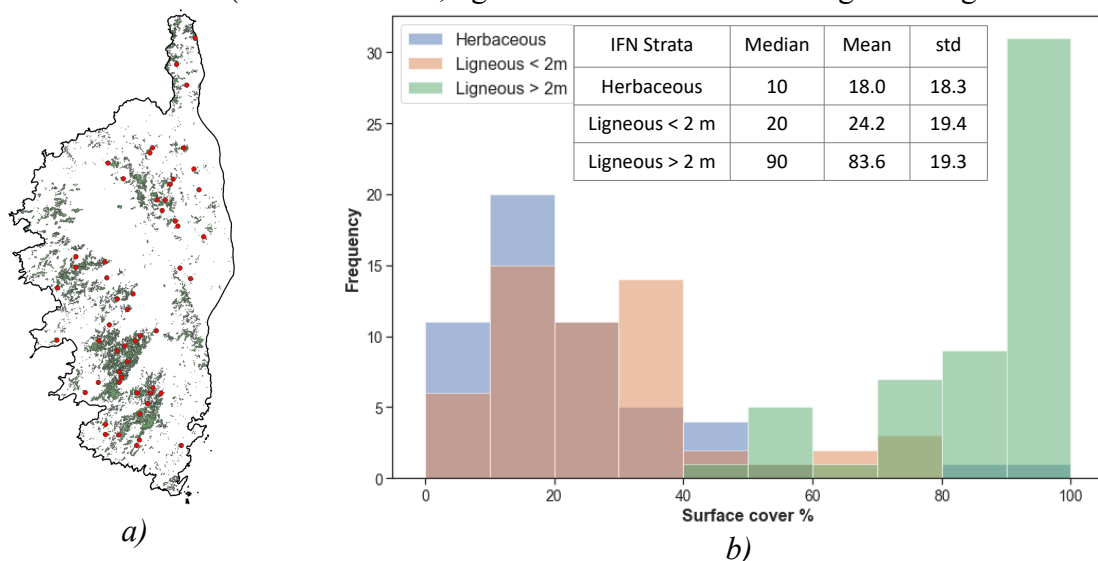


Figure 6 ‘Pure Closed *Quercus ilex* forest’ data. a) Georeferenced distribution and associated IFN sampling points. b) Surface cover per strata data from IFN Sampling points.

The IFN surface cover for the ligneous vegetation higher than 2 m, is representative for the surface cover of the high-shrub layers, in addition to the intermediate and overstorey canopy layers, as already detailed, and the median value for this stand type is 90 %. Table 5 shows the canopy cover results for the six more representative species corresponding to the overstorey and the intermediate canopy strata, as well as, the associated Braun-Blanquet score for these species. As it can be observed there are differences between the number of observations for the canopy cover data and the Braun-Blanquet Score data. This is due to the fact that the canopy

cover data concerns only trees (defined as ligneous plants higher than 5 m) and the Braun-Blanquet Score concerns the surface covering of a species in all the strata.

Table 5 – Canopy cover for the 6 more relevant species and the corresponding Braun-Blanquet Score. N°Obs: Number of observations, this is, the number of IFN sampling points where the corresponding species has been observed. std: standard deviation.

	Canopy cover (%)				Braun-Blanquet Score (corresponding surface cover % for median values)			
	N°Obs	Median	Mean	std	N°Obs	Median	Mean	std
<i>Quercus ilex</i>	55	80.0	70.0	22.8	55	5 (>75%)	4.4	0.7
<i>Arbutus unedo</i>	33	0	4.8	7.5	33	2 (<25%)	2.4	0.6
<i>Erica arborea</i>	20	0	1.3	3.3	35	2 (<25%)	2.6	0.8
<i>Fraxinus ornus</i>	16	0	1.6	3.5	16	2 (<25%)	2.3	0.6
<i>Phillyrea latifolia</i>	13	0	3.7	7.6	15	2 (<25%)	2.2	0.4
<i>Olea europaea var. sylvestris</i>	6	0	3.1	4.5	6	2 (<25%)	2.2	0.4

As expected, *Quercus ilex* is at the top of the ranking. So, according to the definition of the vegetation stand considered and the results, an overstorey canopy layer composed by *Quercus ilex* is defined, whose canopy cover is 80 %. Next species is the *Arbutus unedo*. For this species, the median canopy cover among all the NFI plots for this stand type is 0, the mean value is 4.8 ± 7.5 , and the median Braun-Blanquet Score is 2 corresponding to a surface cover between 5% to 25 %. It must be noted that the NFI sampling method assign a value of 0 for the canopy cover when a species is present but its canopy cover is lower than 5 %, whereas the corresponding Braun-Blanquet Score is 1. In Table 6 canopy cover statistics when excluding zero values have been detailed. According to these results more than 47 % of the IFN sampling points associated to this stand type present an intermediate canopy stratum with a surface cover higher than 5 % and in average around 10 % of the total surface. It is worth noting that all the IFN sampling points in Table 6 are different, indicating that the intermediate canopy cover layer is mainly constituted by one vegetation species.

Table 6 – Canopy cover statistics for intermediate canopy species when only values higher than 0 are considered.

	Canopy cover (%)			
	N°Observations	Median	Mean	Standard deviation
<i>Arbutus unedo</i>	14	10	12.3	7.0
<i>Erica arborea</i>	3	9	9	0.0
<i>Fraxinus ornus</i>	3	9	8.6	1.5
<i>Phillyrea latifolia</i>	3	20	16.3	6.3
<i>Olea europaea var. sylvestris</i>	3	9	7.3	3.8

To take into account the intermediate canopy cover, the first species in the list, which is the more representative, is retained. This is, an intermediate canopy layer of *Arbutus unedo* with a surface cover of 10 %.

Since the IFN cover for the ligneous vegetation higher than 2 m is 90 % (median value), and the surface occupied by both *Quercus ilex* and *Arbutus unedo* trees is already equal to 90 %, it is assumed that there are no high-shrubs layers for this forest stand type. Due to the lack of other sources of quantitative data, the overlapping of canopies between the overstorey/intermediate canopy layers and the high-shrubs layers cannot be taken into account and this aspect can be a limit of the methodology for very dense forest stands. However, at the end of the automatic determination of layers, a verification/validation step has been carried out. For instance, for this particular forest stand type, the resulting layers' structure and composition have been assessed through comparison to the corresponding description in the *Habitats Manuals* (Bensettiti et al., 2001) have been assessed. The *Habitats Manuals* (Bensettiti et al., 2001) describe forest physiognomy (i.e., general appearance, structural growth forms of dominant species, height, altitudinal variations, etc.) for particular forest stands types of Community importance.

Concerning the low shrubs layers, the IFN cover for the ligneous vegetation lower than 2 m is 20 % (median value). Table 7 shows the Braun-Blanquet Score statistics for the 6 more relevant species that might develop as part of the low shrub layers. According to these values, two species have been retained, the *Erica arborea* and the *Phillyrea latifolia* and thus two layers constitute this stratum. It has been assumed that their surface cover is equal to 10 % in both cases.

Table 7 – Braun-Blanquet Score statistics for species that might develop at low shrubs strata.

	Braun-Blanquet Score (corresponding surface cover % for median values)			
	N°Observations	Median	Mean	Standard deviation
<i>Erica arborea</i>	35	2 (<25%)	2.6	0.8
<i>Phillyrea latifolia</i>	15	2 (<25%)	2.2	0.4
<i>Rubus ulmifolus</i>	14	2 (<25%)	2.0	0.3
<i>Pistacia lentiscus</i>	11	2 (<25%)	2.2	0.6
<i>Ruscus aculeatus</i>	8	2 (<25%)	2.0	0.0
<i>Cytisus villosus</i>	7	2 (<25%)	2.1	0.4

It is worth mentioning that when a species has already been selected for another strata it is not listed for the following strata, as that would be the case in this example if *Erica arborea* should have been considered for the high-shrubs layers.

Concerning the herbaceous layer, *Brachypodium retusum* is the herbaceous species that has been observed in a larger number the NFI plots corresponding to a ‘Pure Closed *Quercus ilex* forest’ stand type (i.e., 18 observations). The median value of the Braun-Blanquet Score is 2.0 and the mean value is 2.2 ± 0.38 . So that, the surface cover for the herbaceous layer is 10 % resulting from the NFI field surveys and is represented by the *Brachypodium retusum*.

Finally, it has been considered that the surface cover of the litter layer is 100 %, since the total surface cover of the vegetation layers that can contribute to the formation of the litter layer is higher than 100 %. So, it is assumed that overlapping of layers occur once all the available surface is covered by fuel layers.

Table 8 presents the results for the stand structure modelling for this particular fuel type, this is the layers, corresponding stratum, species and surface cover.

Table 8 – Layers describing the ‘Pure Closed *Quercus ilex* forest’ stand type and the corresponding surface cover.

Layer	Stratum	Species	Surface cover (%)
O 1	Overstorey	<i>Quercus ilex</i>	80
I 1	Intermediate	<i>Arbutus unedo</i>	10
LS 1	Low-shrub	<i>Erica arborea</i>	10
LS 2	Low-shrub	<i>Phillyrea latifolia</i>	10
H	Herbaceous	<i>Brachypodium retusum</i>	10
L	Litter	----	100

3.3. Layer, Fuel elements and Particles attributes data

The methods and sources to obtain the data associated to the different layers’ attributes varied between surface fuel layers (i.e., litter and herbaceous) and raised fuel layers (i.e., low shrubs, high shrubs and canopy trees). It was assumed that surface layers were homogeneous (i.e., not patchy distribution), and their associated layer and fuel elements attributes were obtained from the literature due to the lack of other sources of data. For raised vegetation layers, the main source of data was the NFI Field Surveys, particularly for intermediate and overstorey canopy trees, since the NFI is focused on forest production by means of the characterization of trees. Table 9 summarizes the data sources for the layer attributes for the different strata considered in this study. The species and vegetation stratum associated to each layer were indeed determined when defining layers, as already detailed in previous section.

Table 9 – Data sources for the different layer attributes depending on their strata

Fuel Layer Attribute	Data Sources	Fuel strata			
		Litter	Herbaceous	Low and high shrubs	Overstorey / intermediate Canopy
Surface cover fraction	NFI Field Surveys	✓	✓	✓	✓
Layer base height	By definition (Soil level)	✓	✓		
	Crown base height Allometric equations			✓	✓
Layer top height	Literature + Field observations	✓	✓	✓	
	NFI Field Surveys				✓
Layer density (Fuel elements/ha)	Hypothesis homogeneous distribution	✓	✓		
	Derived from Fuel Elements Attributes			✓	✓
Fuel load (Dead & Live)	Literature	✓	✓		
	Derived from Fuel Elements Attributes + Allometric equations			✓	✓

Fuel layer and fuel element attributes are intrinsically linked since some fuel layer attributes were derived from allometric equations based on fuel element attributes or associated attributes as the diameter at breast height (DBH) which is only considered for overstorey, and intermediate trees as illustrated in Figure 7.

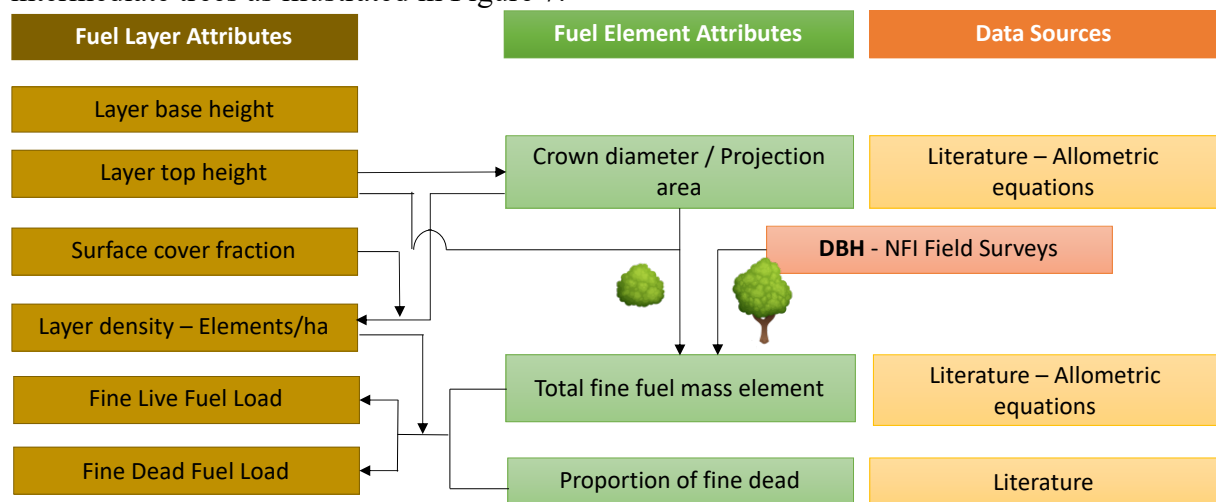


Figure 7 Scheme of the link between fuel layer and fuel element attributes.

Two attributes deserve a more detailed explanation. First, the *layer top height* attribute for the layers corresponding to shrub's strata, both low and high. Due to the lack of available data, a value for this attribute has been predefined for the different vegetation species in its form as a low or high plant according to field observations and the expertise of the authors. The selected values are those being representative of the worst-case scenario in terms of fire risk. These values are independent of the vegetation stand type. While this is a rough approximation, it allows to automate the method for the definition of layers and its implementation. The second attribute needing further details is the *proportion of fine dead fuel*, which has been used to

estimate the *fine dead fuel load* attribute of the corresponding layer. The amount of fine dead fuel of raised vegetation is related to the successional stage and the specie's regeneration strategy (Baeza & Santana, 2015), and it is not expected to change dramatically over short periods of time unless a disturbance occurs. Thus, for layers corresponding to low/high shrubs or overstorey/intermediate canopy strata this attribute has been mainly determined from literature values. However, herbaceous species can exhibit an annual cyclic growth – development – senescence pattern, or survive for more than one season (e.g., perennial grasses) undergoing a process of dieback after seeding. For these fuels, the amount of fine dead fuel, referred in the literature as degree of curing, is strongly related to the species adaptations and climate conditions (Duff et al., 2019). So, it can change significantly during short periods of time and consequently during the fire season. Due to the role of the curing degree on fire behavior, the values for the *proportion of fine dead fuel* attribute associated to herbaceous layers have been chosen to be representative of the more hazardous scenarios.

Concerning the fuel particle attributes, they were all obtained from the literature. It should be mentioned that in the absence of information for a given species when determining either fuel element or fuel particle attributes, the fuel characteristics of a similar species were considered.

4. Application case

Quantitatively assess or compare the data in these paper to other fuel parametrizations will require the presentation of a large case database of cases and statistical analysis of results that is an ongoing work yet out the scope of this methodology paper. The aim of this section is to illustrate both the use of the data presented in this paper for wildfire simulations at landscape scale, as well as the linkage to a particular fire spread model. Thus, the data gathered from the database have been used to generate formatted fuel data as necessary input to run fire simulations with the model known as the *Balbi* model (Santoni et al., 2011) in order to simulate a well-document wildfire which occurred in Corsica in 2009, the *Favone* fire. The results obtained by Santoni et al. (2011) to simulate this particular fire have been included for qualitative comparison purposes, mostly because the authors developed specific fuel models based on vegetation data obtained from classical destructive field sampling procedures (Brown et al., 1982) to simulate this fire. Destructive sampling techniques imply locating sampling points, taking inventory, cutting and weighting vegetation on site to then sorting, drying and weighing it again in a laboratory. While being direct observations and therefore the best available data to perform simulation, these techniques are highly laborious, time consuming and costly, they are compared here to the systematic use of FCFDS.

4.1. Favone fire

The *Favone* fire occurred on July the 8th of 2009, in the South-East of Corsica and burned around 30 ha of cork oak woodlands and typical Mediterranean shrublands. During the fire, the wind speed varied between 18 to 25 km/h, air temperatures between 25°C to 27°C, and the relative humidity of the air between 41 % to 46 %, according to the recordings of the closest weather stations which are located between 6 to 10 km from the ignition point. This human-caused fire gained intensity rapidly limiting the direct suppression attack of the fire crews to the flanks, especially the left one in order to protect a residential area. In this regard, aerial suppression means (8 air tankers) also focused their actions on the left flank to protect human lives and assets. As soon as this area was secured, aerial means were deployed on the right flank, with the intention to guide the fire towards the sea. Once the fire reached the sea, firefighting actions were focused on containing the area burnt by limiting the fire flanks progression. A more detailed description of the *Favone* fire can be found at Santoni et al. (2011), including the site and the environmental conditions.

4.2. Fuel models and linkage to the ForeFire tool

To run the simulations, the ForeFire tool (Filippi et al., 2010; Filippi & Grandi, 2014), which includes the *Balbi* model, was used. An export of the database was generated to build the fuel models through a fuel description file matching the input format for the ForeFire tool. For each fuel type, the following parameters were extracted to obtain the corresponding fuel model: the fine fuel load (dead/live), the fuel bed height, the fuel density (dead/live), the surface-to-volume ratio (SAV, dead/live) and the heat content (dead/live). As semi-physical fire behavior models, the *Balbi* model requires global surface input fuel attributes, this is, a unique fuel attribute value by category (live and dead) and particle size class. In the database, fuel attributes are split by fuel layer and category, so linkages were necessary to build fuel models that meet the fire model requirements. Since the *Balbi* model has been developed for surface fires, it was assumed that the litter, herbaceous and low-shrub layers contributed to the fire spread, as well as, the high-shrubs layers with a base height (i.e., canopy base height) lower than 1.5 m, when the previous layers were also present contributing thus to the vertical continuity of fuel.

The fine fuel load by category (i.e., dead/live) was computed by adding the fuel load of all the layers considered weighted by the surface area. The fuel bed height, was calculated as the maximum value of the fuel layer's height weighted by the surface area within each layer. Concerning particle attributes (i.e., fuel density, SAV and heat content), they were computed as the average value for all the layers contributing to fire spread weighted by the surface area within each layer and category. The fuel moisture content and the specific heat content were taken from Santoni et al. (2011) as well as the wind speed and the model parameters. In this regard, wind was considered constant in this work, while Santoni et al. (2011) used a realistic precalculated wind taken into account the effect of the topography into the local wind.

The landscape mapping was generated by the overlaying of the *BDForêt® version 2.0 - Corsica* modified to take into account all the fuel types as previously detailed, and the Corine Land Cover (CLC) map (Ministère de la Transition écologique, 2018). CLC is a land use inventory which takes into account not only vegetation but also, the urban tissue, agricultural areas, industrial/commercial areas, roads and rail networks among others. So that, overlapping both maps allows to consider all the territory and not only the areas covered by vegetation. In this regard, there might be also differences with the maps used by Santoni et al. (2011) which considered previous versions of the CLC map.

Results

Figure 8 presents simulated fire perimeters over time coupled to the final observed area burnt. Moreover, the final perimeter of the simulations run by Santoni et al. (2011) is also included. It is important to highlight that the simulations do not take into account the firefighting actions and consequently, as expected, the final perimeter of the simulations is larger than that of the actual fire. However, the position of the fire over time can be compared to that predicted by the model since firefighting actions were only carried out at the flanks or far ahead of the fire front. According to firefighter's observations, the fire jumped over the road at 4:00 pm and reached the sea at about 4:15 pm. The simulations agree with the observations of firefighters. Moreover, there are not significant differences with the results of Santoni et al. (2011), which used a more realistic wind as already mentioned.



Surface area burnt Favonne's Fire
 Santoni et al., (2011) Simulated perimeter

Figure 8 Simulated fire perimeters over time with final surface area burnt and simulated final fire perimeter from Santoni et al. (2011).

Overall, it can be noted from both approaches that passing from a specific site parametrization to a generic does not introduce a significant error for this particular case. There is indeed a need for a systematic database of well documented wildfires to perform a more systematic evaluation of wildfire models and fuel models, but this example shows that simulation results are qualitatively comparable.

5. Discussion and Conclusions

This work, conducted under the framework of the FireCaster project, presents a fuel data set for Mediterranean basin vegetation stand types and in particular for those in Corsica, for fire/forest management, risk assessment and decision-support purposes. The building methods and the different data sources have been detailed. NFI data have been mainly used for determining fuel attributes for forest stand types. The harmonization of European NFIs (Vidal et al., 2016) generates a reliable data source available to extend and generalize the methodology presented herein to other regions or countries. Even if remote sensing products are more and more abundant at finer resolution scales, field data, as that of NFI are still necessary either to validate the methods used to generate these products or to complete them. In fact, both data sources are needed and complementary. Moreover, NFI data can be used to build 3D-spatially explicit fuel data by statistical imputation and machine learning (Riley et al., 2021). However, in this work fuel attributes have been defined to be meaningful at regional/landscape scales and are representative of stand-level characteristics. This choice was deliberate and based on the current fire model's uses, knowledge and computing capabilities by the fire/forest agencies responsible for fire risk assessment and management. Indeed, these agencies mainly use semi-physics models like those known as *Rothermel* or *Balbi* which require fuel models as input data, need reasonable computing resources and can give a rapid response (i.e., computational time lower than real time) and thus be used as decision-support tools. This choice was also guided by the need to overcome the lack of fuel data sets adapted to the Mediterranean vegetation. However, the approach presented herein is not limited to the fuel attributes necessary to build fuel models adapted to semi-physics models, and the fuel data includes a higher level of detail which can be helpful and useful for other fire modeling approaches through linkages. Ongoing work presenting the systematic statistical evaluation of the FCFDS system will be presented in a separate paper.

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References

- Allaire, F., Filippi, J.B., Mallet, V. 2020. Generation of an ensemble of wildland fire simulations. *Int. J. Wildland Fire*, 29, 160–173.
- Allaire, F., Filippi, J.B., Mallet, V., Vaysse, F. 2022. Simulation-based high-resolution fire danger mapping using deep learning. *Int. J. Wildland Fire*, 31(4), 379–394.
- Allaire, F., Mallet, V., Filippi, J.B. 2021a. Emulation of wildland fire spread using deep learning. *Neural Networks*, 141, 184–198.
- Allaire, F., Mallet, V., Filippi, J.B. 2021b. Novel method for a posteriori uncertainty quantification in wildland fire spread simulation. *Appl. Math. Model.*, 90, 527–546.
- Andrews, P.L., 2018. The Rothermel surface fire spread model and associated developments: A comprehensive explanation. Gen. Tech. Rep. RMRS-GTR-371. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 121 p.

Aragoneses, E., García, M., Salis, M., Ribeiro, L.M., Chuvieco, E. 2023. Classification and mapping of European fuels using a hierarchical-multipurpose fuel classification system. *Earth Syst. Sci. Data*, 15(3), 1287–1315.

Arroyo, L.A., Pascual, C., Manzanera, J.A. 2008. Fire models and methods to map fuel types : The role of remote sensing. *Forest Ecol. Manag.* 256, 1239–1252.

Baeza, M.J. & Santana, V.M. 2015. Biological significance of dead biomass retention trait in Mediterranean Basin species: an analysis between different successional niches and regeneration strategies as functional groups. *Plant Biology*, 17(6), 1196–1202.

Benali, A., Ervilha, A.R., Sá, A.C.L., Fernandes, P.M., Pinto, R.M.S., Trigo, R.M., Pereira, J.M.C. 2016. Deciphering the impact of uncertainty on the accuracy of large wildfire spread simulations. *Sci. Total Environ.* 569-570, pp.73–85.

Bensettiti F., Rameau J.-C. & Chevallier H. (coord.), 2001. "Habitats Manuals" Natura 2000. Knowledge and management of habitats and species of Community interest. Tome 1 - Forest habitats. MATE/MAP/MNHN. Ed. The French Documentation, Paris, 2 volumes : 339 p. et 423 p.

Braun-Blanquet J (1965) *Plant sociology; the study of plant communities*. Mc Graw-Hill, New York.

Brown, J.K., Oberheu, R.D., Johnson, C.M., 1982. Handbook for inventorying surface fuels and biomass in the Interior West. USDA For. Serv. Gen. Tech. Rep. INT-129.

Calvo, R.C., Varo Martínez, M.Á., Ruiz Gómez, F., Ariza Salamanca, A.J., Navarro-Cerrillo, R.M. 2023. Improvements of Fire Fuels Attributes Maps by Integrating Field Inventories, Low Density ALS, and Satellite Data in Complex Mediterranean Forests. *Remote Sens.* 15.

Chuvieco, E., Yebra, M., Martino, S., Thonicke, K., Gómez-Giménez, M., San-Miguel, J.; Oom, D., Velea, R., Mouillot, F., Molina, J.R., et al. 2023. Towards an Integrated Approach to Wildfire Risk Assessment: When, Where, What and How May the Landscapes Burn. *Fire*, 6, 215.

Cruz M.G., Gould J.S., Hollis J.J., McCaw W.L., 2018. A Hierarchical Classification of Wildland Fire Fuels for Australian Vegetation Types. *Fire*, 1(1), 13.

Duff, T.J., Bessell, R., Cruz, M.G. 2019. Grass Curing/Cured Fuels. In Manzello, S.L. (Eds): *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Springer, Cham. https://doi.org/10.1007/978-3-319-51727-8_238-1.

Fernandes, P.M. 2009. Combining forest structure data and fuel modelling to classify fire hazard in Portugal. *Ann. For. Sci.*, 66, 415.

Filippi, J.B., Allaire, F., Vaysse, F. 2022. Using simulation and deep learning to derive synthetic high resolution daily fire danger maps. In Viegas, D.X. & Ribeiro, L.M. (Eds): *Advances in Forest Fire Research*, Coimbra University Press. doi: 10.14195/978-989-26-2298-9_207.

Filippi, J.B., & Grandi, D. 2014. ForeFire: Open-source code for wildland fire spread models. In Viegas, D.X. (Ed): *Advances in Forest Fire Research*, Coimbra University Press. doi:10.14195/978-989-26-0884-6_29.

Filippi, J.B., Morandini, F., Balbi, J.H., Hill, D.R., 2010. Discrete event front-tracking simulation of a physical fire-spread model. *Simulation*, vol. 86, no. 10, pp. 629 – 644.

Hervé J.C., 2016. The French National Forest Inventory. In: Vidal C., Alberdi I., Hernández Mateo L., Redmond J. (eds) *National Forest Inventories*. Springer, Cham. https://doi.org/10.1007/978-3-319-44015-6_20.

Hollis J.J., Gould J.S., Cruz M.G., McCaw W.L., 2015. Framework for an Australian fuel classification to support bushfire management. *Aust. Forestry*, 78(1):1-17.

Keane R.E., 2013. Describing wildland surface fuel loading for fire management: a review of approaches, methods and systems. *Int. J. Wildland Fire*, 22, 51–62.

IGN – Inventaire forestier national français, Données brutes, Campagnes annuelles 2005 et suivantes, <https://inventaire-forestier.ign.fr/dataIFN/>. Accessed 20/06/2022.

Lafore, J.P., Stein, J., Asencio, N., Bougeault, P., Ducrocq, V., Duron, J., Fischer, C., Hérel, P., Mascart, P., Masson, V., Pinty, J.P., Redelsperger, J.L., Richard, E., Vilà-Guerau de Arellano, J. 1998. The Meso-NH Atmospheric Simulation System. Part I: adiabatic formulation and control simulations. *Ann. Geophys.*, 16(1), 90–109.

Lutes D.C., Keane R.E., Caratti J.F., 2009. A surface fuel classification for estimating fire effects. *Int. J. Wildland Fire*, 18, 802-814.

Martin-StPaul N., Pimont F., Dupuy J.L., Rigolot E., Ruffault J., Fargeon H., Cabane E., Duché Y., Savazzi R., Toutchkov M. 2018. Live fuel moisture content (LFMC) time series for multiple sites and species in the French Mediterranean area since 1996. *Ann. For. Sci.*, 75, 57.

Masson V., Le Moigne P., Martin E., Faroux S., Alias A., Alkama R., Belamari S., Barbu A., Boone A., Bouyssel F., Brousseau P., Brun E., Calvet J.C., Carrer D., Decharme B., Delire C., Donier S., Essaouini K., Gibelin A.L., Giordani H., Habets F., Jidane M., Kerdraon G., Kourzeneva E., Lafaysse M., Lafont S., Lebeaupin Brossier C., Lemsu A., Mahfouf J.F., Marguinaud P., Mokhtari M., Morin S., Pigeon G., Salgado R., Seity Y., Taillefer F., Tanguy G., Tulet P., Vincendon B., Vionnet V., and Voldoire A. 2013. The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. *Geosci. Model Dev.*, 6, 929–960.

McLauchlan KK, Higuera PE, Miesel J, et al. 2020. Fire as a fundamental ecological process: Research advances and frontiers. *J Ecol.*, 108, 2047–2069. <https://doi.org/10.1111/1365-2745.13403>

Mell WM, Maranghides A, McDermott R, Manzello SL. 2009. Numerical simulation and experiments of burning douglas fir trees. *Combust. Flame*, 156, 2023-2041.

Ministère de la Transition écologique (2018) - Dataset: CORINE Land Cover - Occupation des sols en France 2018 <https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0>. Accessed 30/5/2022.

Moritz M.A., Morais M.E., Summerell L.A., Carlson J.M., Doyle J., 2005. Wildfires, complexity, and highly optimized tolerance. *Proc. Natl. Acad. Sci.* 102(50), 17912–17917.

Ottmar R.D., Sandberg D.V., Riccardi C.L., Prichard S.J., 2007. An overview of the Fuel Characteristic Classification System – quantifying, classifying, and creating fuelbeds for resource planning. *Can. J. Forest Res.*, 37, 2383 – 2393.

Parsons R.A., Pimont, F., Wells, L., Cohn, G., Jolly, W.M., de Coligny, F., Rigolot, E., Dupuy, J.L., Mell, W., Linn, R.R. 2018. Modeling thinning effects on fire behavior with STANDFIRE. *Ann. For. Sci.*, 75, 7.

Pérez-Ramirez, Y., Filippi, J.B., Ferrat, L. 2018. FireCaster Decision Support System: On the need for a new fuel description approach. In Viegas, D.X. (Ed): *Advances in Forest Fire Research*. Chapter 7. doi: 10.14195/978-989-26-16-506_146.

Pettinari, M.L. & Chuvieco, E. 2016. Generation of a global fuel data set using the Fuel Characteristic Classification System. *Biogeosciences*, 13, 2061 – 2076.

Pimont F., Parsons R., Rigolot E., de Coligny F., Dupuy, J.L., Dreyfus, P., Linn, R.R. 2016. Modeling fuels and fire effects in 3D : Model description and applications. *Environ. Model. Softw.*, 80, 225-244.

Reeves, Matthew C.; Ryan, Kevin C.; Rollins, Matthew G.; Thompson, Thomas G. 2009. Spatial fuel data products of the LANDFIRE Project. *Int. J. Wildland Fire*, 18: 250-267.

Riley, K.L., Grenfell, I.C., Finney, M.A., Wiener, J.M. 2021. TreeMap, a tree-level model of conterminous US forests circa 2014 produced by imputation of FIA plot data. *Scientific Data*, 8, Article number: 11.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. 40 p.

Santoni, P.A., Filippi, J.B., Balbi, J.H., Bosseur, F. 2011. Wildland Fire Behaviour Case Studies and Fuel Models for Landscape-Scale Fire Modeling. *Journal of Combustion*. Article ID 613424.

Scott, JH.; Burgan, RE. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p

Sharples, J.J., McRae, R.H.D., Weber, R.O., Gill, A.M. 2009. A simple index for assessing fuel moisture content. *Environ. Modell. Softw.* 24, 637-646.

Sullivan, A.L. 2009a. Wildland surface fire spread modelling, 1990-2007. 1: Physical and quasi-physical models. *Int. J. Wildland Fire*, 18, 349-368.

Sullivan, A.L. 2009b. Wildland surface fire spread modelling, 1990-2007. 2: Empirical and quasi-empirical models. *Int. J. Wildland Fire*, 18, 369-386.

Sullivan, A.L., McCaw W.L., Cruz M.G., Matthews S., Ellis P.F. 2012. Chapter 3 - Fuel, fire weather and fire behavior in Australian ecosystems. In Bradstock R.A., Gill A.M., Williams R.J.(Eds.): *Flammable Australia* (pp. 51-77).

Thom, D. and Seidel, R., 2016. Natural disturbance impacts on ecosystems services and biodiversity in temperate and boreal forests. *Biol. Rev.* 91, 760-781.

Van Wagner, C.E. (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Headquarters, Ottawa. Forestry Technical Report 35. 35 p.

Vidal, C., Alberti, I., Redmond, J., Vestman, M., Lanz, A., Schadauer, K. 2016. The role of European National Forest Inventories for international forestry reporting. *Ann. For. Sci.*, 73, 793-806.