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A FOREST FIRE HAZARD MODEL AND MAP FOR A WILDLAND URBAN INTERFACE NOT METEOROLOGICALLY PRONE TO FOREST FIRES*

UM MODELO E MAPA DE PERIGO DE INCÊNDIO FLORESTAL PARA UMA INTERFACE URBANA-SILVESTRE NÃO METEOROLOGICAMENTE PROPENSADA A INCÊNDIOS FLORESTAIS

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ABSTRACT

Fire Hazard (FH) modelling is a relevant fire prevention/assessment tool. This work proposes a FH model and generates a FH map for a wildland urban interface area in Germany that is not prone to extreme fires. The main input data include weather, topography, fuel, and anthropic-related potential ignition points. The main steps include (1) identification/description of weather scenarios, and for each scenario (2) analysis of potential fire ignition through simulation of Fire Probability (FP), (3) modelling the potential fire behaviour through simulation of Fireline Intensity (FLI), (4) generation of a FH map by combining FP and FLI maps, and (5) integration of all maps into a final FH map. Extreme ignition and propagation conditions were considered: (1) a fuel model that describes the fire performance in an extreme drought scenario, (2) the human influence through mechanistic ignitions, and (3) the worst case of all scenarios. As results, four weather scenarios were identified and described. FP maps, FLI maps, and FH maps were created for each of them, and finally an integrated FH map (IFHM) was derived.

Keywords: Fire, hazard, modelling, ignition, propagation.

RESUMO

A modelação de Risco de Incêndio (FH) é uma ferramenta relevante para prevenção/avaliação de incêndio. Este trabalho propõe um modelo FH e gera um mapa FH para uma área de Interface Urbana-Silvestre na Alemanha que não é propensa a incêndios extremos. Os principais dados de entrada incluem condições meteorológicas, topografia, combustível e pontos de ignição potenciais relacionados a antrópicos. As etapas principais incluem (1) identificação/descrição de cenários climáticos e, para cada cenário, (2) análise de potencial de ignição de incêndio por meio de simulação de probabilidade de incêndio (FP), (3) modelação do comportamento potencial de incêndio por meio de simulação de intensidade da linha de fogo (FLI), (4) geração de um mapa FH combinando mapas FP e FLI e (5) integração de todos os mapas em um mapa FH final. Foram consideradas condições extremas de ignição e propagação: (1) um modelo de combustível que descreve o desempenho do fogo em um cenário de seca extrema, (2) a influência humana através de ignições mecânicas e (3) o pior caso de todos os cenários. Como resultados, quatro cenários climáticos foram identificados e descritos. Para cada um deles foram criados mapas FP, mapas FLI e mapas FH e, por fim, derivou-se um mapa FH Integrado.

Palavras-chave: Incêndio, perigo, modelação, ignição, propagação.

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Introduction

Forest fires have negative global impacts, such as burning forested areas, increasing soil erosion and degradation, releasing greenhouse gas emissions, decreasing biodiversity, destroying infrastructures, and even losing of human and animal lives. Forest fires' frequency and intensity are significantly increasing in the last years in some areas due to, among other factors, climate change and societal factors. The 2021 year was the second-worst wildfire season in the European Union since 2000 (European Commission, 2022).

Forest Fire Hazard (FH) modelling is a relevant fire prevention and assessment tool. Fire hazard refers to the likely frequency of occurrence of different intensity fires for several areas, as determined from historical data or scientific analysis.

The goals of this paper are to (1) propose a FH model that considers the combination of ignition sources, fuel availability, and conditions for fire ignition and spread, including the prevailing meteorological conditions, and (2) generate a FH map using that model for a Wildland Urban Interface (WUI) area that is not historically prone to extreme forest fires.

Study area

The area under study (Area Of Interest, AOI) is a 431 km^2 territory located in Arnsberg city, in Hochsauerland County, State North Rhine-Westphalia (Germany) (fig. 1). It includes a vast extension of the Arnsberger Wald Nature Park (482 km^2), representing a natural asset of great importance for the regional economy for forestry and tourism. Arnsberg city (with a population of 73,437 inhabitants in 2015, Arnsberg, N.d.) is entirely encircled by forest, implying zones of transition between wildland and human development named as Wildland Urban Interface (WUI). This area is not considered by the European Forest Fire Information System (EFFIS) as a very prone area to fires according to their meteorological data at global scale.

Material and Methods

Input data

The main input variables required in the model are (1) historical data about meteorological variables (T^a, RH, Wd, and Ws), (2) historical data about Fire Weather Index (FWI) and Drought Code (DC) provided by the European Forest Fire Information System (EFFIS), (3) road networks and buildings vector information, (4) topography data (slope, aspect, elevation), (5) land cover data (Land Use/Land Cover, LULC) and (6) the Canopy Height Model (CHM).

LULC data are required for deriving the vegetation type and the canopy coverage data. The vegetation type joined to the vegetation height (CHM) is required for obtaining the surface fuel model.

Note that to gather the local variability and trends of the main driving factors of any area, both spatially and temporally, the input data must have a detailed spatial resolution and a representative temporal resolution.

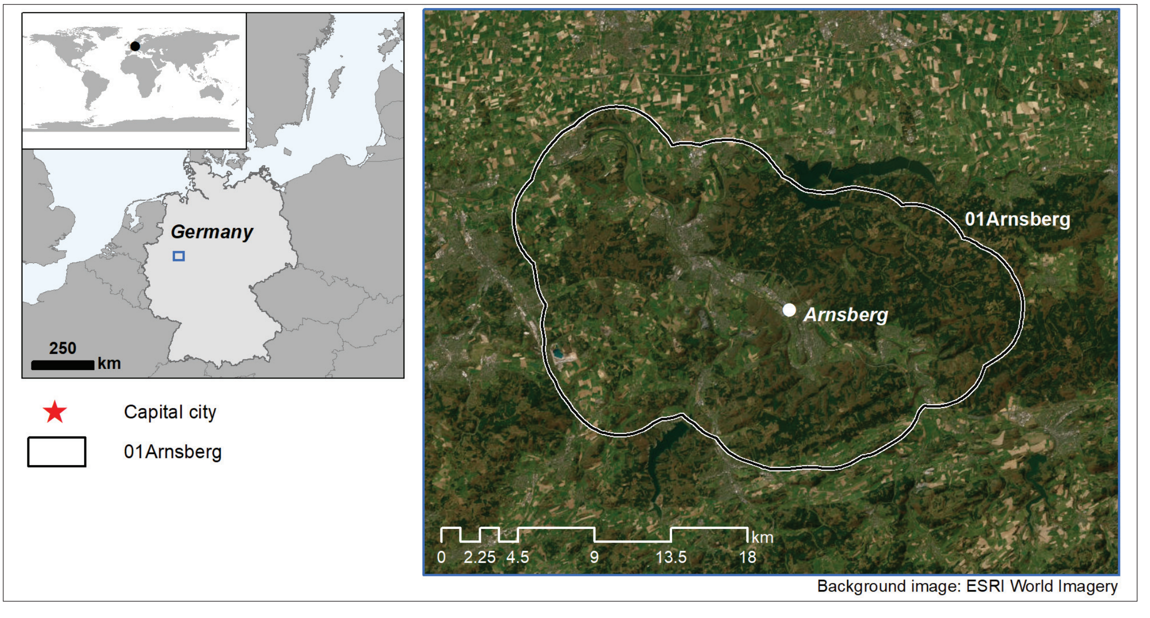

Fig. 1 - Area under study in Germany.

***Fig. 1** - Área em estudo na Alemanha.*

Preparation of input data

Given the characteristics of the proposed model, based on simulation and high computing requirements, a compromise resolution of 30m was adopted to facilitate the fine-tuning of the model in an agile way. This cell size is fine enough to discriminate the relevant driving factors of fire hazard. It is coarse sufficient to ensure a reasonable computation time and to simulate thousands of potential fire outbreaks.

Meteorological data for the 2009-2019 period were gathered from two weather stations of the German Meteorological Service (Deutscher Wetterdienst, DWD) through its Climate Data Centre (CDC) (DWD, N.d.). Daily data related to temperature (T_{max}), and relative humidity (RH) were obtained from station 7330-Arnberg-Neheim, and hourly data related to wind (Ws, Wd) were obtained from 13952 - Arnsberg-Müschede.

The historical *fire danger* (daily FWI) and *DC* indices were downloaded for the 2009-2019 period from the Climate Data Store (CDS) of Copernicus (Copernicus Climate Change Service, N.d), which implies 4363 rasters of each index. The maximum of FWI (FWImax) and DC (DCmax) of the pixels included in a tangential rectangle to the study area were calculated and recorded in an Excel file using ArcPy. Note that the Canadian FWI was adopted by EFFIS in 2007 as the method to assess the fire danger level in a harmonized way throughout Europe.

The *road network* and the *building footprints* were downloaded from OSM (OpenStreetMap contributors, 2021). Tracks and paths were excluded from the original road network dataset, keeping only high driving frequency roads.

Elevation (m), slope (%) and aspect (o) information (*topographical data*), LULC, and canopy height model (CHM) already available for the AOI were used (Copernicus Emergency Management Service, 2020). The mentioned source (Copernicus Emergency Management Service, 2020) indicated that CHM was created as the difference between Digital Surface Model (DSM) and Digital Terrain Model (DTM) (CHM=DSM-DTM) derived from LiDAR datasets available from Cologne Government Regional Office. According to the source, a 1m CHM was created and then, resampled to 5m. Finally, we resampled the data to 30m to have all input data at this spatial resolution to run the model, as mentioned before, to ensure a reasonable computation time and to simulate thousands of potential fire outbreaks. *Vegetation types* were extracted from the available LULC map. Fig. 2 shows the topographical and vegetation-related maps for the AOI. Note that the grey surface within the study area in the maps of Fig. 2D and Fig. 2E corresponds to the urban surface. This note is also valid for the rest of the maps shown in the paper having grey surface within the study area.

The *surface forest fuel model* was created by assigning a fuel type to the combination of the vegetation type and the vegetation height data. Thus, the different combinations of vegetation type and the vegetation height were reclassified into two fuel model types (Table I). This reclassification was based on the simplified catalogue of 13 standard fuel models as proposed by Anderson (1982) (see Annex 1, Table I) following Tables II and III of Annex 1. Fuel Model II (extreme) was selected to simulate the fire ignition and propagation considering the vegetation status in an extreme drought scenario. Thus, this fuel model describes the fire performance in a scenario of extreme drought.

Table I - Types of surface forest fuels models, depending on the vegetation type and height.

***Tabela I** - Tipos de modelos de combustíveis florestais de superfície dependendo do tipo de vegetação e altura.*

LULC CODE	VEGETATION TYPE	HEIGHT RANGE (m)	FUEL MODEL I ADVERSE	FUEL MODEL II EXTREME
2111 3211	Non irrigated arable lands Managed grasslands	All	1	1
		All	1	1
3111 3112 3113 3114	Riparian and fluvial broadleaved forest Broadleaved evergreen forest Other natural and semi-natural broadleaved forest Highly artificial broadleaved plantations	0.5-2	6	6
		2-4	4	4
		4-10	6	6
		>10	9	6
3123 3122 3131	Highly artificial coniferous plantations Other natural and semi-natural coniferous forest Other natural and semi-natural mixed forest	0.5-2	7	7
		2-4	4	4
		4-10	7	7
		>10	8	4
3212 3241	Semi-natural grassland with trees TDC $\geq$ 30% Transitional woodland and shrub	< 0.5	5	5
		0.5-2	7	7
		>2	4	4

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco.

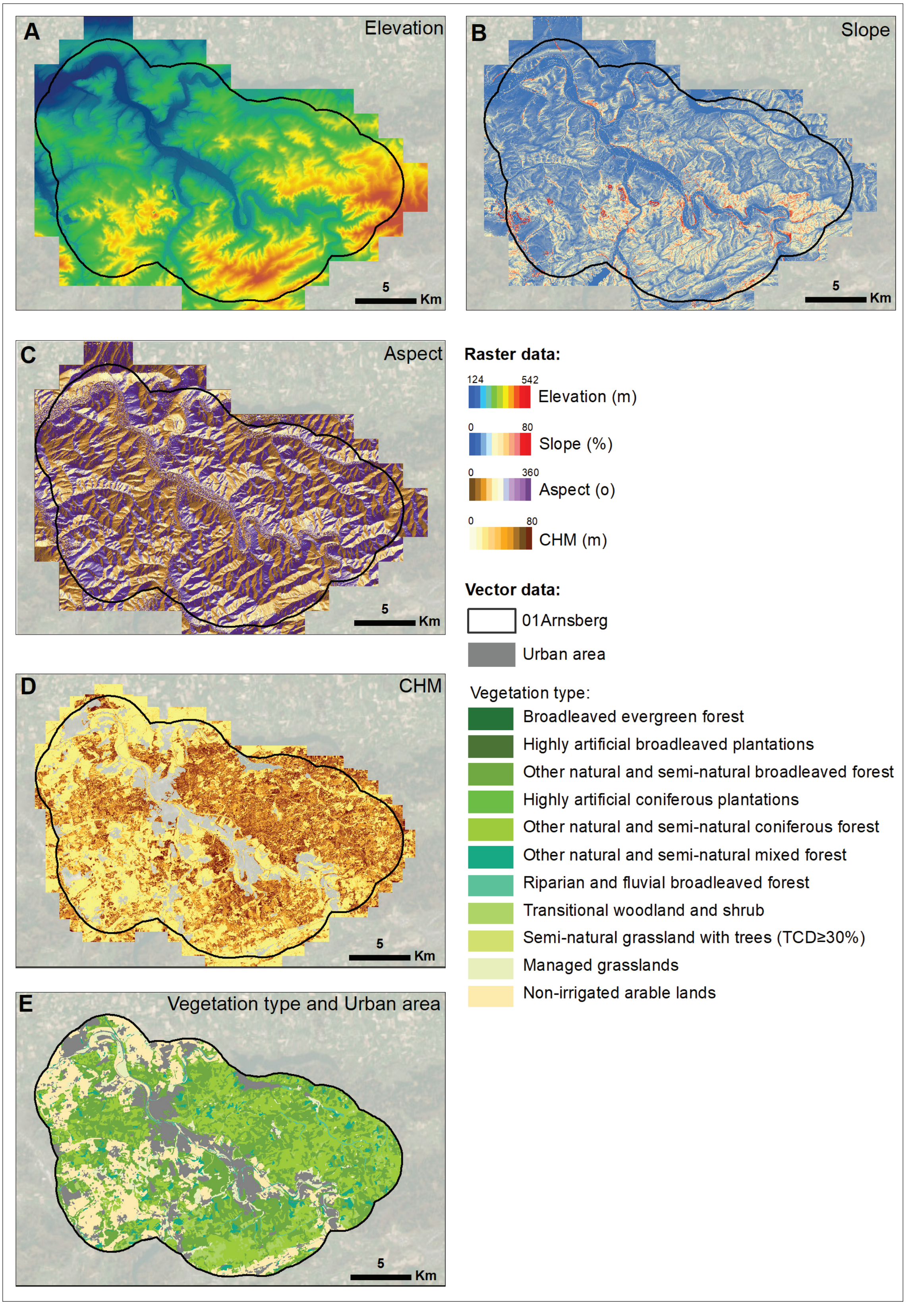

Fig. 2 - Topographical and vegetation related data for the study area:
(A) Elevation, (B) Slope, (C) Aspect, (D) Canopy Height Model (CHM), and (E) Vegetation type.

Fig. 2 *- Dados topográficos e relacionados à vegetação para a área de estudo:*
(A) Elevação, (B) Declividade, (C) Aspecto, (D) CHM e (E) Tipo de vegetação.

The Fuel Model II is an adaptation of Fuel Model I where fuel types 8 (Compact Timber Litter) and 9 (Hardwood Litter) are assigned to the highest sector of the forest, *i.e.*, assuming that the fire does not travel through the forest canopy but through the pine-needle and leaf litter of the understory of forest stands. This fuel model assumes that the pine forests behave like a highly energetic surface fuel type (Fuel type 4: Chaparral, tall flammable shrubs) in which the propagation occurs through the crowns. Making this assumption, the propagation and the intensity of fires that occur under very extreme circumstances like severe droughts can be simulated. Fig. 3A shows the map of Fuel model II for the study area.

Canopy coverage data was created to differentiate the areas of fine dead fuel exposed (<50% coverage) and covered (≥ 50%). This layer assumes as covered, vegetation areas with vegetation height higher than 4m (CHM>4m) in forest LULC (extracted from the LULC map). Fig. 3B shows the canopy cover map for the study area.

Proposed Forest Fire Hazard Model

A fire hazard model is proposed based on the results of a literature review previously performed (out of the scope of this paper), after comparing the reviewed models regarding their usefulness, applicability, robustness, simplicity, etc., and also considering the AOI's characteristics. The performed literature review showed the use of very different terms to refer to fire hazard (e.g., fire danger, fire intensity, fireline intensity, fire severity, fire behaviour, fuel property, burn probability + fire intensity, likelihood and intensity), which adds much confusion. In this paper, we have adopted the hazard terminology established by the United Nations International Strategy for Disaster Reduction (UNISDR, 2009), *"Hazard is a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. In technical settings, hazards are described quantitatively by the likely frequency of occurrence of different intensities for different areas, as determined from historical data or scientific analysis"*.

Additionally, in the performed literature review, different types of fire hazard models were analyzed, such as statistical models, multi-criteria/linear weighting evaluation models, national operational fire danger rating systems, etc. Finally, a fire hazard model incorporating scientific principles about fire behaviour and providing meaningful physical maps has been selected for a local scale fire hazard map's development, such as the required in the Arnsberg AOI. The selected model is more demanding than other models in terms of computing sources and execution time, but is worth it for its most realistic and meaningful results. The proposed model is based on models such as those of Chuvieco *et al*. (2010, 2012), Keane *et al*. (2010), Scott *et al*. (2013), Loeks *et al*. (2020), etc., and also uses

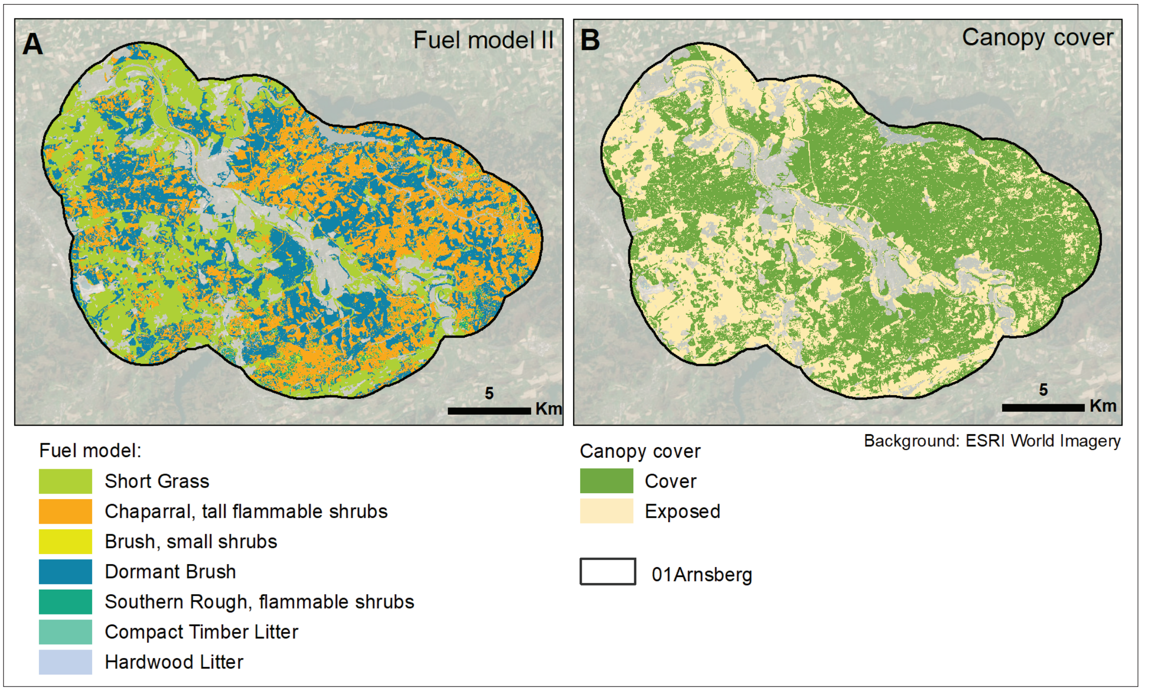

Fig. 3 - Fuel Model II (A) and canopy cover (B) for the study area.

***Fig. 3** - Modelo de combustível II (A) e cobertura do dossel (B) para a área de estudo.*

as input data information derived from the short-term meteorological models, such as those of EFFIS (N.d.) and of the Government of Canada (N.d.).

The proposed model allows generating fire hazard maps considering the fire ignition and propagation factors and using simulation techniques for different meteorological/weather scenarios. It consists of the following five main steps:

I. Identification and description of *meteorological scenarios*, based on (1) the evolution of the Fire Weather Index (FWI) over a long period, and (2) the analysis of meteorological variables such as air temperature (T^a), air relative humidity (RH), wind direction (Wd), and wind speed (Ws). Final weather scenarios (*i*) are, then, selected and characterised, particularly their fuel moisture content and meteorological data, mainly the wind patterns (Wd, Ws).

II. Analysis of potential *fire ignition* for each weather scenario through the estimation of **fire probability**, later rescaled (*rescaled conditional fire probability, RCFP*), which is the probability of fire outbreak in each point of the territory (x, y). The RCFP is obtained for each scenario, based on three probabilities that will be presented later;

III. Modelling the *potential fire behaviour* (*fire propagation*) for each weather scenario. The potential fire behaviour is described using the fireline intensity (FLI, kW/m), an objective and measurable fire hazard index. Fireline intensity is estimated by simulation;

IV. Generation of the *Fire Hazard Map* (*FHM*) for each weather scenario. Every FHM is generated by incorporating the information about (1) fire ignition, *i.e.*, the calculated RCFP data, and (2) fire propagation, *i.e.*, the calculated FLI of the advancing fire front;

V. Generation of a final *Integrated Fire Hazard Map* (*IFHM*) by the combination of the FHM from all scenarios, taking from them the highest fire hazard value in each pixel. The resulting map represents the worst case in each cell.

Steps II and III are performed with the *FlamMap* free software developed by the US Forest Service, USDA (Weinstein, and Woodbury, N.d.). The software includes a set of algorithms assembled by the US Forest Service and is free of use and worldwide applied for forest fire behaviour assessment.The general approach of the proposed method improvement is synthesised (fig. 4), and the input data and the methodological procedures are presented below.

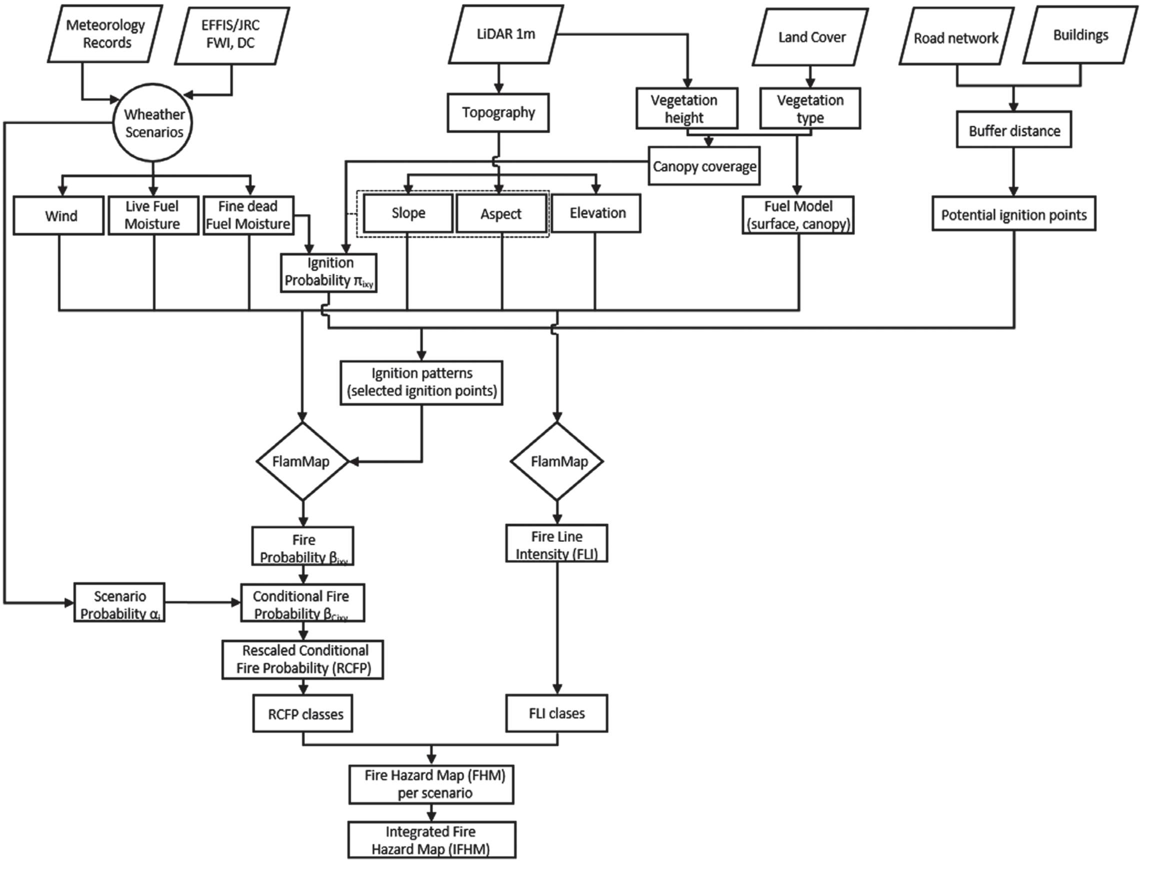

Fig. 4 - Scheme/workflow of the proposed fire hazard model.

***Fig. 4** - Esquema/fluxo de trabalho do modelo de risco de incêndio proposto.*

The five main **methodological steps** of the proposed Forest Fire Hazard Model are presented below.

I. *Identification and description of meteorological scenarios*

It includes three main tasks:

(1) *Identification of fire weather scenarios*: It tries to identify, over a long period (several years), the days presenting adverse meteorological conditions, or even the worst ones, *i.e.*, the days very prone to fire based on the spatially averaged FWI data provided by EFFIS (EFFIS. N.d.). As an example, the days within several years that present FWI ≥ 25 (high fire danger according to EFFIS) can be identified and meteorologically characterised (maximum air Tª, minimum air RH, wind direction and wind speed). In this work, the identification of extreme fire weather days was performed based on the historical daily FWI data for the period 2009-2019, considering the days having FWI ≥ 25. The frequency of each of the eight main possible wind directions (N, NE, E, SE, S, SW, W, and NW) in the identified days, as well as the wind speed ranges are summarised;

(2) *Selection of final weather scenarios*: The most frequent adverse conditions (prone to fires) are selected; *i.e.*, the adverse conditions that are the most frequently repeated within those extracted days are selected as weather scenarios; and

(3) *Description of final selected weather scenarios*: It includes (a) meteorological description (mean values of maximum Tª, average or minimum RH, wind direction and speed), (b) estimation of live fuel moisture content (LFMC) from the DC, according to bibliography (Viegas *et al.*, 2001) (Table IV of Annex 1), and (C) calculation of fine dead fuel moisture content (FDFMC); this was initially estimated from tables considering meteorological data (Tª, RH) (see Tables V, VI of Annex 1). Note that in the following step, this initial FDFMC will be spatially corrected (final FDFMC = FFDFMCxy) considering information about canopy cover, slope, aspect and bibliographic tables that relate those mentioned variables (National Wildfire Coordinating Group, N.d.) (see Tables VII, VIII, IX of Annex 1), thus providing an estimation of spatial variability.

II: *Analysis of potential fire ignition for each weather scenario through simulation of fire probability*

The proposed model considers the calculation of the conditional fire probability (ßCixy), based on three probabilities, and its ulterior rescaling (*rescaled conditional fire probability, NCFB*). The conditional fire probability refers to the likelihood of a forest fire visiting each point (x, y) in the territory for each weather scenario, also considering the probability of occurrence of each scenario (αi). It is based on: (1) the *probability of fire ignition* derived from the fuel moisture content spatially corrected, *i.e.*, from FFDFMCxy (πixy, %) (see below for more details for the spatial correction), (2) the *fire probability* related to the *human pressure* (ßixy, %), *i.e.*, the likelihood of the fire potentially visiting each point in the territory as a consequence of the human activity, and (3) the *probability of occurrence* of each *weather scenario* (αi, %). The calculation of all probabilities is presented below:

- *Calculation of Ignition Probability based on the fuel moisture content spatially corrected (πixy, %):* The ignition probability is interpreted as a measurement of the likelihood of a fire to start over dry fine fuels when a source of heat is applied, *e.g.*, a match, or more specifically, the number of positive ignitions when a source of heat is applied 100 times, or the number of fires that actually should initiate and propagate for a total number of 100 potential fires in a specific area. It is calculated for each point (x, y) of the territory and for each scenario based on the FFDFMCxy, also considering the cloud coverage and the Tª (see Tables X and XI of Annex 1 for its calculation).

  Thus, *Ignition Probability* (πixy, %) was calculated for each point (x, y) of the territory and for each scenario based on the basic fine dead fuel moisture content (BFDFMC). For each scenario, this scalar value was spatially corrected according to the aspect, slope and canopy coverage found in each point to obtain a final fine dead fuel moisture content (FFDFMCxy) that provides an estimation of its spatial variability. To this aim, a canopy cover mask that indicates the areas of exposed fine dead fine fuel (<50% coverage) and covered (≥ 50%) was used. For this, the forest LULC higher than 4m was assumed as covered vegetation. This vegetation mask, together with the aspect and the slope, was used to correct the moisture of the fine dead fuel by applying the rules set in some bibliographic tables (National Wildfire Coordinating Group, N.d.) (see Tables VII, VIII, and IX of Annex 1). The integrated correction values were added to the BFDFMC values, thus obtaining variability throughout the territory.

  Ignition probability for the worst-case conditions was obtained from FFDFMC, cloud coverage and Tª after applying the rules set in Annex 1, Tables X and XI, and after considering as the worst-case conditions, a maximum exposure to the solar radiant heat (*i.e.*, percentage of 0% of cloudiness, exposition type 1).

- *Calculation of Fire Probability based on human pressure (ßixy, %):* Its calculation considers the potential ignition derived from human activity. Most of the fires are human-related, *i.e.*, caused by negligence or arson. The calculation of fire probability is based on the simulation of multiple fires starting from previously defined ignition points. Three main sub-tasks include:

- *Identification of potential points of ignition*: The network of main roads and streets and the buildings are places prone to human activity and, consequently, considered potential sources of fire. The AOI's *road network* and the *building footprints,* already downloaded from OSM, were used after excluding tracks and paths, *i.e.*, just keeping only high driving frequency roads. A buffer of 50m around each building and road (FAO, N.d.) was considered as area of influence. In it, just the points in the territory classified as burnable, *i.e.*, with fuel model greater than 0, can be selected. A very high number (tens of thousands) of potential ignition points are located in the burnable area within the area of human influence.
- *Extraction of ignition patterns (selection of ignition points)*: For practical purposes (a compromise between significance and computational time), from the full set of potential ignition points, a random selection of significant but smaller number of representative ignition points was performed. Thus, 10,000 representative ignition points (ignition patterns) were randomly selected considering the ignition probability (πixy) in each point of the territory, selecting points with high ignition probability. Knowing the ignition probability, which indicates how many ignition attempts would there have to be at each point to obtain an effective ignition, the number of ignition attempts required to generate 10,000 ignition points can be calculated. For example, having an ignition probability of 80%, 1.25 ignition attempts would be necessary to obtain one effective ignition (1.25 = 1/0.8). Obviously, the total number of ignition attempts is greater than 10,000 (target number of ignition points), and somewhat indicates the required ignition pressure in each scenario to achieve such ignition pattern.
- *Calculation of fire probability* (βixy): The *Fire Probability* was estimated by simulation of a free-spreading fire (no suppression efforts) for each of the 10,000 selected ignition points using the Minimum Travel Time (MTT) module included in FlamMap. This module limits the number of fires that could reasonably be simulated. It searches for the fastest path of fire spread along straight-line transects connected by the cell corners (nodes). The time for simulating the fire spread was set in 180 minutes. The main input data used for the simulation include (1) fuel model, (2) topography data (slope, aspect, elevation), (3) wind data, (4) fuel moisture content, and (5) the ignition points. This process accounts the number of times the fire reaches each point in the territory and divides the result by the number of ignitions, and the result is interpreted as the fire probability, also named "burn probability".
- *Calculation of probability of occurrence of each weather scenario (scenario probability, ai, %):* It was obtained as the percentage of the number of days corresponding to each selected scenario with respect to the total number of the most adverse days (*i.e.*, total number of days with FWI ≥ 25).
- *Calculation of the conditional fire probability (βCixy, %) and its rescaling:* Considering that each weather scenario has an associated fire probability value, the conditional fire probability was obtained (βCixy) by multiplying, for each point, the fire probability value (βixy) by the probability associated to the corresponding weather scenario (βCixy = βixy * αi). The result was, then, rescaled (multiplied) by the number of ignitions, to have larger quantities and, thus, facilitate classification, obtaining a *rescaled conditional fire probability map* (RCFP). Subsequently, the RCFP values were reclassified into five classes according to the maximum RCFP value observed.

III. *Modelling the potential fire behaviour for each weather scenario through estimation of fireline intensity*

This process simulates the potential fire behaviour (fire propagation) over the landscape through the estimation of a meaningful fire behaviour component, the fireline intensity, using FlamMap. The fireline intensity (kW/m) is a measure of the energy released by an advancing fire front (Loeks *et al.*, 2020) and it encompasses the rate of spread and the heat release rate of the advancing fire front.

Considering (1) the fuel model data, (2) the topography data (slope, aspect, elevation), (3) the wind data (speed, direction), and (4) the fuel moisture content, the fireline intensity was simulated per each weather scenario. Thus, a set of fireline intensity (FLI) maps was obtained. Each FLI map is an indicator of potential fire behaviour for each weather scenario.

The fireline intensity maps were then classified into five classes according to the implications for wildfire suppression extracted from (Loeks *et al.*, 2020). Higher fireline intensity classes represent greater problems for fire controlling and suppression, *i.e.*, more uncontrollable fires, higher fire hazard.

IV. *Generation of a Fire Hazard Map for each weather scenario*

A Fire Hazard Map (FHM) was generated for each scenario, combining the above derived classified fireline intensity map (indicator of fire behaviour/fire propagation) with the calculated likelihood of fire occurrence in each point over the territory, represented by the classified rescaled conditional fire probability map (indicator of fire ignition). Five fire hazard classes (values 1 to 5) are proposed to be established based on the combination of the RCFP and FLI classes.

Each point in the territory (raster cell, pixel), for each scenario *i*, has an associated likelihood of fire occurrence (RCFP class) and a FLI class. The combination of both values results in a fire hazard class (values 1 to 5). Low FLI classes combined with a low probability of occurrence represent a low fire hazard, whereas high FLI classes combined with a high probability of occurrence lead to a high fire hazard. Values 1 to 5 correspond, respectively, to Very low, Low, Medium, High and Very high fire hazard.

V. *Generation of the Integrated Fire Hazard Map (IFHM)*

This map was created by combining all the individual FH maps created for each weather scenario. The Integrated Fire Hazard map (IFHM) was generated by selecting, for each pixel, the highest fire hazard category observed in the previously created FH maps (for all weather scenarios). The resulting map will represent the worst case in each cell, regardless of the likelihood of occurrence of the scenarios. Again, values 1 to 5 correspond, respectively, to Very low, Low, Medium, High and Very high fire hazard. In order to present the IFHM with a continuous legend, an interpolation can be made.

Results

Below, the results of the application of the proposed forest Fire Hazard model to the study area are presented.

I. *Identification and description of meteorological scenarios*

The identification of extreme fire weather days (days having FWI ≥ 25), based on the historical daily FWI data for the period 2009-2019, resulted in 36 days. Those 36 days were initially extracted, 8 of them did not have valid weather data; therefore, finally, the remaining 28 days were considered for the study (fig. 5). For those days, an averaged value of the daily maximum temperature, daily average air relative humidity and the average wind direction and speed were obtained from the DWD meteorological centre. The frequency of the eight main wind directions (N, NE, E, SE, S, SW, W, NW) was calculated according to the average daily wind direction. The most frequent adverse conditions correspond to the days when winds are blowing from SW (8 days) and W (7 days), followed by winds from SE (4 days) and S (2 days), overall in July (13 days) and August (8 days) with wind speed about 5m/s, except for the S scenario where has almost 3m/s. Consequently, 4 weather scenarios (SE, S, SW and W cases) were selected. The DC values corresponding to those days were also considered.

The selected weather scenarios were characterized in terms of fuel moisture content and weather parameters, see Table II. The Basic Fine Dead Fuel Moisture Content

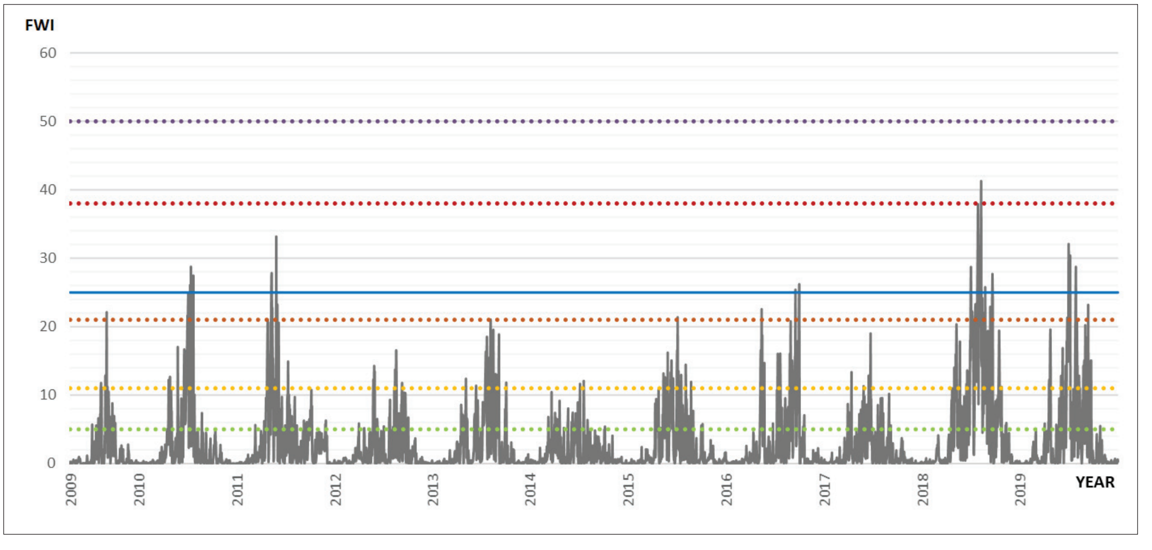

Fig. 5 - Daily fire weather index (FWI) trend calculated in the study area for the period 2009-2019. Dotted lines represent the FWI threshold set by EFFIs (EFFIs, N.d.) to categorise the fire danger as Extreme (purple), Very High (red), High (orange), Moderate (yellow), and Low (green). The blue line indicates the FWI threshold used to select the extreme local fire weather days, FWI≥25.

Fig. 5 - *Evolução do FWI diário calculado na área de estudo para o período 2009-2019. As linhas pontilhadas representam o limite FWI definido pelo EFFIS (EFFIS, N.d.) para categorizar o perigo de incêndio como Extremo (roxo), Muito Alto (vermelho), Alto (laranja), Moderado (amarelo) e Baixo (verde). A linha azul indica o limite de FWI usado para selecionar os dias de clima de incêndio local extremo, FWI≥25.*

(BFDFMC, %) was estimated for each weather scenario from the average Tmax and HR (as indicated in Tables V, VI of Annex 1). Average Live Fuel Moisture Content (LFMC, %) was estimated from the average DC observed in each of the identified fire weather scenarios, taking as reference the experience and measurements in some publications (Viegas *et al.*, 2001) (see Table IV of Annex 1).

Table II - Characterisation of the selected weather scenarios in terms of the weather parameters and the fuel moisture content.

Tabela II - Caracterização dos cenários climáticos selecionados em termos de parâmetros climáticos e teor de umidade do combustível.

Selected scenarios (Wind dir.)	Ws m/s	Wd °	Tmax°	RH %	BFDFMC %	LFMC %
SE	4.5	136	29.3	52	7	140
S	2.7	182	33.3	68	8	105
SW	5.0	220	30.8	60	8	113
W	5.2	268	29.3	62	8	116

II. Analysis of potential fire ignition for each weather scenario through simulation of fire probability

Ignition Probability based on the fuel moisture content (πixy, %)

The Ignition Probability is strongly related to the fine dead fuel moisture content. Thus, *Ignition Probability* (πixy, %) was calculated for each point (x, y) of the territory and each scenario based on the basic fine dead fuel moisture content (BFDFMC) shown in Table II. For each scenario, this scalar value was spatially corrected according to the aspect, slope and canopy coverage found in each point to obtain a final fine dead fuel moisture content (FFDFMCxy) that provides an estimation of its spatial variability. The integrated correction values were added to the BFDFMC values, thus obtaining variability throughout the territory. Given that scenarios S, SW, and W show the same BFDFMC values, only two FFDFMCxy were computed, one for those scenarios and one for the SE scenario. Fig. 6A shows, as an example, FFDFMCxy data for SE scenario. Ignition probability for the worst-case conditions was obtained from FFDFMC, cloud coverage and T^{a} after considering a maximum exposure to the solar radiant heat (*i.e.*, percentage of 0% of cloudiness, exposition type 1). As an example, Fig. 6B shows the Ignition Probability (πixy) for the scenario SE.

Fire Probability based on human pressure (βixy, %):

Previously to the calculation of Fire Probability for each scenario, 10,000 representative *ignition points* were randomly selected in the burnable area within the area of human influence. Fig. 6B shows the representative ignition points selected for the SE scenario.

Fire Probability based on human pressure (βixy) was calculated based on the simulation of multiple fires starting from the previously defined 10,000 ignition points in the area of human influence. The simulation was performed for each scenario using as input data the slope, aspect, elevation, fuel model II, wind speed,

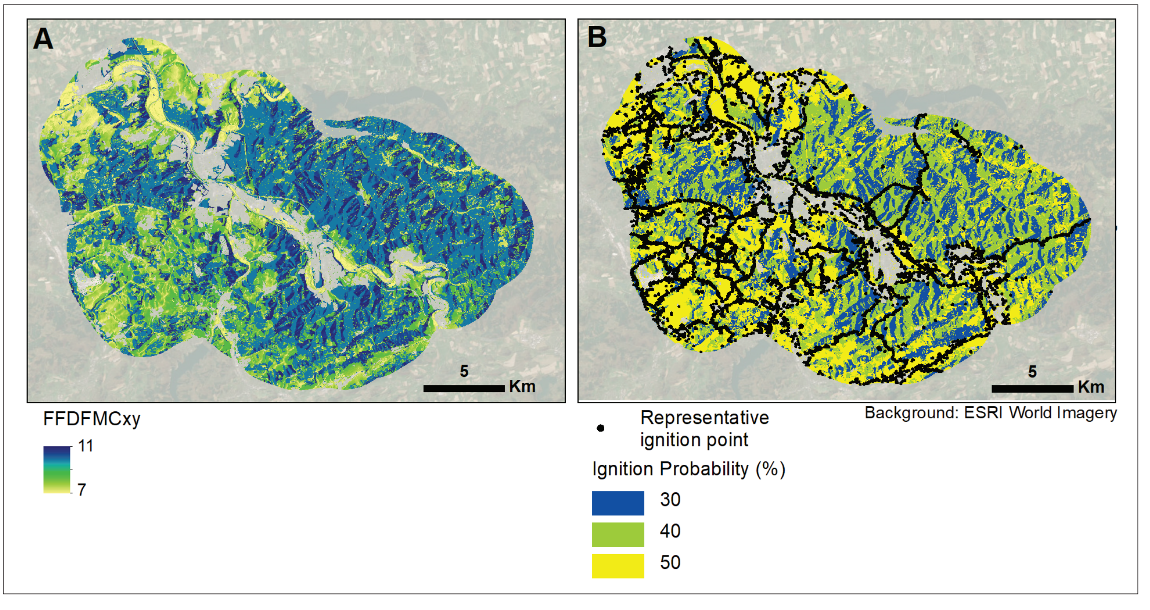

Fig. 6 - FFDFMCxy map for scenario SE (wind direction) (A) and Ignition Probability (πixy, %) map and representative ignition points for SE scenario (B).

***Fig. 6** - Mapa FFDFMCxy para o cenário SE (A) e mapa de probabilidade de ignição (πixy, %) e pontos de ignição representativos para o cenário SE (B).*

wind direction, fuel mositure content and the ignition patterns/ignition points. Fig. 7 shows the fire probability maps obtained for the four scenarios.

Probability of occurrence of each weather scenario (scenario probability, ai, %)

The *Scenario Probability* (αi), derived as the percentage of the number of days corresponding to each selected scenario with respect to the total number of the most adverse days (total number of days with FWI ≥25), had values of 0.14, 0.07, 0.28, and 0.25 for the SE, S, SW and W scenarios, respectively.

Conditional fire probability (ßCixy, %)

The *Conditional Fire Probability* (ßCixy), obtained by multiplying, for each point, the fire probability value (ßixy) by the probability associated with the corresponding weather scenario (αi), was then, rescaled it by multiplying it by the number of ignitions, to have larger quantities and facilitate classification. The final result is the *rescaled conditional fire probability map* (RCFP). Subsequently, the RCFP values were reclassified into five classes (Table III). Fig. 8 shows the classified rescaled conditional fire probability (RCFP) maps obtained for the four scenarios.

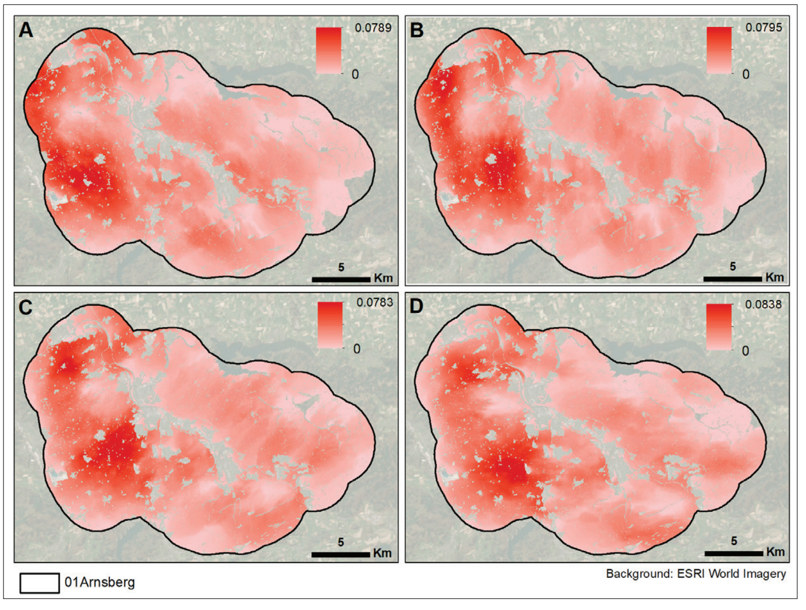

Fig. 7 - Fire Probability (ßixy) estimated for the scenario (A) SE, (B) S, (C) SW, and (D) W. Fire Probability theoretically ranges from 0 to 1.

Fig. 7 *- Probabilidade de Incêndio (ßixy) estimada para o cenário (A) SE, (B) S, (C) SW e (D) W. A probabilidade de incêndio teoricamente varia de 0 a 1.*

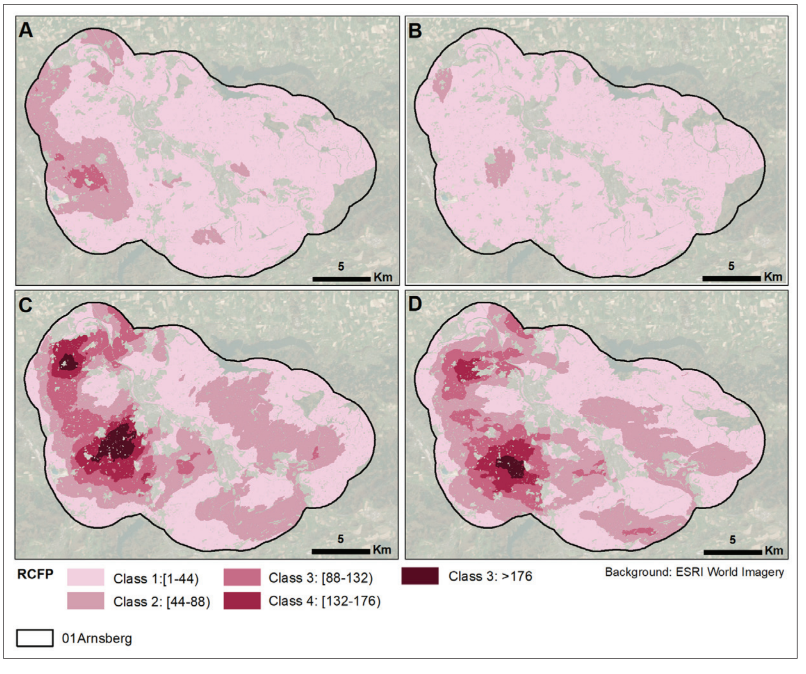

Fig. 8 - Classified Rescaled Conditional Fire Probability (RCFP) for the scenario (A) SE, (B) S, (C) SW, and (D) W.

Fig. 8 *- Probabilidade de incêndio condicional redimensionada classificada (RCFP) para o cenário (A) SE, (B) S, (C) SW e (D) W.*

Table III - Rescaled Conditional Fire Probability (RCFP) classes.

Tabela III - Classes de probabilidade de incêndio condicional redimensionadas (RCFP).

ID class	Name class	RCFP
1	Low	1-44
2	Average	44-88
3	High	88-132
4	Very high	132-176
5	Extreme	176-220

III. Modelling the potential fire behaviour for each weather scenario through estimation of fireline intensity

Fireline intensity (FLI) maps represent the potential fire behaviour (fire propagation) over the landscape. FLI maps were obtained for the four scenarios, through simulation in FlamMap, using the following input data: slope, aspect, elevation, fuel model II, wind speed, wind direction, and fuel moisture content. The obtained values were classified into five classes according to the implications for wildfire suppression (Table IV). As an example, FLI values > 2,000 kW/m entail that the fire control is very difficult. Fig. 9 presents the four FLI maps for the four scenarios, showing the FLI values already classified into the five classes. These FLI maps (fig. 9) are useful *per se*, as they provide a measure for evaluating fire suppression effectiveness (Loeks *et al.*, 2020). The greater the class, the greater the problems for controlling and suppressing the fire.

Fig. 9 shows the classified Fireline Intensity (FLI) maps obtained for the SE, S, SW, and W scenarios.

IV. Generation of a Fire Hazard Map (FHM) for each weather scenario

Fire hazard maps were obtained as the result of combining propagation and ignition information. Five fire hazard classes (values 1 to 5) were proposed based on the combination of the RCFP classes and FLI classes, following Table V. FH values 1 to 5 correspond, respectively, to Very low, Low, Medium, High and Very high fire hazard. Low FLI classes combined with a low probability of occurrence represent a low fire hazard, whereas high FLI classes combined with a high probability of occurrence lead to a high fire hazard.

For each scenario, the reclassified RCPF maps (fig. 8) and FLI maps (fig. 9) were combined using the categorization presented in Table V to generate the corresponding FHMs, see Fig. 10. These maps synthesize both fire ignition and propagation factors into a single fire hazard index. The highest fire hazard values were found in the SW and

Table IV - Fireline intensity (FLI) data classified according to the implications for wildfire suppression.

Tabela IV - Dados de intensidade da linha de fogo (FLI) classificados de acordo com as implicações para a supressão de incêndios florestais.

FLI class	Intensity (kW/m)	Description
1	<10	Mop-up or complete extinguishment of fires that are already burning may still be required provided there is sufficient fuel and it is dry enough to support smouldering combustion.
	10-500	Fire activity is limited to creeping of gentle surface burning with maximum flame heights of less than 1.3m. Control of these fires is fairly easy but can become troublesome as adverse fire impacts can still result, and fires become costly to suppress if not attended to immediately. Direct manual attack around the entire fire perimeter by fire fighters with only hand tools and water from back-pack pumps is possible; a “light” helicopter(s) with bucket is also very effective. Fireguard constructed with hand tools should hold.
2	500-2,000	Both moderately and highly vigorous surface fires with flames up to just over 1.5m high or intermittent crowning (i.e. torching) can occur. As a result, fires can be moderately difficult to control. Hand-constructed fire guards are likely to be challenged and the opportunity to “hotspot” the perimeter gradually diminishes. Water under pressure (e.g., fire bulldozers, “intermediate” helicopter with bucket) are generally required for effective action at the fire’s head.
3	2,000-4,000	Burning conditions have become critical as intermittent crowning and short-range spotting is commonplace and as a result control is very difficult. Direct attack on the head of the fire by ground forces is feasible for only the first few minutes after ignition has occurred. Otherwise, any attempt to attack the fire’s head should be limited to “medium” or “heavy” helicopters with buckets or fixed-wing aircraft, preferably dropping long-term chemical fire retardants; control efforts may fail. Until the fire weather severity abates, resulting in the subsidence of a fire run, the uncertainty of successful control exists.
4	4,000-10,000	Intermittent crown fires are prevalent and continuous crowning is also possible as well in the lower end of the spectrum. Control is extremely difficult and all efforts at direct control are likely to fail. Direct attack is rarely possible given the fire’s probable ferocity except immediately after ignition and should only be attempted with the utmost caution. Otherwise, any suppression action must be restricted to the flanks and back of the fire.
5	>10,000	The situation is considered as explosive or super critical in the upper portion of the class. The characteristics commonly associated with extreme fire behaviour (e.g., rapid 10 spread rates, continuous crown fire development, medium to long-range spotting, fire whirls, massive convection columns, great walls of flame) is a certainty. Fires present serious control problems as they are virtually impossible to contain until burning ameliorate. Direct attack is rarely possible given the fire’s probable ferocity except immediately after ignition and should only be attempted with the utmost caution; and escaped fire should in most cases, be considered a very real possibility. The only effective and safe control action that can be taken until the fire run expires is at the back and up along the flanks.

Source/*Fonte*: Loeks *et al.*, 2020.

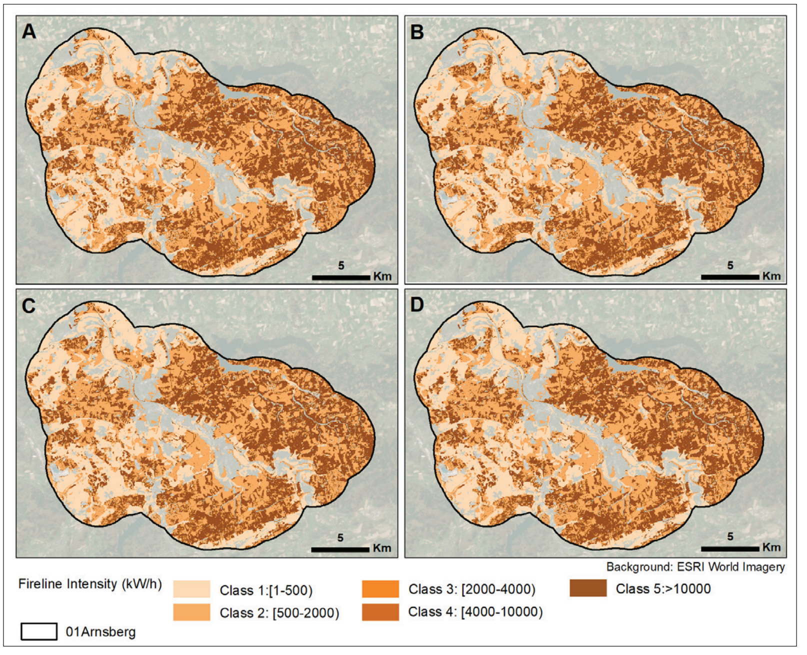

Fig. 9 - Classified Fireline Intensity (FLI, KW/h) maps for the scenarios (A) SE, (B) S, (C) SW, and (D) W.

Fig. 9 *- Mapas de intensidade de linha de fogo classificados (FLI, KW/h) para os cenários (A) SE, (B) S, (C) SW e (D) W.*

Table V - Fire hazard classes based on the combination of classified RCFP and classified FLI.

Tabela V *- Classes de risco de incêndio com base na combinação de RCFP classificado e FLI classificado.*

FLI classes	RCFP Classes				
	1	2	3	4	5
1	1	1	1	2	3
2	1	2	2	3	3
3	2	3	3	4	4
4	3	3	4	5	5
5	3	4	4	5	5

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco

W scenarios (fig. 10C and D). A combination between wind characteristics, topography and fuel types could explain the different fire hazard values in the scenarios, considering also that the fire develops in the direction of the wind. The worst case is in the SW scenario (SW-NE wind direction). In this case, the SW-NE valleys in the south of the study area (fig. 3C), seem to be channelling the SW-NE winds, accelerating them, and making them more dangerous.

The interpretation of the FHMs will be more complete if they are analysed jointly with FLI and RCFP maps. Pink and blue frames highlight areas with low and high fire hazard values, respectively. The blue framed area is characterized by being assigned a fuel type 4 (Chaparral, tall flammable shrubs), which produces, as observed in the FLI map (fig. 9C), very energetic fires. It is an area of high human activity and, therefore, a high density of ignition points is observed. The high density of ignition points was translated into a low fire probability (Class 2, fig. 7). This seems to indicate that, although the number of started fires in the simulations is high, the number of times that the fire reaches each point of the territory is low, which would imply that the developed fires are not very extensible. It can be interpreted that it is an area of high human activity where very energetic, not very extensible fires could be developed.

The pink framed area is characterized by a fuel type 1 (short grass) that produces low energetic fires. It is an area of high human activity and, therefore, with a high density of ignition points. The probability of fire is high (Class 5, fig. 7), indicating that the number of times that the fire could reach each point of the territory is high, and it would indicate that it could be developed extensive fires. Thus, it could be interpreted that it is an area of high human activity where low energetic but extensible fires could be developed.

V. *Generation of the Integrated Fire Hazard map (IFHM)*

The previously created fire hazard maps for the four scenarios were combined into an Integrated Fire Hazard Map (IFHM) (fig. 11), by selecting, for each pixel, the highest fire hazard category observed in the four maps (worst case of all scenarios). The final IFHM shows relatively large areas with medium and high fire hazard values. This final fire hazard map is of interest to the users (firefighters, local administrations, etc.) for planning forest fire prevention.

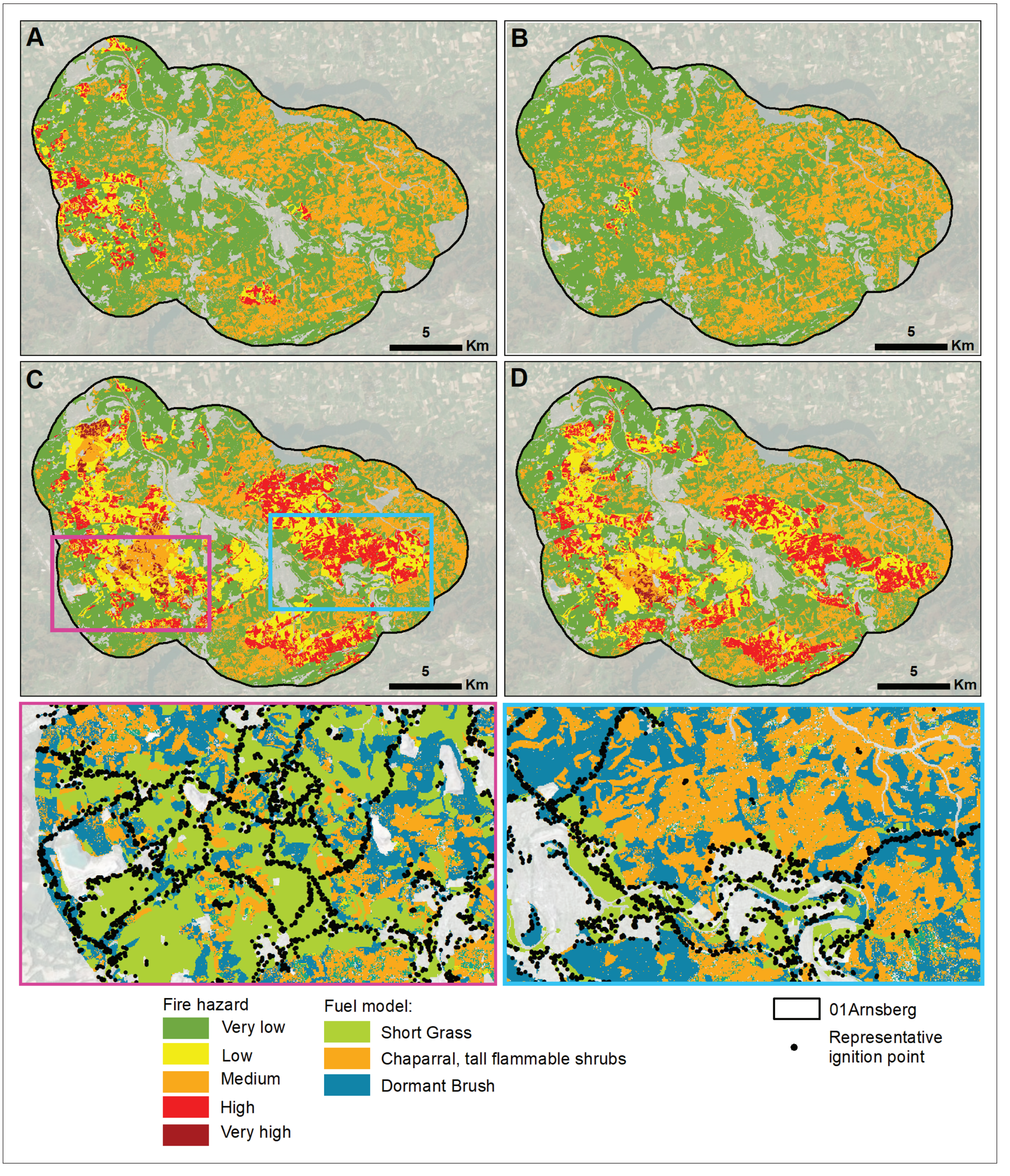

Fig. 10 - Fire hazard maps obtained for the scenarios (A) SE, (B) S, (C) SW, and (D) W. Pink and blue frames present the areas for which detailed information about their fuel model II and ignition points are shown below.

***Fig. 10** - Mapas de risco de incêndio obtidos para os cenários (A) SE, (B) S, (C) SW e (D) W. Os quadros rosa e azul apresentam as áreas onde abaixo informações detalhadas sobre seu modelo de combustível II e pontos de ignição são mostrados.*

Conclusions

A fire hazard model has been proposed that consists of (1) identifying and describing meteorological scenarios, (2) analyzing the potential ignition, for each scenario, by simulating the fire probability, (3) modelling the potential spread of the fire, for each scenario, by simulating the fireline intensity, (4) creating a fire hazard map for each scenario considering the fire probability and the fireline intensity, and (5) creating a final integrated fire hazard map by combining the fire hazard maps for all scenarios.

This model has been applied to a wildland urban interface area that is not historically prone to large

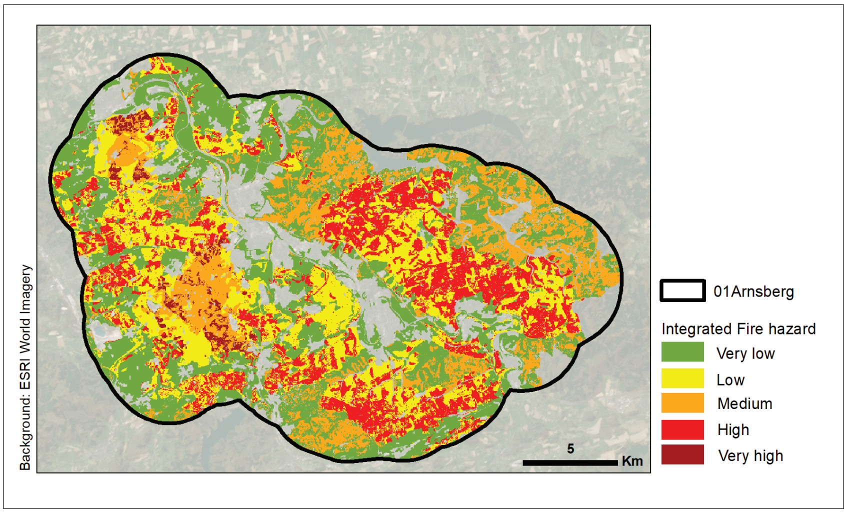

Fig. 11 - Final Integrated Fire Hazard map (IFHM).

***Fig. 11** - Mapa Final Integrado de Risco de Incêndio (IFHM).*

wildfires. Knowing the area is not very prone to forest fires, extreme ignition and propagation conditions (the worst conditions) were considered to identify, for the worst conditions, which would be the areas with the highest fire hazard values. Thus, to generate the final map, it was considered: (1) a fuel model that describes the fire performance in a scenario of extreme drought, (2) the possible human influence on the ignition of the fire, and (3) the worst case of all scenarios.

The final fire hazard map created shows relatively large areas with medium and high fire hazard values.

In addition to the final fire hazard map, the fireline intensity and fire probability maps provide additional useful information on fire behaviour that may be of interest to users (firefighters, local administrations, etc.) when developing fire prevention plans, etc.

Acknowledgement

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Annex 1

This annex presents the generation of relevant data to be used in the proposed fire hazard model, such as the extraction of surface forest fuels (section 1.1.), estimation of live and dead fuel moisture content (sections 1.2 and 1.3, respectively), and estimation of ignition probability (section 1.4).

1.1 Definition of Surface Forest Fuels

Fuel models are parameterised idealisations of certain vegetation structures that render specific fire behaviour under wind and topography combinations. Including vegetation structure adds much more variability over the landscape than just obtaining general estimations of fuel loads from vegetation types.

The generation of the surface forest fuel models requires the following actions: (1) Extraction of the vegetation types. The use of local/detailed data with 1m resolution is encouraged, but CORINE Land Cover could be used in case of inexistence; (2) Extraction of the vegetation height. It can be derived from the difference between the Digital Surface Model (DSM) and the Digital Terrain Model (DTM). The use of a resolution of 1m is encouraged to avoid errors due to the misinterpretation of relative heights. Once obtained, a reclassification of 5m resolution using averaged values can be performed; and (3) Association of fuel models to each pair vegetation type-vegetation height. According to the vegetation type and the calculated vegetation height, a reclassification into fuel model types must be done. It is suggested to use, as a first stage, the simplified catalogue of 13 fuel models as proposed by Anderson (1982) (Table I of Annex 1).

Table I - Simplified catalogue of 13 fuel models as proposed by Anderson (1982).

Tabela I - *Catálogo simplificado de 13 modelos de combustível propostos por Anderson (1982).*

Nº	Description
1	Short Grass
2	Timber Grass and Understory
3	Tall Grass
4	Chaparral, tall flammable shrubs
5	Brush, small shrubs
6	Dormant Brush
7	Southern Rough, flammable shrubs
8	Compact Timber Litter
9	Hardwood Litter
10	Timber Understory
11	Light Slash
12	Medium Slash
13	Heavy Slash

Source/*Fonte*: Anderson, 1982.

The standard parameters describing these models are used in the computer programs (*e.g.*, Flammap) for the estimation of fire behaviour. They also serve a proper association to the existing local fuel structures. The vegetation height is classified following the intervals shown in Table II of Annex 1.

Table II - Vegetation height classes.

Tabela II *- Classes de altura de vegetação.*

Height Class	Height Range (m)
1	0-0.5
2	0.5-2
3	2-4
4	4-10
5	10-20
6	>20

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco.

Two vegetation-fuel model associations are suggested in Table III of Annex 1. The first one (Fuel Model I) classifies the vegetation in the understory of forest stands and the second one (Fuel Model II) interprets the forest stands as surface forest fuels.

Table III - Fuel models derived from the combination of vegetation type and vegetation height: (I) Fuel Model for adverse conditions and (II) Fuel Model for extreme conditions.

Tabela III *- Modelos de combustível derivados da combinação do tipo de vegetação e altura da vegetação: (I) Modelo de combustível para condições adversas e (II) Modelo de combustível para condições extremas.*

Vegetation type	Vegetation height (m)	Fuel Model (I) Adverse	Fuel Model (II) Extreme
Urban	-	0	0
Grasslands	-	1 (considered all cured)	1 (considered all cured)
Scrub transitional forest	<0.5	5	5
	0.5-2	7	7
	>2	4	4
Broadleaved forests	0.5-2	6	6
	2-4	4	4
	4-10	6	6
	>10	9 (litter), 10 (slash)	6
Conifer forest	0.5-2	7	7
	2-4	4	4
	4-10	7 (understory)	7
	>10	8 (litter), 10 (slash)	4

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco.

1.2 Estimation of average Live Fuel Moisture Content

Real live fuel moisture content (from field surveys) is related to some meteorologically-based indices, such as the Drought Code (DC). Table IV of Annex 1 presents some indicative LFMC values derived from the DC, taking as reference the experience and measurements in existing publications, such as Viegas *et al*. (2021). For mixed conifer-broadleaved forests, an average value was considered.

Table IV - Live Fuel Moisture Content (LFMC, %) values derived from DC (drought code) for (1) broadleaves (B) and (2) coniferous (C) taking as reference the experience and measurements in existing publications.

***Tabela IV** - Live Fuel Moisture Content (LFMC, %) valores derivados de DC para (1) folhas largas e (2) coniferas tomando como referência a experiência e medições em publicações existentes.*

Broadleaved (B)		Coniferous (C)	
DC	LFMC (%)	DC	LFMC (%)
0-50	210	0-50	180
50-70	180	50-100	150
70-100	130	100-200	120
100-200	110	200-300	110
200-300	100	>300	100
>300	90		

Source/Fonte: Viegas *et al*., 2001.

1.3 Estimation of Fine Dead Fuel Moisture Content

The Basic Fine Dead Fuel Moisture Content (BFDFMC) is initially estimated based upon meteorological data, using the dry bulb thermometer temperature and the relative air humidity. BFDFMC represents the amount of water expressed in percentage with respect to the oven dry weight of the same fuel component, and it is closely related to the micro-conditions of air surrounding the vegetation. The estimation must be adapted to the reality of the local response of the vegetation structures to the weather conditions. When no field measurements are available, BFDFMC can be calculated using the data shown in Table V (for daytime hours) and Table VI (for late evening and night), both of Annex 1.

The obtained initial value (BFDFMC) should be corrected depending on other factors such as exposition, slope and aspect of the terrain where the fuel is located to obtain the Final Fine Dead Fuel Moisture Content (FFDFMC). Table VII to Table IX of Annex 1 (National Fire Danger

Table V - Estimation of basic fine dead fuel moisture content (BFDFMC) (%) based on meteorological data for daytime hours (08:00 to 20:00).

***Tabela V** - Estimativa de BFDFMC (%) com base em dados meteorológicos para o horário diurno (08:00 às 20:00).*

Air Relative Humidity (%)	BASIC FINE DEAD FUEL MOISTURE CONTENT (BFDFMC, %) (08:00 to 20:00)					
	Dry Thermometer Temperature °C					
	<0	0-9	10-20	21-31	32-42	>42
0-4	1	1	1	1	1	1
5-9	2	2	2	1	1	1
10-14	2	2	2	2	2	2
15-19	3	3	3	2	2	2
20-24	4	4	4	3	3	3
25-29	5	5	5	4	4	4
30-34	5	5	5	5	4	4
35-39	6	6	6	5	5	5
40-44	7	7	6	6	6	6
45-49	8	7	7	7	7	7
50-54	8	7	7	7	7	7
55-59	8	8	8	8	8	8
60-64	9	9	8	8	8	8
65-69	9	9	8	8	8	8
70-74	10	10	9	9	9	9
75-79	11	10	10	10	10	10
80-84	12	11	11	10	10	10
85-89	12	12	12	11	11	11
90-94	13	13	12	12	12	12
95-99	13	13	12	12	12	12
100	14	13	13	13	13	12

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco.

Table VI - Estimation of basic fine dead fuel moisture content BFDFMC (%) based on meteorological data for late evening and night (20:00 to 08:00).

Tabela VI - Estimativa de BFDFMC (%) com base em dados meteorológicos para final de tarde e noite (20:00 às 08:00).

Air Relative Humidity (%)	BASIC FINE DEAD FUEL MOISTURE CONTENT (20:00 to 08:00)					
	Dry Thermometer Temperature ˚C					
		0-9	10-20	21-31	32-42	>42
0-4		1	1	1	1	1
5-9		2	2	2	2	2
10-14		3	3	3	3	3
15-19		4	4	4	3	3
20-24		5	5	4	4	4
25-29		6	6	5	5	5
30-34		7	6	6	6	6
35-39		8	8	7	7	6
40-44		9	8	8	8	9
45-49		9	9	9	9	9
50-54		11	10	10	9	9
55-59		11	11	10	10	9
60-64		12	11	11	10	10
65-69		13	12	12	11	11
70-74		14	14	13	13	12
75-79		16	16	15	14	14
80-84		18	17	17	16	16
85-89		21	20	20	19	19
90-94		24	23	23	22	21
95-99		25	25	25	25	24
100		25	25	25	25	25

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco.

Rating System, NFRDS N.d.) present the corrections of fine dead fuel moisture content based on the time of the day and the month of the study, and the shading factor, the slope, and the aspect of the terrain where the fuel is located. In case of the worst scenario, the correction factor is calculated for the middle of the day (14:00). Regarding the shading factor, the tree stand canopy coverage in percentage must be considered as reference. By default, the column L that corresponds to the area within 300m altitude difference is considered. Finally, the obtained values in the mentioned three tables are added to the basic fine dead fuel moisture content (BFDFMC) to obtain the final fine dead fuel moisture content (FFDFMC).

Table VII - Values for correcting the basic fine dead fuel moisture content (BFDFMC) for May, June and July.

Tabela VII - Valores para correção do teor de umidade do combustível morto fino básico (BFDFMC) para os meses de maio, junho e julho.

MAY, JUNE, JULY																			
Exposed - Less than 50% Shading of Surface Fuels																			
Aspect	% Slope	08:00 >			10:00 >			12:00 >			14:00 >			16:00 >			18:00 >		
		B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A
N	0-30%	2	3	4	1	1	1	0	0	1	0	0	1	1	1	1	2	3	4
	≥ 31%	3	4	4	1	2	2	1	1	2	1	1	2	1	2	2	3	4	4
E	0-30%	2	2	3	1	1	1	0	0	1	0	0	1	1	1	2	3	4	4
	≥ 31%	1	2	2	0	0	1	0	0	1	1	1	2	2	3	4	4	4	6
S	0-30%	2	3	3	1	1	1	0	0	1	0	0	1	1	1	1	2	3	3
	≥ 31%	2	3	3	1	1	2	0	1	1	0	0	1	1	1	1	2	3	3
W	0-30%	2	3	4	1	1	2	0	0	1	0	0	1	0	1	1	2	3	3
	≥ 31%	4	5	6	2	3	4	1	1	2	0	0	1	0	0	1	1	2	2
MAY, JUNE, JULY																			
Shaded - Greater than or equal to 50% Shading of Surface Fuels																			
N	> 0%	4	5	5	3	4	5	3	3	4	3	3	4	3	4	5	4	5	5
E	> 0%	4	4	5	3	4	5	3	3	4	3	4	4	3	4	5	4	5	6
S	> 0%	4	4	5	3	4	5	3	3	4	3	3	4	3	4	5	4	5	5
W	> 0%	4	5	6	3	4	5	3	3	4	3	3	4	3	4	5	4	4	5
	B = Area of concern 1000’-2000’ (304.8m-609.6m) below weather site location																		
	L = Area of concern within ± 1000’ (304.8m) of weather site location																		
	A = Area of concern 1000’-2000’ (304.8m-609.6m) above weather site location																		

Source/Fonte: NFRDS (N.d.).

Table VIII - Values for correcting the basic fine dead fuel moisture content (BFDFMC) for the months of February, March, April, August, September, and October.

***Tabela VIII** - Valores para correção do teor de umidade do combustível morto fino básico (BFDFMC) para os meses de fevereiro, março, abril, agosto, setembro e outubro.*

FEBRUARY, MARCH, APRIL, AUGUST, SEPTEMBER, OCTOBER																			
Exposed - Less than 50% Shading of Surface Fuels																			
Aspect	% Slope	08:00 >			10:00 >			12:00 >			14:00 >			16:00 >			18:00 >		
		B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A
N	0-30%	3	4	5	1	2	3	1	1	2	1	1	2	1	2	3	3	4	5
	≥ 31%	3	4	5	3	3	4	2	3	4	2	3	4	3	3	4	3	4	5
E	0-30%	3	4	5	1	2	3	1	1	1	1	1	2	1	2	3	3	4	5
	≥ 31%	3	3	4	1	1	1	1	1	1	1	2	3	3	4	5	4	5	6
S	0-30%	3	4	5	1	2	2	1	1	1	1	1	1	1	2	3	3	4	5
	≥ 31%	3	4	5	1	2	2	0	1	1	0	1	1	1	2	2	3	4	5
W	0-30%	3	4	5	1	2	3	1	1	1	1	1	1	1	2	3	3	4	5
	≥ 31%	4	5	6	3	4	5	1	2	3	1	1	1	1	1	1	3	3	4
Shaded - Greater than or equal to 50% Shading of Surface Fuels																			
N	> 0%	4	5	6	4	5	5	3	4	5	3	4	5	4	5	5	4	5	6
E	> 0%	4	5	6	3	4	5	3	4	5	3	4	5	4	5	6	4	5	6
S	> 0%	4	5	6	3	4	5	3	4	5	3	4	5	3	4	5	4	5	6
W	> 0%	4	5	6	4	5	6	3	4	5	3	4	5	3	4	5	4	5	6
	B = Area of concern 1000’-2000’ (304.8m-609.6m) below weather site location																		
	L = Area of concern within ± 1000’ (304.8m) of weather site location																		
	A = Area of concern 1000’-2000’ (304.8m-609.6m) above weather site location																		

Source/*Fonte*: NFRDS (N.d.).

Table IX - Values for correcting the basic fine dead fuel moisture content (BFDFMC) for November, December, and January.

***Tabela IX** - Valores para correção do teor de umidade do combustível morto fino básico (BFDFMC) para os meses de novembro, dezembro e janeiro.*

NOVEMBER, DECEMBER, JANUARY																			
Exposed - Less than 50% Shading of Surface Fuels																			
Aspect	% Slope	08:00 >			10:00 >			12:00 >			14:00 >			16:00 >			18:00 >		
		B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A
N	0-30%	4	5	6	3	4	5	2	3	4	2	3	4	3	4	5	4	5	6
	≥ 31%	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
E	0-30%	4	5	6	3	4	4	2	3	3	2	3	3	3	4	5	4	5	6
	≥ 31%	4	5	6	2	3	4	2	2	3	3	4	4	4	5	6	4	5	6
S	0-30%	4	5	6	3	4	5	2	3	3	2	2	3	3	4	4	4	5	6
	≥ 31%	4	5	6	2	3	3	1	1	2	1	1	2	2	3	3	4	5	6
W	0-30%	4	5	6	3	4	5	2	3	3	2	3	3	3	4	4	4	5	6
	≥ 31%	4	5	6	4	5	6	3	4	4	2	2	3	2	3	4	4	5	6
Shaded - Greater than or equal to 50% Shading of Surface Fuels																			
N	> 0%	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
E	> 0%	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
S	> 0%	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
W	> 0%	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
	B = Area of concern 1000’-2000’ (304.8m-609.6m) below weather site location																		
	L = Area of concern within ± 1000’ (304.8m) of weather site location																		
	A = Area of concern 1000’-2000’ (304.8m-609.6m) above weather site location																		

Source/*Fonte*: NFRDS (N.d.).

1.4 Estimation of Ignition Probability based upon the Fine Dead Fuel Moisture Content

The ignition probability (πixy, %) is interpreted as a measurement of the likelihood of a fire to start over dry fine fuels when a source of heat is applied, or more specifically, as the number of positive ignitions when a source of heat is applied 100 times. Thus, it depends on the fine dead fuel moisture content, which also depends on the exposure to solar radiant heat and the air temperature. A value of cloudiness (in percentage) is considered an estimate of the exposure to solar radiant heat. Table X of Annex 1 shows the relationship between the percentage of cloudiness and the solar exposition type.

The ignition probability is, then, calculated considering those mentioned variables. Table XI of Annex 1 shows the estimation of the ignition probability depending on the values of the (1) final fine dead fuel moisture content (FFDFMC), (2) air temperature (T^a), and (3) type of exposition to the solar radiant heat. For the worst case conditions for fires, a percentage of 0% of cloud coverage is applied (maximum exposure, type 1). In other cases, the exposition type to be used in Table XI for estimating the ignition probability is extracted from Table X of Annex 1.

Table X - Relationship between the cloudiness (%) and the type of exposure to the solar radiant heat.

***Tabela X** - Relação entre a nebulosidade (%) e o tipo de exposição ao calor radiante solar.*

Cloudiness %	Exposition type
0-10	1 (complete)
10-50	2 (average)
50-90	3 (poor)
90-100	4 (none)

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco.

Table XI - Ignition probability estimation based on FFDFMC and air Tª for (A) Type 1 exposure, (B) Type 2 exposure, (C) Type 3 exposure, and (D) Type 4 exposure.

***Tabela XI** - Estimativa de probabilidade de ignição baseada em FFDFMC e Tª do ar para (A) Exposição Tipo 1, (B) Exposição Tipo 2, (C) Exposição Tipo 3 e (D) Exposição Tipo 4.*

	Probability of Ignition (Exposition Type 1)															
	Final Fine Dead Fuel Moisture Content (FFDFMC, %)															
Tª (°C)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
>40	100	100	90	80	70	60	50	40	40	30	30	30	20	20	20	10
35-40	100	90	80	70	60	60	50	40	40	30	30	20	20	20	10	10
30-35	100	90	80	70	60	50	50	40	30	30	30	20	20	20	10	10
25-30	100	90	80	70	60	50	40	40	30	30	20	20	20	20	10	10
20-25	100	80	70	60	60	50	40	40	30	30	20	20	20	10	10	10
15-20	90	80	70	60	50	50	40	30	30	30	20	20	20	10	10	10
10-15	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
5-10	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
0-5	90	70	60	60	50	40	40	30	30	20	20	20	10	10	10	10
	Probability of Ignition (Exposition Type 2)															
	Final Fine Dead Fuel Moisture Content (FFDFMC, %)															
Tª (°C)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
>40	100	100	80	70	60	60	50	40	40	30	30	20	20	20	20	10
35-40	100	90	80	70	60	50	50	40	40	30	30	20	20	20	10	10
30-35	100	90	80	70	60	50	40	40	30	30	30	20	20	20	10	10
25-30	100	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10
20-25	100	80	70	60	50	50	40	40	30	30	20	20	20	10	10	10
15-20	90	80	70	60	50	50	40	30	30	20	20	20	20	10	10	10
10-15	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
5-10	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
0-5	80	70	60	50	50	40	30	30	20	20	20	10	10	10	10	10
	Probability of Ignition (Exposition Type 3)															
	Final Fine Dead Fuel Moisture Content (FFDFMC, %)															
Tª (°C)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
>40	100	90	80	70	60	50	50	40	40	30	30	20	20	20	10	10
35-40	100	90	80	70	60	50	50	40	30	30	30	20	20	20	10	10
30-35	100	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10
25-30	100	80	70	60	60	50	40	40	30	30	20	20	20	10	10	10
20-25	90	80	70	60	50	50	40	30	30	30	20	20	20	10	10	10
15-20	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
10-15	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
5-10	90	70	60	50	50	40	30	30	30	20	20	20	10	10	10	10
0-5	80	70	60	50	50	40	30	30	20	20	20	10	10	10	10	10
	Probability of Ignition (Exposition Type 4)															
	Final Fine Dead Fuel Moisture Content (FFDFMC, %)															
Tª (°C)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
>40	100	90	80	70	60	50	50	40	30	30	30	20	20	20	10	10
35-40	100	90	70	70	60	50	40	40	30	30	20	20	20	20	10	10
30-35	100	80	70	60	60	50	40	40	30	30	20	20	20	10	10	10
25-30	90	90	70	60	50	50	40	30	30	30	20	20	20	10	10	10
20-25	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
15-20	90	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10
10-15	90	70	60	60	50	40	40	30	30	20	20	20	10	10	10	10
5-10	80	70	60	50	50	40	30	30	20	20	20	10	10	10	10	10
0-5	80	70	60	50	40	40	30	30	20	20	20	10	10	10	10	10

Source: Personal communication from David Caballero (Spain), expert in fire hazard and risk assessment.

Fonte: Comunicação pessoal de David Caballero (Espanha), especialista em risco de incêndio e avaliação de risco.