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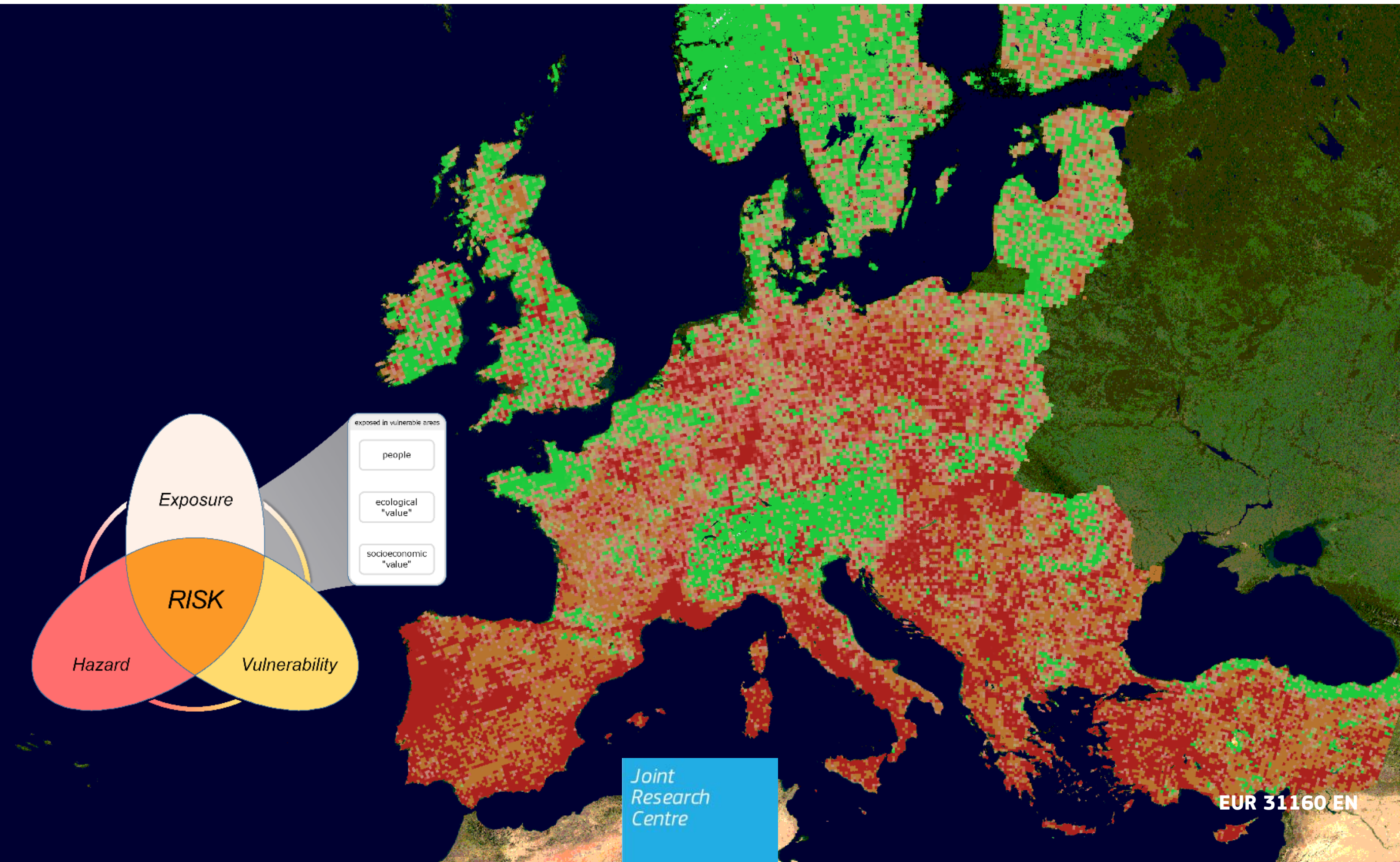
Pan-European wildfire risk assessment



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Cover image: EFFIS – Fire Risk Viewer in 2022

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Executive summary

Wildfires, as a global phenomenon, are an integral part of the Earth system which affects different regions of the planet quite unevenly. They are of great concern in Europe: in the European Union alone, over 4000 km^2 of our land were burnt in 2019; 3400 km^2 in 2020; 5000 km^2 in 2021. Depending on the proximity to where people live, and the extent and typology of ecosystems and goods exposed in areas vulnerable to wildfires, the level of risk may vary greatly. However, many components contribute to worsen or mitigate the risk, so that their interplay is not always easy to predict, and the natural variability of climate, environmental, and human factors is an intrinsic part of the problem.

The impacts of wildfires may result in long-lasting effects to social, environmental, and economic systems. In a context of global heating along with many other rapidly changing aspects of climate and of our human activity, and extreme events becoming more frequent, it is crucial to respond with more robust preparedness and planning, identifying spatially the risks posed by wildland fires, to foster better fire management policy tools, and develop mitigation strategies accordingly. However, given the irreducible complexity of the problem, scope and methods for wildfire risk assessment vary widely among countries and research teams leading to different regional/national approaches that are not always comparable, although wildfires are often trans-border events and may affect several countries simultaneously. These uneven approaches understandably focus on the corresponding regions of interest, and the chosen methods are affected by the specificities of each country.

To integrate currently incompatible approaches, harmonised procedures for wildfire risk assessment are needed at the pan-European scale, enhancing planning and coordination of prevention, preparedness, and cross-border firefighting actions to mitigate the damaging effects of wildfires. The development of a pan-European approach follows from a series of European Union (EU) regulations requiring the European Commission (EC) to have a wide overview of the wildfire risk in Europe, to support the actions of its Member States and to ensure compliance in the implementation of EU regulations related to wildfires. The conceptualization of a European Wildfire Risk Assessment (WRA) as the combined impact of wildfire hazard on people, ecosystems, and goods exposed in vulnerable areas, explicitly accounts for the multiplicity of risk dimensions and sources of uncertainty. Already serving as an integrated framework for gathering the European countries' experience on fire management and risk, it will support the inter-comparison of WRA among countries, with the aim to complement existing national WRA with a simpler, but harmonised, methodology. A semi-quantitative approach, designed to be robust to uncertainty and flexible in ingesting new components, has led to the development of the first pan-European prototype WRA version, while maintaining its development in close cooperation with the EC Joint Research Centre (JRC), other Commission services, and the Commission Expert Group on Forest Fires which is now composed of fire management representatives from 43 countries in the region. Additionally, the harmonised framework can serve as a first approach for assessing wildfire risk in those countries that have not yet performed a national WRA, and as a guideline for extending the approach to larger areas, where data coverage may be scarcer and more uncertain.

Pan-European wildfire risk assessment in the context of EFFIS

The development of this first pan-European approach to assess wildfire risk follows from a series of EU regulations that require the EC to have a wide overview of the risk by wildfires in the European region, to support the actions of its Member States and to ensure compliance in the implementation of EU regulations related to wildfires. The process is closely linked with the Expert Group on Forest Fires (EGFF), composed of fire management representatives from 43 countries in the region and part of the European Forest Fire Information System (EFFIS), which was established jointly by the EC services (DG ENV and JRC) and the relevant fire services from the EU Member States, other non-EU European countries and Middle East and North African countries. The collaboration with the EGFF countries' experts was essential for the design and first prototype implementation of the pan-European wildfire risk assessment. The spatial extent of this first prototype version of the risk ranking was carefully selected to ensure the broadest possible spatial coverage, given the limits and gaps of the currently available data, with a perspective to potentially expand the assessment whenever broader reliable and harmonised data would become available in future.

Methods

Given the inescapable complexity and the non-linear interplay between the components of wildfire risk, a mere aggregated risk ranking – isolated from basic contextual information – may be difficult to understand alone. This is why the proposed approach is explicitly designed to provide not only the final risk ranking, but also to complement it with a rich set of spatial quantities, either directly used to estimate the risk, or useful as basic layers to ease a contextual comparison with selected background data. An integrated framework of interconnected components associated with the fire process (Chuvieco et al., 2012; Xi et al., 2019) should support risk modelling to provide an integrated view of both fire likelihood and consequences (Dunn et al., 2020). Figure 1 illustrates the WRA scheme proposed here, designed to be scale-independent and easily applicable to local, regional, and global scale. Two main groups of components are defined by considering the fire danger (or hazard) and the vulnerability (including the exposure of people and assets) on three categories: people, ecological, and economic values exposed in vulnerable areas.

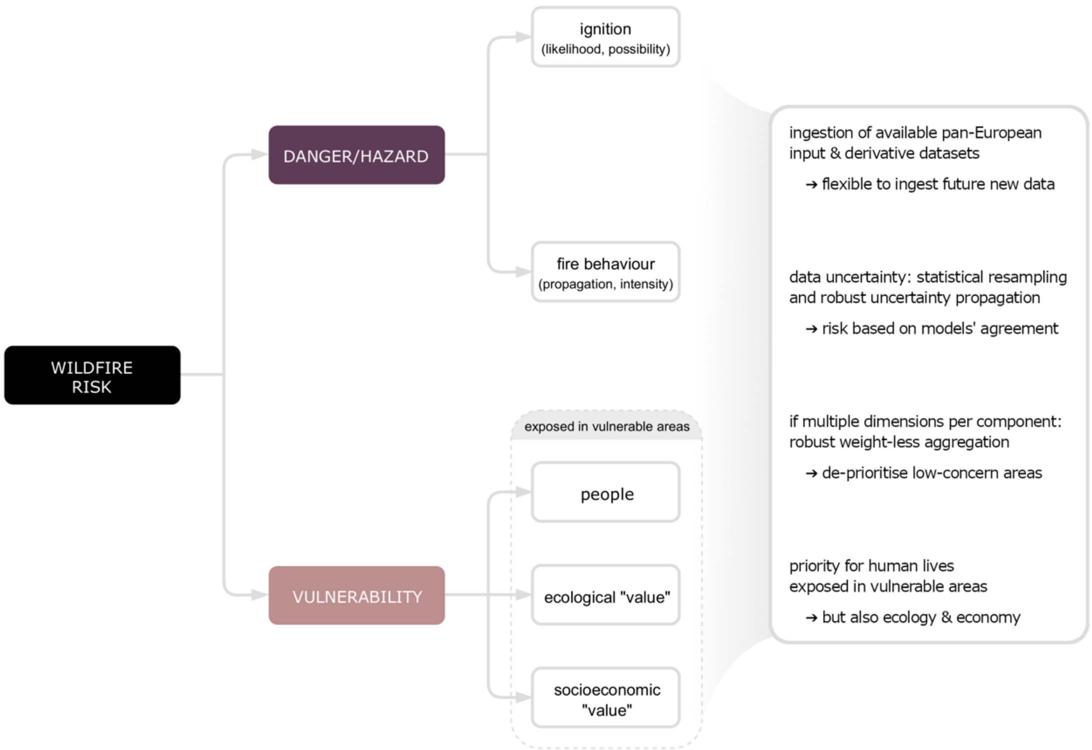


Figure 1. The main components of the first pan-European wildfire risk assessment (WRA). The scheme is a simplified version of the one discussed with the EGFF countries' experts and published in Oom *et al.*, 2021 (see Figure 6).

The WRA was assessed through a semi-quantitative approach by using the available quantitative data (see Data section) as proxy information for the wildfire danger and vulnerability components, along with a robust quantitative aggregation of them in classes of importance (from low to high importance).

Multiplicity, uncertainty, and robustness – The integration of multiple dimensions is the very basis for a sound risk assessment, which requires us to consider together the possibility (wildfire hazard, with its components) of negative outcomes (vulnerability for people, ecosystems, and assets, with their components). In addition to the many components in Figure 1 (and Figure 6), several components themselves are described by using multiple dimensions (e.g. multiple proxy indicators). Their proposed integration (based on Pareto ranking, Ben-Tal, 1980; Fonseca and Fleming, 1993; Tracey *et al.*, 2018) is stable for any possible transformation of the components where the ranking of values is preserved, including change of units and percentile ranking. Moreover, lower priority is given to the areas where all the dimensions of a risk component are consistently lower than in other areas. This mathematically ensures that, irrespective of any special preference for a given dimension over the other ones, these lower-concern areas would be de-prioritised in the same consistent, unambiguous way – allowing the assessment to focus on the higher-concern areas. This mathematical property adds to the robustness of the final risk ranking.

Virtually all the components in Figure 1 are associated with an intrinsic uncertainty, so that integrating them in order to estimate the final risk magnifies the cumulative aggregated uncertainty. Therefore, this structural uncertainty is the key element of a robust method for identifying which areas to prioritise, where the estimated risk is consistently higher than in other areas. This robust risk assessment is computed by considering multiple simulations of the uncertainty, as explored in a corresponding set of multiple model instances (or model runs). In each model instance, the risk components and their dimensions are aggregated with the aforementioned integration up to a corresponding risk ranking for each instance. The degree of agreement between model instances is estimated, thereby identifying the high-priority areas where most instances agree on these areas being at high risk. Analogously, areas with relatively low risk (lower priority areas) can also be identified, where most instances agree on the same low-risk classification.

Wildfire risk is assessed by considering the vulnerable areas where people, ecological, and socioeconomic values are exposed to fire danger. An aggregated wildfire risk index is proposed, which prioritizes the risk for human lives, while also considering ecological and socioeconomic aspects. This is done by ranking as high-risk areas those where people may be exposed to wildfires, and secondarily other areas where ecological and socioeconomic aspects are at stake.

Overall, this approach offers a *robust integration* of available data, accounting for their systemic uncertainty and their multi-annual *variability*. The goal is to anticipate (even where not yet manifest) *structural* wildfire risk which, given the high variability between years of weather conditions and other factors, may be quite different from the immediate, short term fire danger. This first assessment of structural wildfire risk in Europe aims not to lose sight of long-term potential impacts while daily addressing fire prevention and response..

Introduction

Given the potential increase of the risk due to wildfires in the Mediterranean-type climate regions due to climate change (Pechony *et al.*, 2010), wildfire risk assessment is fundamental for developing prevention, mitigation and preparedness plans, but also is a key element to disentangle the complex relationships between fire occurrence, their drivers and the impacts caused by fires at different levels (Oliveira *et al.*, 2021, Moreira *et al.*, 2020). Many countries have customized approaches to assess wildfire risk, and these vary widely among them using different variables and methodologies (San-Miguel-Ayanz *et al.*, 2003, 2017). Usually, these different approaches are not only related to the frequency and impact of fires, level of preparedness, and data availability, but also to the way the risk components are incorporated in the decision-making processes at different levels, such as landscape management or risk governance. Hence, this process repeated at multiple scales and for very different territories and specific purposes has led to different regional/national approaches, to tackle specific needs and priorities, that are difficult to compare at the European scale (Fernandez-Anez *et al*, 2021), although (especially during peak fire periods) wildfires are often transborder events and may affect several countries simultaneously. Fire-risk terminology is far from standardized, and even the concept itself is subject to several (sometimes incompatible) definitions (Hardy, 2005). A large fraction of published fire risk systems only considers the wildfire likelihood (more specifically, several approximations for components of this likelihood, which is very challenging to properly estimate) and behaviour, and the expected damage caused by fire impacts is usually not considered in operational fire danger assessment systems (San Miguel-Ayanz *et al.*, 2003). However, some other systems integrate fire danger and fire vulnerability, the two components in the risk approach as frequently conceptualised in the wildfire research domain (e.g. Calkin *et al.*, 2010; Chuvieco *et al.*, 2010; 2012; Tutsch *et al.*, 2010; Thompson *et al.*, 2011; Oliveira *et al.*, 2020). Depending on the perspective and goals, and most importantly on the specificities of their study area, these integrated approaches may focus on different aspects while de-emphasising other ones, maybe less important locally. Overall, an effort is urgently needed to converge on a clear and concise wildfire risk terminology, in order to overcome the ambiguities due to different quantitative risk analyses being made in the context of wildland fire management (Bachmann and Allgöwer, 2001) and of disaster risk management. This work proposes a basic harmonised approach, simplified but able to remain flexible to address multiple needs and integrate new emerging factors in the context of wildfire risk assessment in Europe (while keeping in mind that a continental perspective cannot be as accurate and specific as national and local assessments; but hopefully able to complement them with a simple harmonised assessment nonetheless). The main goal of this report is to describe the development of a pan-European wildfire risk assessment (WRA) based on the definition of risk adopted by the United Nations International Strategy for Disaster Reduction (UNISDR, 2009) which was also followed by the JRC Science for Disaster Risk Management report published in 2017 (San-Miguel-Ayanz *et al.,* 2017) and subsequent JRC's reports (San-Miguel-Ayanz *et al.*, 2019; Oom *et al.*, 2021) by presenting a first set of data that would enable the implementation of the proposed assessment, and a preliminary prototype approximation of the risk based on them.

Within a quantitative framework, the wildfire risk is conceptually defined (for a moment neglecting the challenges in implementing this conceptual definition) as the product of the probability of a wildfire occurring or/and propagating (hazard), and the damage that it may cause (exposure and vulnerability) (Finney, 2005; Scott, 2006; Chuvieco *et al.*, 2010; Calkin *et al.*, 2010; Miller and Ager, 2013) (Figure 2). Hence, this involves three main fire research areas: on fire ignition/occurrence, fire behaviour/propagation (and intensity at which they might occur) and fire effects (potential loss of resources as a result of wildfires and exposure of assets located in wildfire-prone areas).

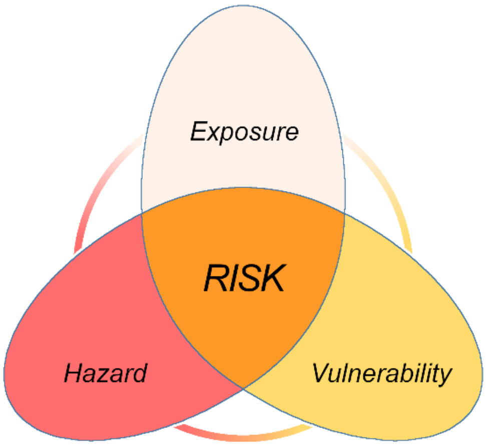


Figure 2. Components of the risk (Risk as a function of hazard, exposure and vulnerability). In non-trivial risk assessment (as in the case of wildfire risk, where human aspects are essential), some components are often interdependent (Fischer et al., 2017; Liu et al., 2007a; 2007b) so that their estimation cannot be done separately.

Detailed literature reviews on the prevalence of ambiguous, incomplete or incorrect definitions of wildfire risk are largely missing. However, a recent review dealing with fire risk studies in Canada (Johnston *et al.*, 2020) may help to highlight the vast landscape of ambiguity and uncertainty which currently affects the research labelled as "fire-risk" (even when this labelling may be misleading and generating confusion at the science-policy interface). While noting that "social aspects of fire should not merely be a direct effect considered in risk calculations, but central to the main risk determination", the authors lament that most "research on wildland fire risk has focused on its physical components, largely neglecting the social, political, economic, and cultural aspects" (Johnston *et al.*, 2020). By reviewing the risk definitions in wildland fire research literature, the same authors reported that only 21 % of the papers used the appropriate technical definition of risk and 79 % instead confused it with other concepts, or failed to define it behind general terms (Figure 3).

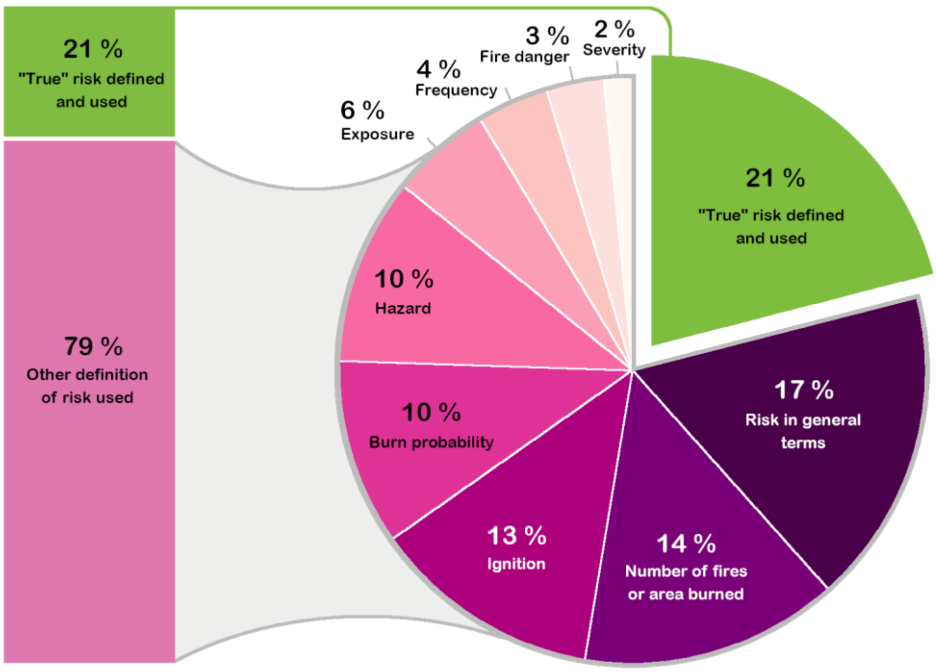


Figure 3. Analysis of fire risk definitions used within wildland fire research literature in Canada (derived after Johnston *et al.*, 2020).

The harmonised risk assessment here proposed aims to support the full disaster management cycle (from prevention to preparedness, response and recovery) and will allow the inter-comparison of wildfire risk assessment among countries, acting as a complementary component to the existing national wildfire risk assessments. Additionally, it can serve as a first approach to assess wildfire risk in those countries that have not yet performed a national wildfire risk assessment.

Work on forest fires in the context of EFFIS

The work of the European Commission on forest fires started many years ago, in the context of the Council Regulation 2158/92 (Council of the European Union, 1992).

The European Forest Fire Information System (EFFIS) has been established jointly by the European Commission services (Directorate-General for Environment DG ENV; and Joint Research Centre, JRC), the relevant fire services in the EU Member States, other non-EU European countries and Middle East and North African countries (Forest Services and Civil Protection services). In 1998, the Expert Group on Forest Fires (EGFF) was established in connection with the development of the European Forest Fire Information System (San-Miguel-Ayanz et al., 2013b). Research activities for the development of the system initiated at JRC in 1998 and the first EFFIS operations were in the year 2000.

In 2003, EFFIS was embedded in the new Regulation (EC) No 2152/2003 (Forest Focus) of the European Council and Parliament on monitoring of forests and environmental interactions (European Parliament, Council of the European Union, 2003) until it expired in 2006. Since then, EFFIS has operated as a voluntary system of information on wildfires until 2015, when it became part of the EU Copernicus program, under the Emergency Management Services. Currently there is no EU legislation regarding forest fire protection.

Acting as the focal point of information on forest fires, EFFIS supports the national services in charge of wildfire management. Currently, the EFFIS network is made up of 43 countries in Europe, Middle East and North Africa (25 EU Member States, 13 non-EU countries and 5 MENA countries). EFFIS provides specific support to the Emergency Response Coordination Centre (ERCC, formerly Monitoring and Information Centre: MIC) of Civil Protection as regards near-real time information on wildfires during the fire campaigns and assists other DGs through the provision of both pre-fire and post-fire information on wildfire regimes and impacts. It provides information that supports the needs of the European Parliament with regards to wildfire management, impact in natural protected areas and harmonized information on forest fires in the EU.

One of the key components of EFFIS is the European Fire Database (Camia *et al.*, 2014) which centralizes the national fire data that the countries collect through their national forest fire programs, with over 3 million individual fire event records from 27 countries and information on location, time, size and cause. One of the main components of EFFIS[1] is the modular web geographic information system that provides near real-time and historical information on forest fires and forest fires regimes in the European, Middle Eastern and North African regions and was assessed by government organizations and citizens, with nearly 300 000 users from 178 countries in 2020. Fire monitoring in EFFIS comprises the full fire cycle, providing information on the pre-fire conditions and assessing post-fire damages (Figure 4) providing regularly updates to EC services during the main fire season and is continuously updated on the EFFIS web site (up to 6 times, daily), which can be interactively queried[2]. EFFIS provides daily fire danger maps and forecasts of fire danger for up to 10 days in advance, updated maps of the latest active fires, wildfire perimeters and post-fire evaluation of damage

Every year, an annual report on “Forest Fires in Europe, Middle East and North Africa” is published by the JRC and authored by Commission services and the experts in the Expert Group on Forest Fires (EGFF). The whole collection of these reports is available in EFFIS at https://effis.jrc.ec.europa.eu/reports-and-publications/annual-fire-reports where the latest annual report can be accessed as soon as it is published.

[1] https://effis.jrc.ec.europa.eu/
[2] https://effis.jrc.ec.europa.eu/apps/effis_current_situation/

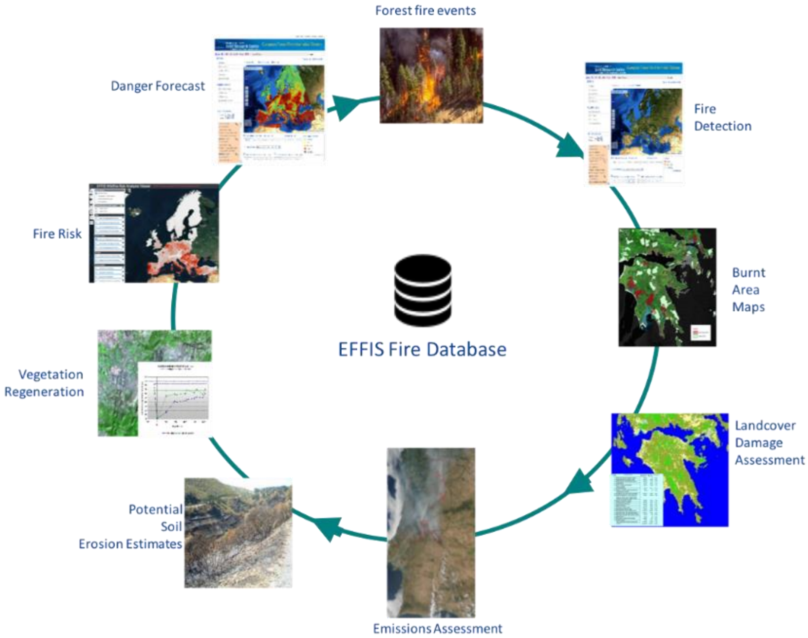


Figure 4. European Forest Fire Information System (EFFIS) services.

The Expert Group on Forest Fires: roles and components

The Expert Group on Forest Fires (EGFF) was set up in 1998 in relation to the initial activities on the establishment of a European Forest Fire Information System (EFFIS) coordinated by DG ENV and JRC. It is now established as a sub-group of a wider Commission Expert Group on Forest Information and is co-financed by ENV/JRC/GROW as part of the EFFIS Work Program under Copernicus. The EGFF is managed by DG ENV and co-chaired by DG ENV/JRC.

The EGFF has several advising roles as regards forest fires in cooperation with the European Commission. In a nutshell, the EGFF role is:

- Contribution to the conception and development of the European Forest Fire Information System (EFFIS);
- Contribution to the harmonization of data/information in the EFFIS fire database (fire event information reported by the countries;
- Contribution to sustainable forest management and exchange of information to increase forest resilience;
- Contribution to the design and usage of EFFIS information, exchange of information on lessons learned on the entire fire cycle, from prevention to restoration, and discussion and posting of good forest fire prevention practices;
- Contribution and drafting of a yearly report on forest fires in Europe, Middle East and North Africa (2000-2020).

The EGFF includes not only EU countries, but also other European non-EU countries, and countries in the Middle East and North Africa. The extension of the EGFF to Middle East and North African countries was implemented in collaboration with the United Nations Food and Agriculture Organization (UN FAO) Silva Mediterranea network. Figure 5 shows the countries that are in the EGFF. In blue are the EU countries, in green are the non-EU European countries and in red the countries in the Middle East and North Africa.

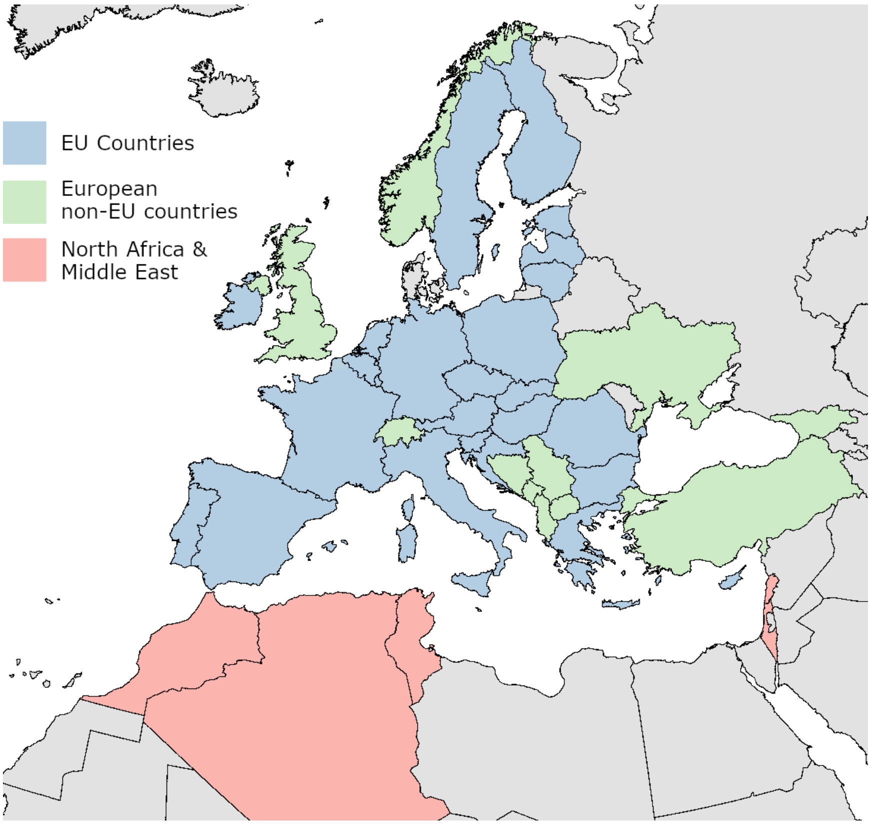


Figure 5. European Forest Fire Information System (EFFIS) network of countries which includes the ones currently part of the Expert Group on Forest Fires (EGFF).

Roadmap: milestones towards the first European wildfire risk assessment

As mentioned before this work is a result of a joint effort between the JRC, other Commission services[3] and the Commission Expert Group on Forest Fires (EGFF).

The first consultation with EGFF on wildfire risk assessment at the pan-European scale took place at the 36th meeting of the EGFF, in October 2017. At that occasion, the JRC presented a basic approach that could eventually be the basis for designing a robust shared methodology as a follow-up to the recently published chapter on Wildfires (San-Miguel-Ayanz *et al.*, 2017), within the report on Science for Disaster Risk Management 2017 (Poljanšek *et al.*, 2017).

The next consultation occurred at the 37th EGFF meeting, in April 2018. At this meeting, it was decided to organize sub-groups on the EGFF to work on two important topics for both the countries and the European Commission. One sub-group would work on the potential elaboration of wildfire risk assessment at the pan-European scale, while a second sub-group would focus on providing guidance for wildfire prevention activities.

A dedicated meeting of the EGFF subgroup on wildfire risk assessment took place at JRC in June 2018. The results of this meeting were presented and discussed at the 38th EGFF meeting in November 2018 and a report describing the datasets that may be used to have a standardized approach at pan-European level was published (San-Miguel-Ayanz *et al.,* 2019). Following that, the methodology was presented at the 41st EGFF meeting on December 10th of 2020 and published as a chapter (Oom *et al.,* 2021) within the Recommendations for National Risk Assessment for Disaster Risk Management in EU (Poljanšek *et al.*, 2021). A preliminary prototype version of the Wildfire Risk Map Viewer was discussed in a dedicated technical workshop with the EGFF held on the 30th of March of 2021. In order to get feedback from the countries to improve the system, bi-lateral discussions

[3] Commission services involved in the work of the JRC with the Expert Group on Forest Fires include the Director Generals Environment (ENV), Humanitarian Office (ECHO), Climate Action (CLIMA) and Research and Innovation (RTD).

were organized and presented to the countries at the 42nd EGFF on 20th May of 2021. At the 43rd EGFF on the 27th of October 2021, the implementations procedures towards version 1 of the viewer were presented.

Wildfire Risk Assessment (WRA) scheme

Risk modelling systems should be the result of an integrated framework of interconnected components associated with the fire process (Chuvieco *et al.*, 2012; Xi *et al.*, 2019) to provide an integrated view of fire likelihood and the consequences caused by them (Dunn *et al.*, 2020). Wildfire risk can be identified as the joint effect of: (1) wildfire danger (also known as fire hazard) and (2) wildfire vulnerability of people, ecosystems and goods exposed to wildfires. The definitions of hazard, exposure and vulnerability are based on the UNISDR terminology on Disaster Risk Reduction (UNISDR, 2009) and are shown in Table 1.

Table 1. Definition of risk components used in this report (from UNISDR, 2009).

Term	Definition
Hazard	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.
Exposure	People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.
Vulnerability	The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.

The WRA scheme here proposed is presented in Figure 6. This scheme is designed to be scale-independent and easily applicable to local, regional and global scale. Two main groups of components are defined by considering the fire danger (or hazard) and the vulnerability on three categories: people, ecological and economic values exposed in vulnerable areas.

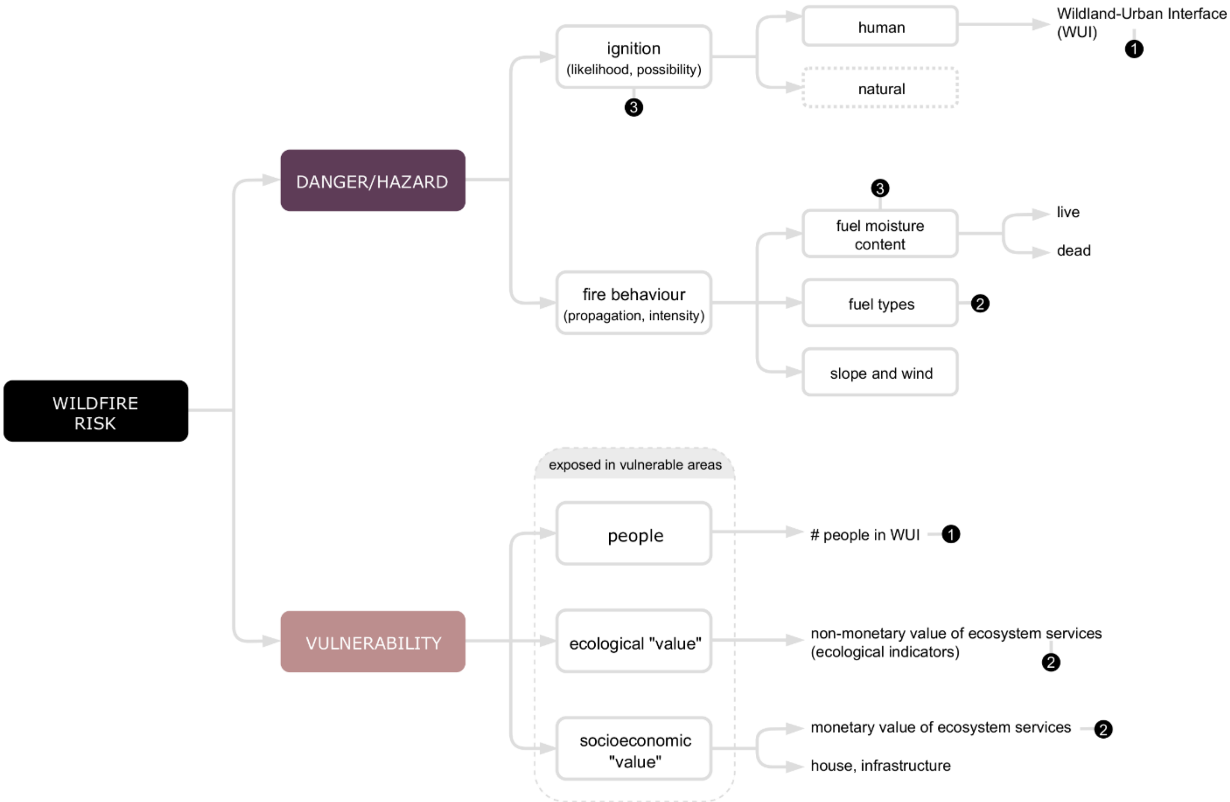


Figure 6. A summary workflow highlighting the key components of the wildfire risk. Two main groups of components are defined by considering the fire danger (or hazard), and the vulnerability on three categories: people, ecological and socioeconomic value exposed in vulnerable areas**.**

The scheme was based on the quantitative analysis of "risk", based on the probability or possibility (*P*) of negative outcomes (damage, *D*)

$$R = P \times D \tag{1}$$

The probability for a fire to start at a given location and time (*P*: fire danger/fire hazard) depends on the likelihood for ignition sources and local conditions to start and spread a fire (fire behaviour); namely it depends on the fuel availability, type and pre-conditions of the fuel, the prevalent meteorological conditions, and on the presence of an event triggering the initial ignition. In Europe, the vast majority of wildfires are linked to human causes (either deliberate or due to accident or negligence, de Rigo *et al.*, 2017b). Therefore, *P* is not only a function of fuel and weather, but prominently also of human behaviour *P*(fuel, weather, human). The expected outcomes/impacts on people, landscape/ecosystems, and/or assets exposed in vulnerable areas (*D :* vulnerability) refer to the susceptibility to suffer damage by fire and may be defined as: "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" (United Nations International Strategy for Disaster Reduction, 2009). Vulnerability, which is also associated with exposure (people, ecosystems, goods exposed in vulnerable areas, so that in the following the two entwined concepts are referred to as the overall "vulnerability" component of wildfire risk), should be assessed based on relevant proxy indicators and data. The impact of wildfire hazard on vulnerability is typically estimated as a structural assessment, also known as climatological risk (San-Miguel-Ayanz *et al.*, 2017) and should explicitly consider the variability and uncertainty of the conditions historically observed. Given that even the damage by fire is a key function of human behaviour (fire prevention, firefighting, post-fire recovery policies) and depends prominently on policy, economic, social and cultural aspects, then even the second component of eq. 1 is a function of human factors for which there is an overwhelming lack of data. Therefore, *P* and *D* cannot be fully estimated "probabilistically", but they might with a simpler semi-quantitative risk ranking (where *P* is a simpler fuzzy possibility subject to uncertainty analysis). Given the complexity and non-linearity of the interplay between

wildfire-risk components, a mere aggregated risk ranking – isolated from basic contextual information – may be difficult to understand alone. This is why the proposed approach is designed to provide not only the final aggregated risk classes, but also to complement it with a rich set of spatial quantities, either directly used to estimate the risk, or useful as basic layers to ease a contextual comparison with selected background data.
The following sections describe the different datasets that were used for each component, or as contextual information, in the assessment of wildfire risk at the pan-European level. A pre-requisite for the data to serve in a continental-scale exercise is the availability of the data for a common subset of the pan-European region. In some cases, the available data only covered most of the region of interest (so that some included areas have partial data gaps and cannot yet rely on an optimal data coverage) and may be complemented in future by national datasets, provided that these more accurate local data can be assimilated to the European datasets in terms of format and information content.

Overall, the spatial extent of this first prototype version of the risk ranking was carefully selected to ensure the broadest possible spatial coverage, given the limits and gaps of the currently available data, and at the price of some sub-optimal approximations. It is essential to note how the availability, quality and harmonisation of the input data is decisive for a reliable final ranking of wildfire risk. At the same time, the presence of multiple regions with a broad diversity in their sensitivity/response to wildfires is important for the final risk ranking to be representative of the rich diversity of local conditions. Therefore, a trade-off exists between the widening of the study area (too small an area would be biased to over-specific local conditions, and not comparable to other regions), and the availability of minimum-quality data to cover the whole spatial extent (otherwise, poor quality proxy data would propagate their negative impact over the whole risk ranking, making it useless).

Data

The development of an operational wildfire risk assessment system for the pan-European scale requires the generation of multiple datasets for each component, and a method to integrate them into a risk ranking. Table 2 describes the datasets used for each component in the WRA.

Table 2. Datasets for the components of the wildfire risk assessment system (grey boxes are variables that are not included in this version, being still the object of exploratory research)

Risk components		Components detail	Variables used	Source
DANGER /HAZARD	Ignition	Human cause	Historical fire data	EFFIS burned area (2003-2020)[1] MODIS thermal anomalies (2003-2020)[2] Corine Land cover[3]
		Natural cause	lightning	
	Fire behaviour	Fuel moisture content	Live Fuel Moisture Content (LFMC)	Yebra *et al.*, 2013
			Dead Fuel Moisture Content (DFMC)	Fire Weather Index system[4]
		Fuel types	vegetation types (burnable wildland: forests, other woodland and non-artificial/agricultural land with burnable vegetation)	Corine Land Cover[3] Potential burnable vegetation (NDVI[a], JRC's Global Water Layer[b], Build-up areas[c]) Fuel Map of Europe[5]
		Climatic conditions	wind, humidity, precipitation and temperature	Fire Weather Index system[4]
		Terrain	slope, aspect	Elevation data[6]
VULNERABILITY	People	# People in WUI	wildland–urban interface (WUI)[7]	Population density[8] Built-up areas[9]
	Ecological "value"	Ecological indicators	- irreplaceability score[10] - protected area - potential burnable land	Natura 2000[11] Protected area[12]
	Socioeconomic "value"	Monetary value of land cover and vegetation	Wildfire-damage restoration costs[13]	Corine Land Cover[3], vegetation age (restoration time)[13] restoration costs[13]
		House, infrastructure		

1 European Forest Fire Information System (EFFIS), https://effis.jrc.ec.europa.eu
2 Fire Information for Resource Management System (FIRMS), https://firms.modaps.eosdis.nasa.gov/active_fire/
3 Corine Land Cover (CLC), https://land.copernicus.eu/pan-european/corine-land-cover
4 Copernicus Emergency Management Service, 2019; Vitolo *et al.*, 2020; Hersbach *et al.*, 2018
5 European Forest Fire Information System, 2017
6 Amatulli *et al.*, 2020
7 Costa *et al.*, 2020
8 Freire *et al.*, 2016; Schiavina *et al.*, 2019
9 Corbane *et al.*, 2018
10 Le Saout *et al.*, 2013
11 The European network of protected sites, Natura 2000, https://www.eea.europa.eu/data-and-maps/data/natura-12
12 The World Database on Protected Areas (WDPA), https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA
13 Mavsar *et al.*, 2011; Oehler *et al.*, 2012; Camia *et al.*, 2017
a Corbane *et al.*, 2018
b Pekel *et al.*, 2016
c Global Land Service of Copernicus from the PROBA-V 333m NDVI

Wildfire Danger

Wildfire danger is influenced by the factors related to the probability of ignition and those affecting fire behaviour. It is therefore composed by the likelihood/possibility of having a fire **ignition**, and the **behaviour** (propagation and intensity) of a fire once it is ignited. All these factors are represented by the upper branch of the scheme presented above in Figure 6.

Wildfire ignitions

In Europe, the vast majority of ignitions are due to human causes (either deliberate, or accidental), exposing the critical role of the human factor in fire occurrence and fire conditions, either by increasing ignitions or by suppressing activities (Chuvieco and Justice, 2010; Dijkstra *et al.*, 2022). Naturally caused fires are normally a very small fraction of the total number of fires in Europe. The available information on fire causes reported by 27 countries, which follows a harmonized scheme of fire causes at the European level (Camia *et al.*, 2013), is included in the Fire Database of the European Forest Fire Database (EFFIS). Although different countries contribute data in the Fire Database with specificities depending on local data-collection design and implementation, de Rigo *et al.*, (2017b) offered a statistical overview for the fires where information on their causes were available in the Fire Database. Considering comparable data reported for 19 European countries in the EFFIS Fire Database, only 4 % of the fires are found not linked with human causes, most of them caused by lightning; while 96 % are related with human activities, mainly due to negligence or accident (Gantaume *et al.*, 2013; de Rigo *et al.*, 2017b; Dijkstra *et al.*, 2022). In Figure 7, from de Rigo *et al.*, (2017b), it can be noticed how at the European scale the information on fire causes is still subject to a high level of uncertainty with almost 50 % of the fire causes unknown.

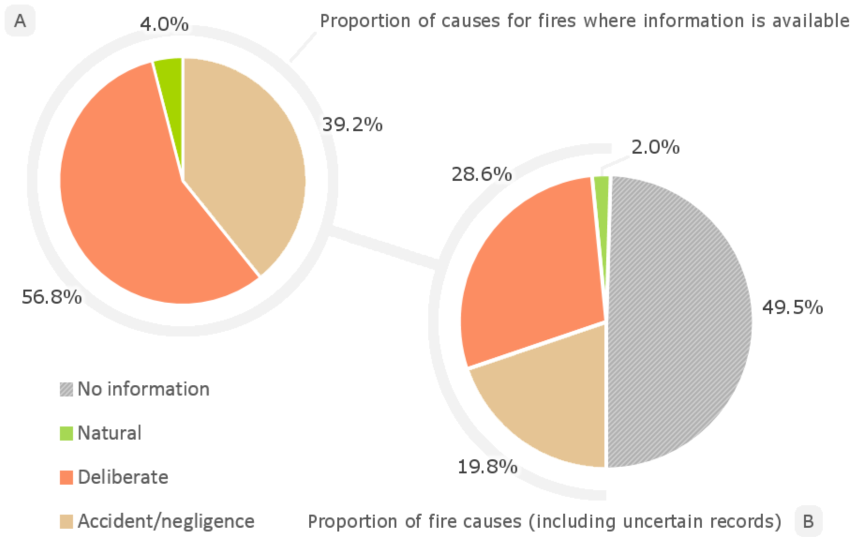
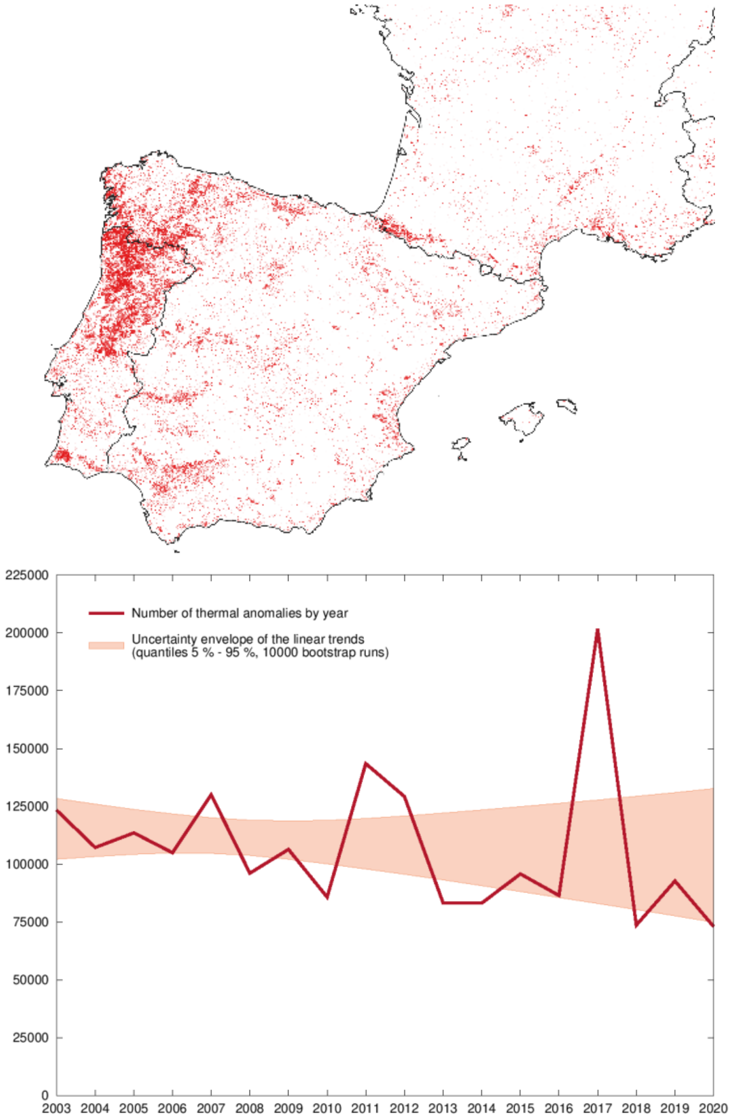


Figure 7. Causes of fire as reported by 19 European countries (Bulgaria, Croatia, Cyprus, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Poland, Portugal, Romania, Slovenia, Spain, Sweden, Switzerland) available in the Fire Database of EFFIS (Camia *et al.*, 2013, information updated to 2016), considering only when the information is (A) available, and (B) including also fires with unknown causes (from de Rigo *et al.*, 2017b).

A temporary increase in fire ignitions may lead to the simultaneity of many fire events and increase the likelihood of fires spreading and for at least some of them to become uncontrolled fires, which can cause substantial damage under environmental conditions conductive to fire growth. Historical records on the number of fires may be used to assess the contribution of fire ignition to wildfire risk. The number of ignitions, next to other key factors such as fuels or weather are used to characterize fire behaviour and thus fire danger (Finney, 2005).

Historical records on the location, damage and number of fires (Oom *et al.*, 2016; Artés Vivancos *et al.*, 2019) could be used to assess the contribution of fire ignition to fire danger. Two datasets were used for the period 2003 to 2020:

i) Active fire/thermal anomalies derived from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites (MCD14DL, C6) (Giglio *et al.*, 2020) were depicted from NASA's Fire Information for Resource Management System (FIRMS). Each MODIS active fire/thermal anomaly location represents the centre of a 1km pixel that is flagged by the algorithm as containing one or more fires within the pixel. Combined (Terra and Aqua) MODIS active fire products (MCD14DL) are processed using the standard MOD14/MYD14 Fire and Thermal Anomalies algorithm (Giglio *et al.*, 2016; Giglio *et al.*, 2020). A total of 1 936 984 thermal anomalies were used (Figure 8).

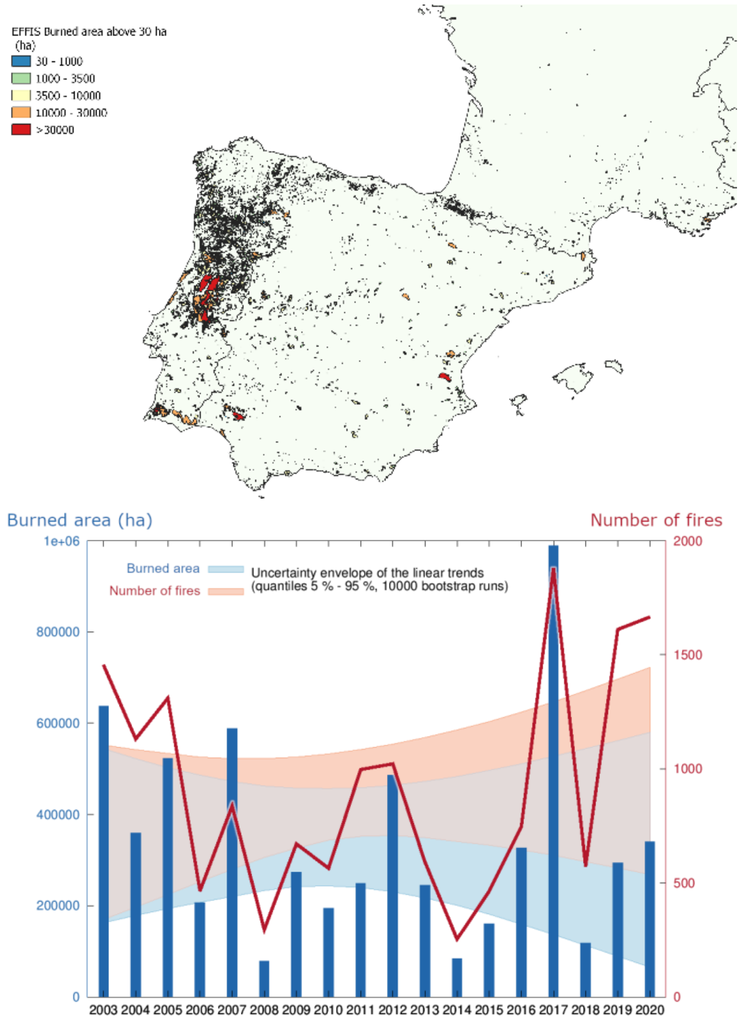


(a)

(b)

Figure 8. (a) Example of the MODIS thermal anomalies (in red) mapped in EFFIS for 2003-2020; (b) total number of MODIS (Terra and Aqua) thermal anomalies recorded by EFFIS from 2003 to 2020, in the wildfire-risk extent. Given the variability of the annual data, the multi-annual trend is affected by high uncertainty. This is demonstrated by the uncertainty envelope of the linear trend (pink, showing the uncertainty band between the quantiles 5 % and 95 % for 10000 bootstrap runs) which highlights the impossibility of detecting a trend with confidence. Source: EFFIS.

ii) EFFIS burned area based on the semi-automatic classification of MODIS satellite imagery using ancillary spatial datasets. Until 2003, maps of fire perimeters (burnt areas) were obtained only at the end of the fire campaign, i.e., end of September/October. After 2003, the processing chain was further automated to process MODIS data in near-real time. Every day, two full image mosaics of the European territory are processed in EFFIS to derive burnt area maps. Burnt scars of approximately 30 hectares in size are mapped, although the product may also include the perimeters of burned areas of smaller dimension. More than 23 thousand fire events were used with a total burned area of 7 814 303 ha (Figure 9).

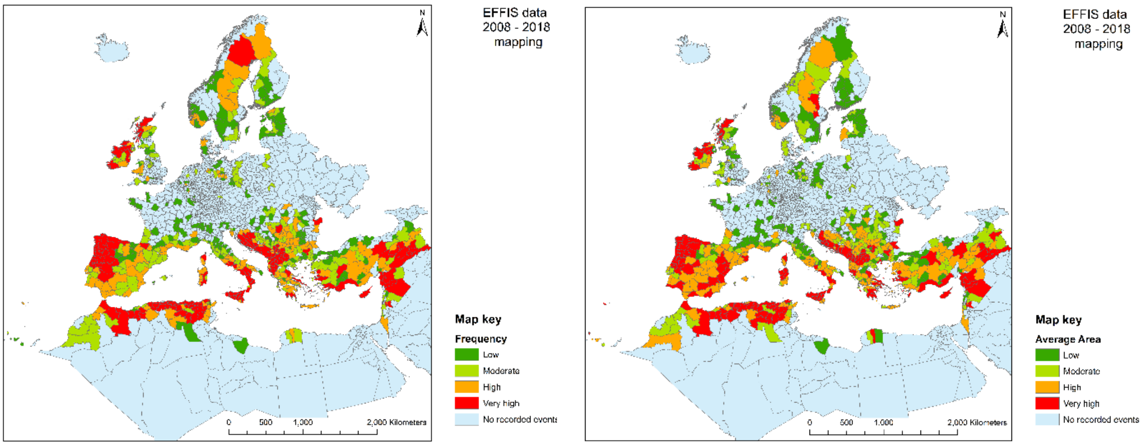


(a)

(b)

Figure 9. (a) example of burned area mapped by EFFIS (legend in fire size, ha); (b) total burned area (ha) and number of fires greater than 30 ha recorded by EFFIS from 2003 to 2020, in the wildfire-risk extent. Given the variability of the annual data for both quantities, their multi-annual trend is affected by high uncertainty. This is demonstrated by the uncertainty envelopes of the linear trend (showing the uncertainty band between the quantiles 5 % and 95 % for 10000 bootstrap runs) which highlight the impossibility of detecting a trend with confidence for the burned areas (pink), and a weak uncertain worsening trend for the number of fires (light blue). Source: EFFIS.

An example of annual fire frequency per province (NUTS3) and annual average burned area per province in EFFIS for the period 2008-2018 is presented in Figure 10 at NUTS3 levels. However, as Figure 8 and Figure 9 underlined, the distribution of satellite-detectable thermal anomalies of actual fire events (and of their resulting damage as burnt areas) is subject to substantial variability even when aggregated total values are considered for the whole continent. This means that relatively milder years may be followed by years with peak damage with an unpredictable trend (see also Figure 4 and 5 in de Rigo *et al.*, 2017b). Consequently, statistical analysis of uncertainty for these quantities is an essential component of a sound wildfire risk assessment (see section Methods).



(a) (b)

Figure 10**.** (a) Annual fire frequency (number of fires per province (NUTS3)/years) and (b) average burned area (total burned area per province (NUTS3)/years) mapped in EFFIS, classified in four categories for the period 2008 - 2018.

Fire behaviour

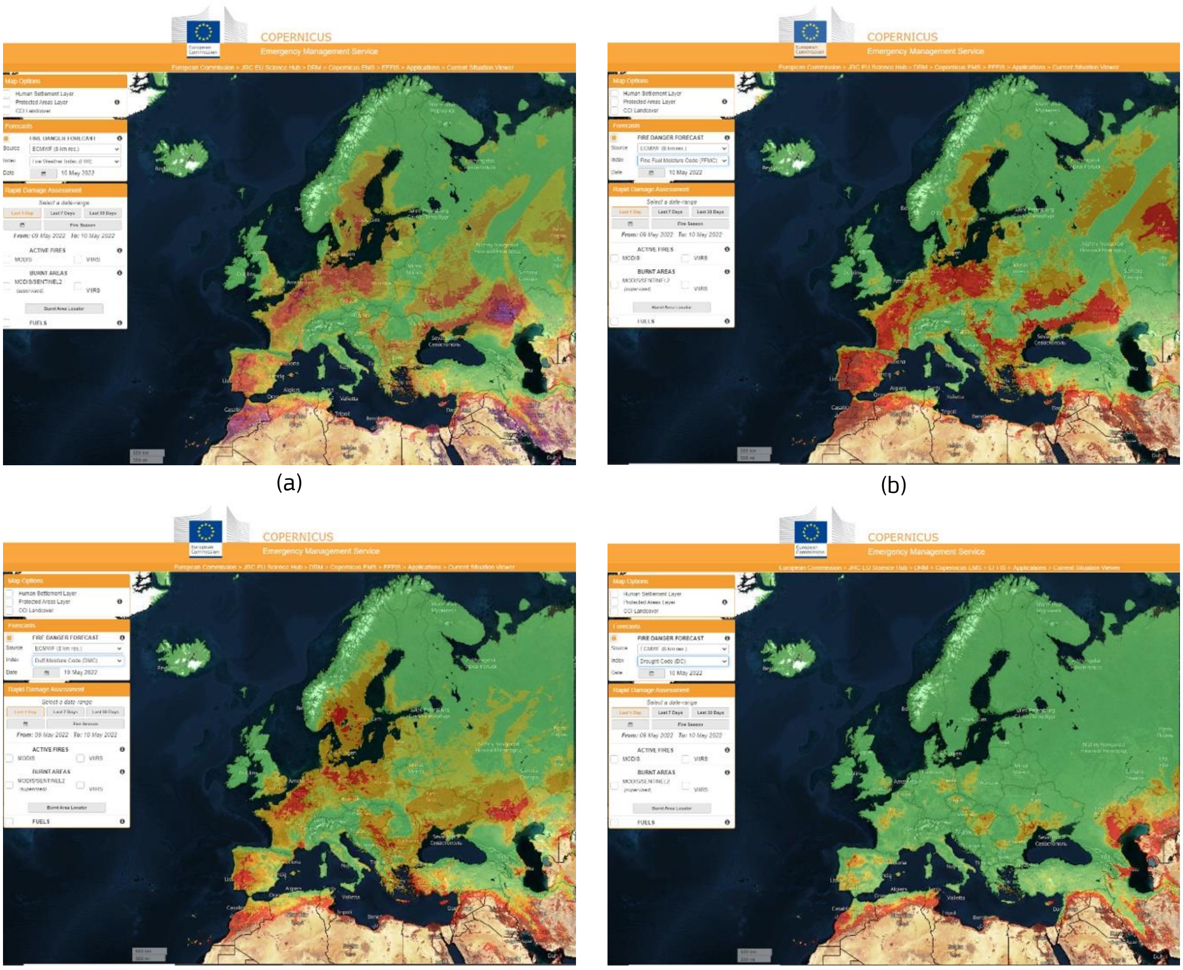
The fire behaviour is conceptually influenced by the fuel moisture content of both dead and live fuels, the different fuel types, slopes, and wind patterns that will determine the propagation (rate of spread and spread direction) of a wildfire.

Fuel moisture

Fuel moisture content is a fundamental element for availability of fuel for combustion, and as dry fuels burn easily is a fundamental element to provide favourable conditions for wildfire propagation (Van Wagner, 1987; Yebra *et al.*, 2013). Two otherwise identical samples of vegetation may react to the same fire ignition differently, if one is dry and the other one is moist. Generally, a moisture content much lower than usual constitutes a danger factor for the potential ignition and spread of fire. The fuel moisture content, defined as the proportion of water contained in the vegetation in relation to dry, fluctuates in time and space and is highly dependent on weather conditions. It can be divided into FMC of dead fuels (DFMC) or live fuels (LFMC) (Chuvieco *et al.*, 2010). In addition to the moisture content of dead fuels, the live fuel moisture content is essential in determining fire spread and intensity. Existing approaches for the estimation of moisture content of live fuels rely on empirical methods or simulations, such as those based on radiative transfer models (RTM) (Chuvieco *et al.*, 2010, Yebra *et al.*, 2013). However, estimation of live fuel moisture content is difficult and has only proven successful for grasslands and shrubs. This layer of information is not yet included in the pan-European assessment of wildfire risk presented here, and its effect on risk is only indirectly accounted for by its approximate correlation with components of DFMC (Viegas *et al.,* 2001; Ceccato *et al.,* 2003; Pellizzaro *et al., 2007;* Ruffault *et al.,* 2018).

Fine fuel components may show a fast response to changing weather, so that a windy, dry day might easily trigger a noticeable drop in their moisture content. On the other hand, thicker parts of the vegetation define quite a different fuel component: if thicker fuel requires more time (even several days or weeks) to dry under weather conditions facilitating the process, it conversely may preserve this dryness for a longer period, with a higher latency to fast changing weather. Even (not major) precipitation events may be unable to significantly increase a low fuel moisture content in thicker fuels, while a minor rainfall could easily saturate the moisture of finer fuels. Therefore, the behaviour of a wildfire is not only linked with the very recent weather conditions, but also with the cumulative effect of the past weather. This implies that numerical estimates of fire danger by weather for a certain time should include modules able to preserve the information of the weather history before that time (i.e., in modelling terminology, fire danger by weather should include not only stateless modules - expressing the current conditions - but also dynamic modules able to memorize the past states of weather). Common indices used for assessing vegetation moisture content of dead fuels are the three moisture indices which are components of the Canadian Fire Weather Index system (FWI), Fine Fuel Moisture Code (FFMC), Duff

Moisture Code (DMC) and Drought Code (DC), focusing respectively on fine, intermediate, and thicker components of fuel (De Groot, 1987; Van Wagner, 1987; de Rigo *et al.*, 2017b). The dynamic nature of these indices, and their ability to keep memory of past weather conditions, have been associated with their partial ability (especially for the components with longer time inertia) to correlate even with live fuel moisture. Examples of the indices, and depicted from EFFIS, are shown in Figure 11.



(a) (b) (c) (d)

Figure 11. Examples depicted from EFFIS current situation for the (a) Canadian Forest Fire Weather Index (FWI), (b) Fine Fuel Moisture Content (FFMC), (c) Duff Moisture Code (DMC) and (d) Drought Code (DC) (conditions on May 10th 2022).

One of these sets of indices, which is widely used in the world and is the standard in EFFIS for Europe, is the Canadian Fire Weather Index system (FWI-sys). The FWI (Figure 11a) is based on three components for assessing the moisture content of dead fuels, and relates to a specific size of fuels that can provide information on the probability of fire ignition, spread or fire intensity: the Fine Fuel Moisture Code, FFMC (Figure 11b), the Duff Moisture Code, DMC (Figure 11c) and the Drought Code, DC (Figure 11d), which refer, respectively, to the moisture content of litter and fine fuels, medium-size fuels, and thicker components of fuel with a longer drying rate (De Groot 1987). When wind is combined with the FFMC mentioned above, an intermediate index referred to as the Initial Spread Index, ISI (Figure 12) is obtained. This index considers the combined effects of wind and the FFMC and represents the expected rate of fire spread.

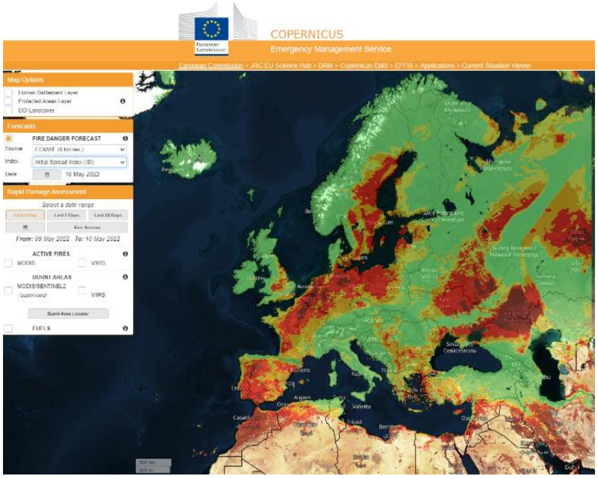


Figure 12. Example of the Initial Spread Index in EFFIS (conditions on May 10th, 2022).

For the risk assessment we used the FWI which is a combination of ISI index and the Buildup Index (BUI) (Figure 13) which by combining DMC with DC, models the total amount of fuel available for consumption, providing a uniform numerical rating of the relative fire potential, by dynamically combining the information from four local meteorological variables such as temperature, wind speed, relative humidity, and precipitation. The higher the FWI is, the more favourable the meteorological conditions would be to start a wildfire.

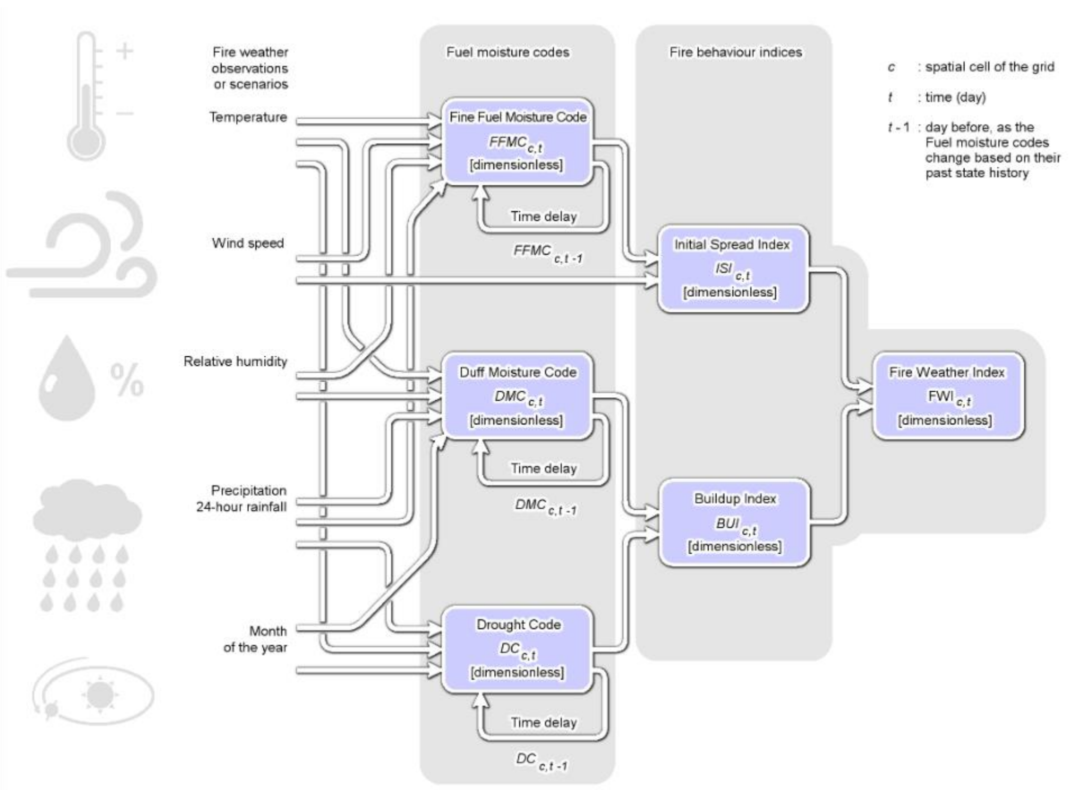


Figure 13. Canadian Fire Weather Index (FWI) System schema. Note how the first layer of components (Fuel moisture codes) is dynamic, so that the value of each component (FFMC, DMC, DC) for a given day depends also on the value of the same component the day before. The dynamic components with longer memory of their past history also approximate the seasonal changes in solar radiation, by considering the month of the year (for a more detailed schema, see de Rigo *et al.*, 2017b; source: https://doi.org/10.5281/zenodo.6558577).

The FWI uses information on the moisture content of dead fuels, as estimated from meteorological variables, and wind speed to determine the level of "fire danger" in different areas (Van Wagner, 1987). Long-term series of FWI data can be used as an explanatory variable in the assessment of wildfire danger at the pan-European level. The FWI has been proven suitable for European conditions (Viegas *et al.*, 1999) and is currently used in the European Forest Fire Information System and widely adopted by many European countries as a best harmonized approach to assess wildfire danger (San-Miguel-Ayanz *et al.*, 2019). The FWI-sys components are computed on the basis of numerical weather reanalysis from the European Centre for Medium-Range Weather Predictions (ECMWF) at a spatial resolution of 0.25° x 0.25° (~27 km at the equator, Hersbach *et al.*, 2018), generating a corresponding set of FWI-sys daily components with the same spatial resolution (Copernicus Emergency Management Service, 2019; Vitolo *et al.,* 2020).For this version we calculate the number of days where the value of FWI was higher than 30 (denoting high-to-extreme conditions of fire danger by weather, Costa *et al.*, 2020) (Figure 14).

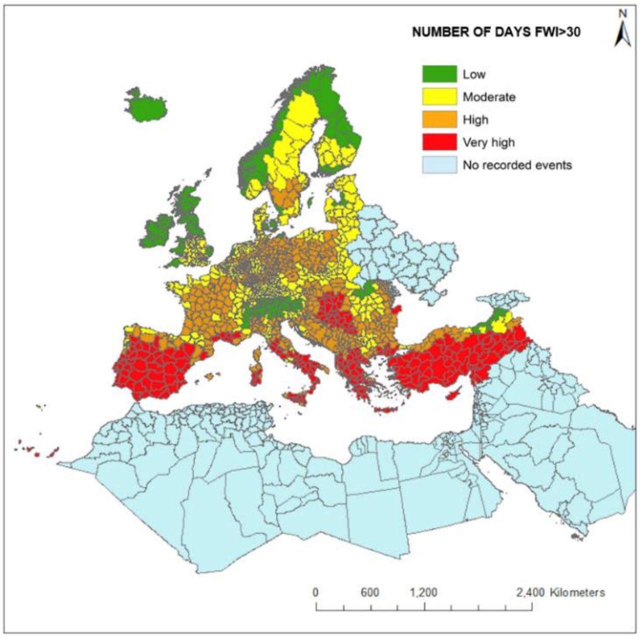


Figure 14. Frequency of days with high-to-extreme fire danger by weather (Fire Weather Index, FWI, greater than 30).

Fuel/vegetation Types

The type of fuel available to burn, which may include trees, shrubs, grasslands, etc., will directly influence the wildfire propagation and is key to fire propagation risk assessment as it considers the changes and dynamics of vegetation due to fire (Aragoneses and Chuvieco, 2021). Each type of vegetation fuel, with its physical and chemical specific attributes and its phenology, affects wildfire behaviour (rate of spread, fire intensity, and propagation) and the impacts of wildfires. Moreover, wildfire behaviour is highly dependent on the horizontal and vertical structure of the fuels and the inter-connection among them, which may determine the horizontal and vertical progression of the fire front (Scott and Burgan 2005). Fully characterising vegetation and its susceptibility to disturbances (including wildfires) would require its composition, structure, and management to be known, along with its suitability/resistance/resilience to the changing bioclimatic conditions of the local habitat, whose detailed characterisation is currently not yet fully feasible at the continental scale (de Rigo *et al.*, 2016; 2017a). Therefore, simplified approximations are required. As the determination of fuel properties and their combinations in practice is a very complex process, they are usually grouped in fuel types following some classification schemes or typologies being a necessary input for risk management and fire effects. Fuel maps are often developed through a combination of ground measurements such as forest and vegetation inventories and remote sensing techniques as they provide updated spatial coverage and are sensitive to some of the critical variables for fuel type definition such as fuel moisture, fuel loads, horizontal and vertical continuity (Pettinari and Chuvieco, 2016). At the European level, a data set that is already available and useful to address fuel types as a criterion for assessing wildfire danger at the European scale is the Fuel Map of Europe (EFFIS, 2017). This data set (Figure 15), which initially maps 42 fuel types that are organized in 9 groups (Grassland, Shrubland, transitional shrubland/forest, conifer forest, broadleaved forest, mixed forest, aquatic vegetation, agro-forestry areas and peat bogs) is further converted into the 13 fuel models of the National Fire Danger

Rating System (NFDRS) of which only 10 are used assess wildfire behaviour (Anderson, 1982). In the first WRA version, the potentially burnable vegetation in each aggregated class of fuel types is provided as basic contextual information. Also, at European scale, a new fuel map is being developed under the FireEuRisk project, funded by the European Union's Horizon 2020 research and innovation programme under the Grant Agreement no. 101003890 (https://fireurisk.eu).

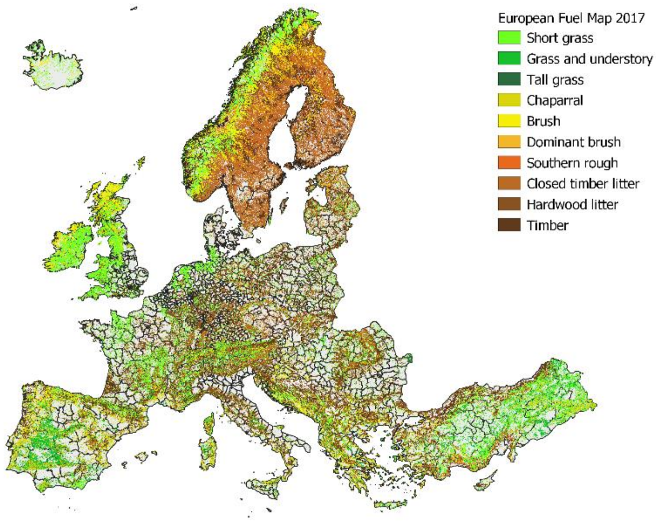


Figure 15. Fuel map of Europe (EFFIS, 2017).

In addition, the Corine Land Cover (CLC) collections (2000, 2006, 2020 and 2018) were used as a first proxy to assess the vegetation classes most affected by fires. CLC, initiated by the European Union in 1985, consists of 44 land cover classes (Bossard *et al.*, 2000) with a Minimum Mapping Unit (MMU) of 25 hectares (ha) and a minimum feature width of 100 m providing a harmonized description of the land use and land change (LULC) in Europe over the last 30 years (Figure 16). Validation assessments were performed for the CLC2000 using data from the LUCAS project (European Land Use/Cover Area Frame Statistical Survey) (Büttner and Maucha, 2006; Büttner *et al.*, 2012) and for the changes between CLC2000 and CLC2006 (Büttner *et al.*, 2011) achieving accuracies of around 85 %. In order to distinguish between fires related with urban or agriculture activities and wildfires, an aggregation of the CLC classes was performed for each collection of the CLC, resulting in two classes designated as 'Wildland (WL)" and 'non-Wildland (NWL)". This aggregation allocated all the artificial and agricultural areas to NWL. In addition, for each land cover class the fraction of potentially burnable vegetation was assessed (see section Methods) at a higher resolution, in order for the limitations due to the Corine MMU, and the heterogenous content of vegetation in several land-cover classes, to be refined and a more accurate estimation of vegetation fuels to become available.

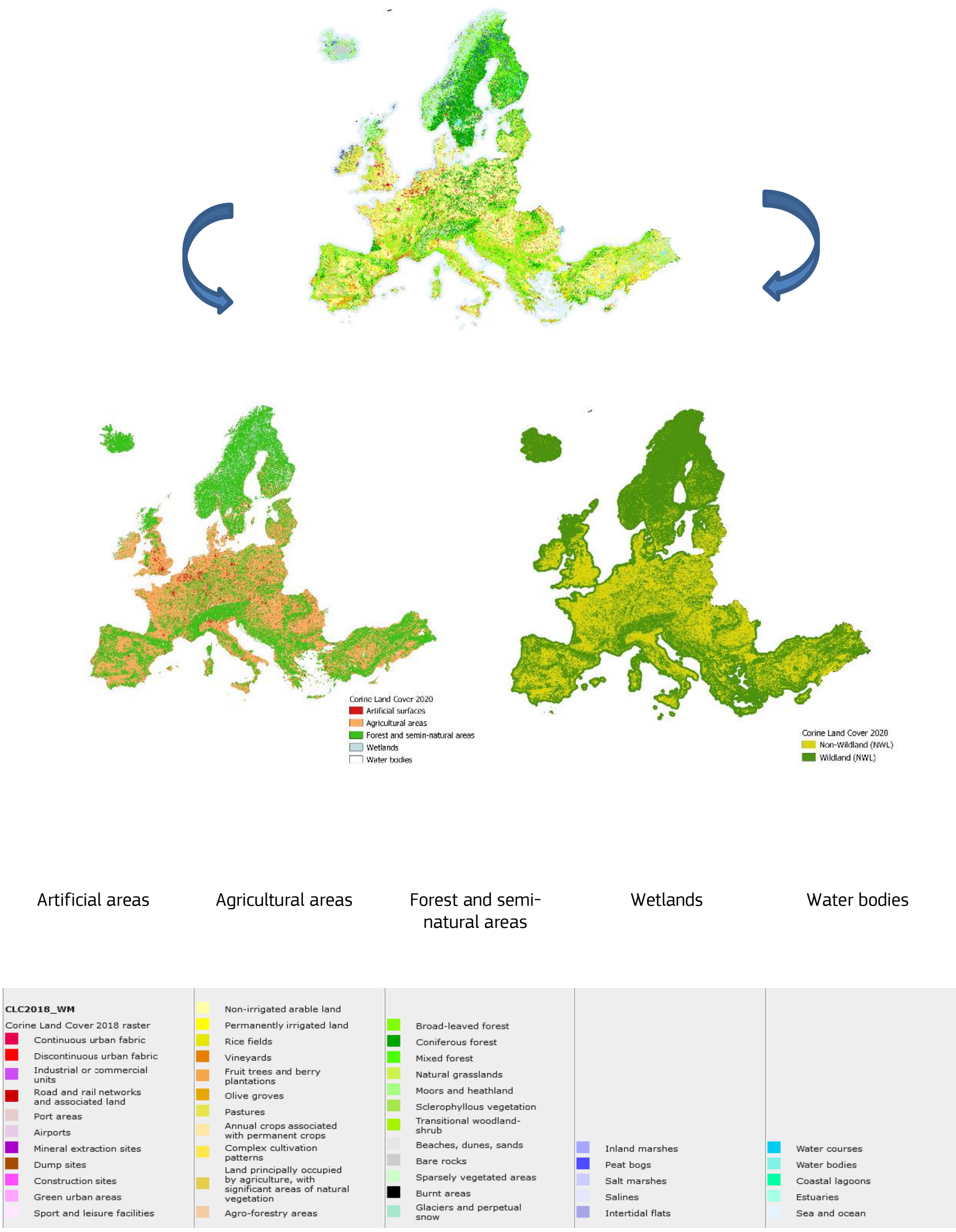


Figure 16.(a) Corine Land Cover (CLC) 2018, Version 2020_20u1 (source: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=mapview) and the correspondent extensive legend displayed, (b) aggregated in 5 classes and (c) aggregated in two-classes Wildland/Non-Wildland.

Slopes/Wind

Slope is the rate of change of elevation in the direction of the water flow line and it is especially important for the quantification of soil erosion, water flow velocity, or agricultural suitability (Amatulli *et al.*, 2020). It is as relevant for fire behaviour and wildfire propagation, as it is the local aspect and elevation. For example, steep slopes (15°-20°) may affect wind direction and speed facilitating fire spread, and southern facing slopes in the northern hemisphere are likely to be hotter and drier as they receive more sunlight, and hence can effectively dry fuels that may become prone to fire ignition and propagation (Conedera *et al.*, 2018). Also, elevation could affect fire behaviour where higher elevations may be associated with low humidity (e.g. in case of rain shadow effects, leeward side) or conversely with increased precipitation (windward side) and increased wind speed, depending on the prevailing winds. In areas subject to frequent fire occurrence, even the local soil and vegetation composition may differ depending on the orography (Sharples, 2008; Hernandez *et al.*, 2015; de Rigo *et al.*, 2017b). Associated with terrain characteristics, local wind conditions (direction, speed) could also affect wildfire propagation and intensity.

Data from the MERIT-Digital Elevation Model (DEM) Geomorpho90m variables (Amatulli *et al.*, 2020) such as slope and aspect were calculated (Figure 17).

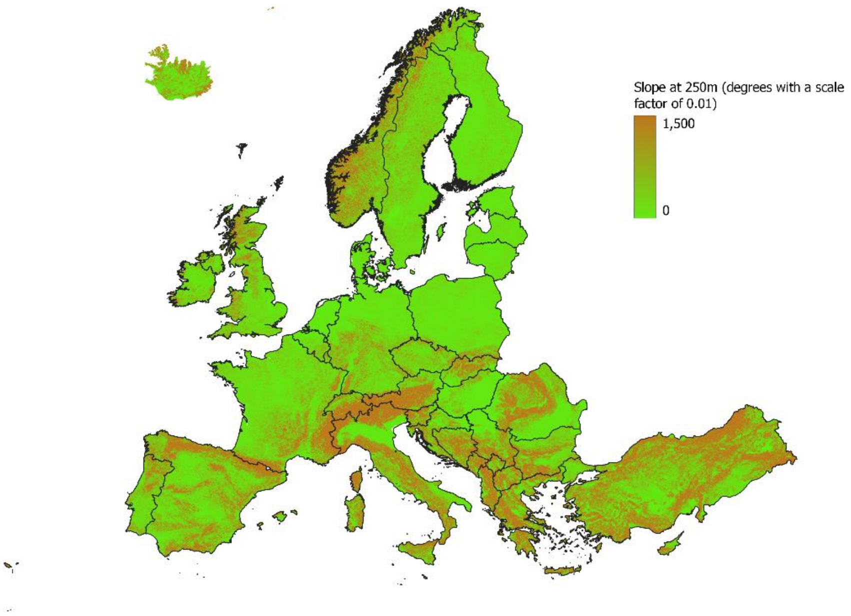


Figure 17. Values of slope at 250m (degrees) with a scale factor of 0.01 (Amatulli et al., 2020).

Winds can be considered for wildfire risk assessment through the Initial Spread Index (ISI) (Figure 12) of the Canadian FWI-system. ISI considers the combined effects of wind and the Fine Fuel Moisture Code (FFMC) and represents the expected rate of fire spread. Both orographic information, and direct use of wind, are currently under exploratory research, to test their potential (and limitations) in refining future versions of the European WRA.

Vulnerability

As aforementioned, in the wildfire domain the concepts of vulnerability and exposure are interlinked and cannot be easily estimated separately. For example, on the one hand people exposed in the vulnerable interface between settlements and wildland have to bear more frequently the effects of wildfires; on the other hand, wildfires are more frequently caused by human activity (either deliberate, or accidental) in those vulnerable areas, so that a feedback exists between exposed people, and vulnerable interface areas, which are defined also because of the human presence and activity (de Rigo *et al*., 2017b; Costa *et al*., 2020). At the same time, while protection measures against milder fires may be effective, large uncontrolled wildfires may cause infrastructure disruption and health effects due to smoke affecting indiscriminately the people exposed, with damage very difficult to estimate (Stefanidou *et al*., 2008; Finlay *et al*., 2012; Reid *et al*., 2016). In the following, the term "*vulnerability*" is intended to encompass people, ecosystems, and goods exposed in vulnerable areas. This concise term includes the presence of assets within hazard zones, UNISDR, 2015), and their susceptibility of suffering damage (San-Miguel-Ayanz *et al*., 2017), and within the risk framework is intended to be evaluated before the fire occurs (Chuvieco *et al*., 2012). Defined as "the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" by UNISDR (2009), it has been recently included in fire risk systems (Chuvieco *et al.*, 2010. 2012; Thompson *et al.*, 2011), referring to the condition of assets that are exposed and subject to being damaged by wildfires. As anticipated, we consider three categories of vulnerability: people (focusing on the population exposed in the wildland-urban interface, WUI); natural ecosystem assets that have an intrinsic ecological value (quantified by ecological indicators beyond economy and market); and assets at the interface between nature and human activity (for example, forests, other woodland, and agricultural land) whose market value (e.g., timber, agriculture products) can be quantified monetarily.

People

Populated areas are often close to wildland, generating a human-nature interface. This may be observed where abandoned agricultural areas lead to an expanding wildland, or conversely where settlements enlarge over areas previously dominated by wildland. The evaluation of the 'social vulnerability' (Chuvieco *et al.*, 2012, Wigtil *et al.*, 2016) is often focused on this interface, designated as the wildland-urban-interface (WUI).
This iinterface between interconnected patches of vegetation fuels and settlements increases the number of potential ignition agents and with lack of fuel management can easily worsen the wildfire risk, especially in a fire-prone landscape such as the Mediterranean-type vegetation, posing a major threat to the population living in the WUI (Oliveira et al., 2018). Ignitions are more frequent because of the accessibility of fuels to people, threatening also neighbouring locations in the WUI because fires may spread in fuel-rich areas within or adjacent to the WUI. Consequently, the risk of fire near the WUI may be especially high for the population (Vilar del Hoyo et al., 2011; Kaim et al., 2018; Fox et al., 2018; Pastor et al., 2020). Particular attention has been given all over the world to the WUI for research, management and prevention of wildfires (Stewart et al., 2007; Syphard et al., 2007; Vilar del Hoyo et al., 2011; Gallardo et al., 2016; Fox et al., 2018; Kaim et al., 2018) because of its large risk of wildfires. Several recent catastrophic fire events have occurred in these areas, such as Greece (2007 and 2018), Russia (2010) or Portugal (2017) with dramatic impacts on human lives and assets. A JRC's WUI layer (Costa et al., 2020) is considered as a component (Figure 18) to determine human vulnerability to wildfires and to be integrated into the wildfire risk assessment in the approach proposed. As contextual information, not directly considered in the computing of the European WRA, but useful to explore visually local details, the JRC's Global Human Settlement Layer (GHSL) is made available in the WRA viewer, as a high-resolution layer of information on human houses/structures derived from remote sensing imagery at a spatial resolution of 30 metres.

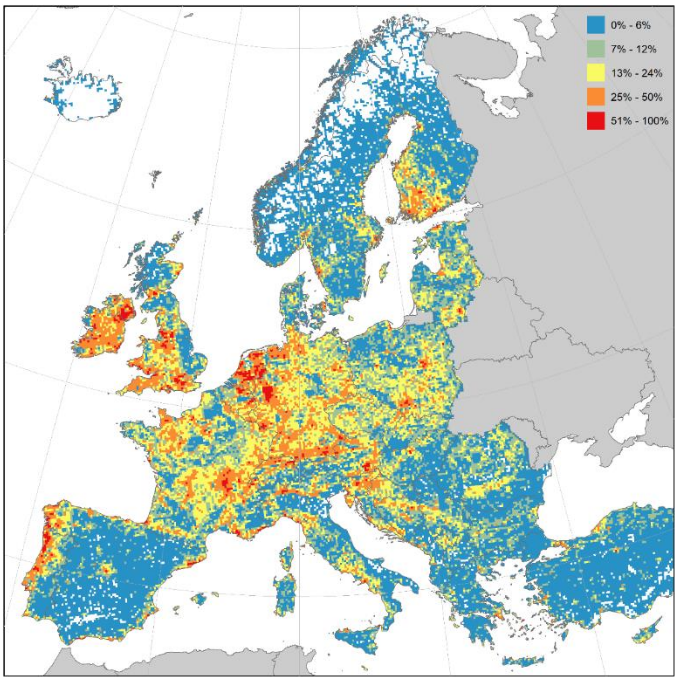


Figure 18. Percentage of land area which lies in the Wildland Urban Interface (WUI) from Costa et al., (2020).

Ecological value

Generally, the ecological impacts from a wildfire are mainly focused on the non-monetary values of ecosystems services, such as the negative impacts of fires on two major components: soils (soil loss, decreasing soil fertility, erosion) and vegetation cover. This 'intrinsic value' is related, according to Chuvieco *et al.*, (2013), with the ecosystem's capacity to provide biodiversity richness/uniqueness, conservation status and habitat fragmentation (connectivity). Additionally, we know that protecting ecological assets is fundamental for all forms of life, including humans. The vulnerability of an ecosystem's environmental value could be assessed through ecological indicators related to these three aspects at several temporal scales, such as short (immediately after the fire) and long term (changes in vegetation structure and composition after few decades including the vegetation response ability). The integration of the two temporal scales could be combined in an index of the degradation potential associated with fire (described in Alloza *et al.*, 2006 and Chuvieco *et al.*, 2010). However, it is difficult to consider the whole ecosystem's short- to long-term response to fire, mainly due to the difficulty of establishing appropriate long-term field-based experiments to assess vegetation responses (Duguy *et al.*, 2012). Examples of ecological indicators may include the distribution of protected natural areas, and of areas of those ecosystems in which the recovery after wildfires may be compromised by weather conditions. This value is related, according to Chuvieco *et al.*, (2013), with the ecosystem's capacity to provide biodiversity richness/uniqueness, conservation status and habitat fragmentation (connectivity).

Considering that ecological values are difficult to measure as they are often intangible, we suggest a qualitative approach to assess the ecological vulnerability within the wildfire risk framework. Therefore, to emphasize the special ecological values of a territory we use the Natura 2000 network Figure 19 as it derives from harmonized criteria for defining protected areas in the European context, ensuring the long-term survival of Europe's most valuable and threatened species and habitats. They include over 1.5 million km^2 across 39 European countries in 2017 (covering almost 26 % of Europe's terrestrial territory) ranging from national parks to forest reserves and from strict nature reserves to resource reserves with more than 100000 sites (https://www.eea.europa.eu/data-and-maps/indicators/nationally-designated-protected-areas-10/assessment).

Natura 2000 is a key instrument to protect biodiversity in the European Union and identifies the most valuable and threatened species and habitats in Europe, whose damage from wildfires represent great loss, in some cases potentially not recoverable in a worst-case scenario. Natura 2000 sites include several different types of protected areas, such as Bird Directive Sites (SPA), and Habitats Directive Sites, which are defined with different motivations and can be used to refine levels of wildfire risk. Additionally, we also use the World Database on Protected areas, WDPA, (https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA), a joint initiative between the United Nations Environment Programme (UNEP) and the International Union for Conservation of Nature (IUCN), managed by UNEP World Conservation Monitoring Centre (UNEP-WCMC). However, there is still a gap in the effectiveness of protected areas for conserving global biodiversity as mentioned by Le Saout *et al.*, (2013). In order to fill that gap and improve the value of the 'intrinsic value' related with the ecosystem's capacity to provide biodiversity richness/uniqueness, conservation status and habitat fragmentation, we also used what is designated as "Ecological irreplaceability score" for each protected area, which reflects the potential contribution of a protected area to conservation goals or, conversely, the extent to which options for meeting those goals are lost if the protected area is lost (Le Saout *et al.*, 2013).

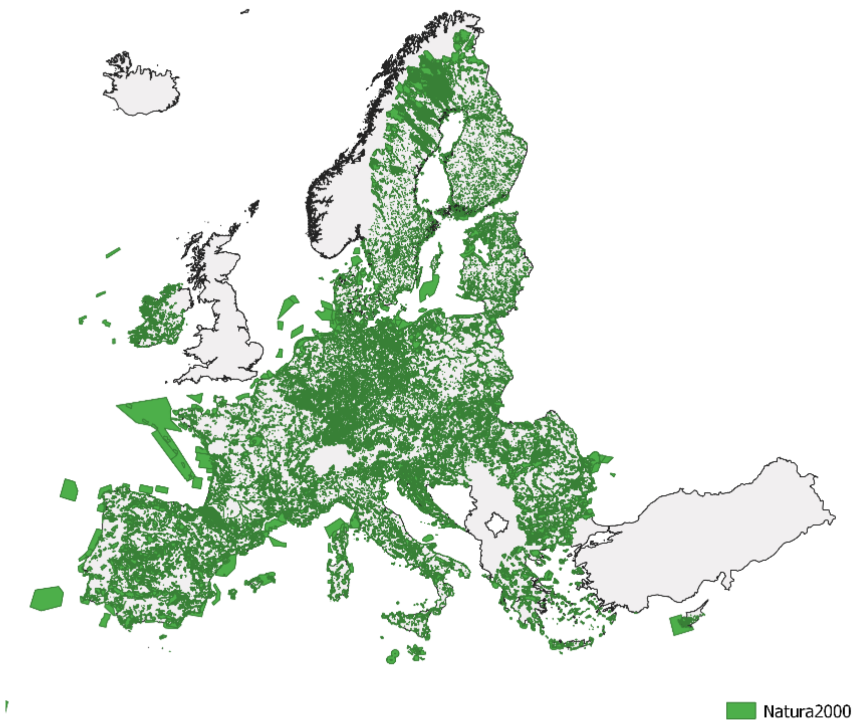


Figure 19. Natura 2000 network sites (https://www.eea.europa.eu/data-and-maps/data/natura-13).

Socio-economic value

Socio-economic damage caused by wildfires affects people's livelihood, safety, health, etc. Vulnerable areas may be identified considering the presence and value of houses and infrastructure, the monetary value of the vegetation and wildlife that may burn, as well as the value of ecosystem services that would be lost after wildfires. Properties, infrastructures, economic services provided by the vegetation (wood, non-wood products, hunting revenues, fungi, etc.), agricultural products, carbon stocks or recreational and tourist services can be associated to economic and social factors and be a part of the 'tangible" values at stake (vulnerability) in the wildfire risk assessment.

A practical approach to address this criterion is to estimate the damage of wildfires in terms of costs of restoring land cover to its former state, before a potential wildfire. Wildfire damage costs have been estimated for Europe based on the restoration cost of CORINE Land Cover classes (Oehler *et al.*, 2012, Camia *et al.*, 2017). These authors established a restoration cost for each land cover class at country level, and an average restoration time was defined according to the recovery capacity of the land cover. The damage caused by wildfire was estimated by discounting the cost of restoring the land cover over a restoration period. Different estimates were produced for three different vulnerability scenarios in which different levels of damage could be caused by low, medium and high wildfire severity (Figure 20).

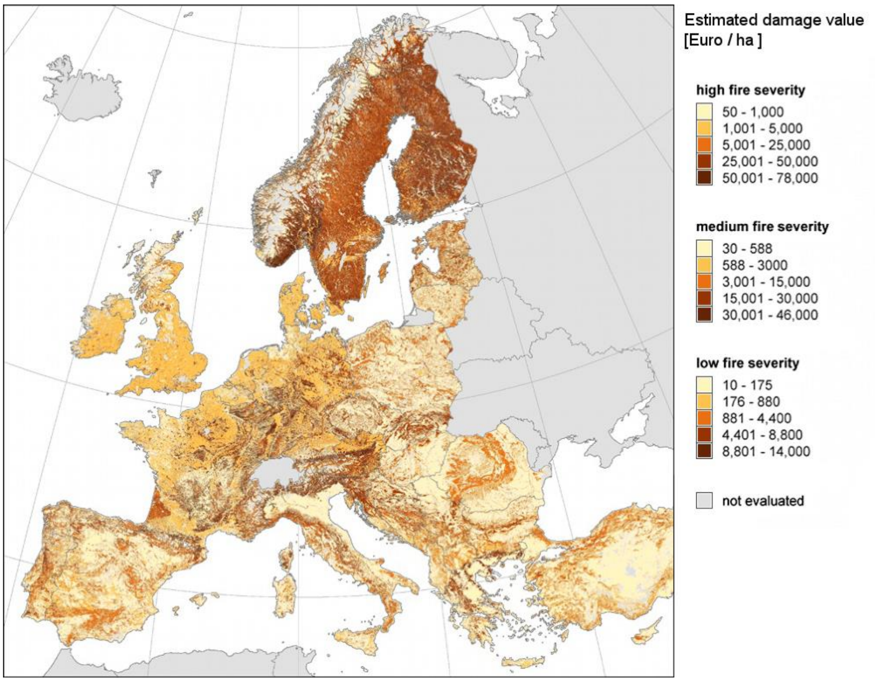


Figure 20. Socio-economic value (reconstruction cost of different land cover types in different countries) (from Oehler *et al.*, 2012).

Table 3 summarises all the data used in this version, with an indication of the corresponding temporal and spatial resolution, also displaying the correspondent maps.

Table 3. Resume of the data used in wildfire risk (version 1) with the temporal and spatial resolution (grey boxes are variables that are not included in this version, being still the object of exploratory research).

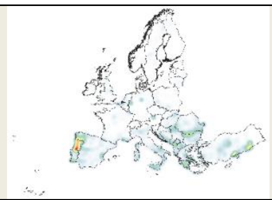
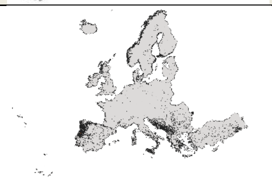
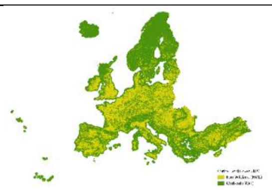
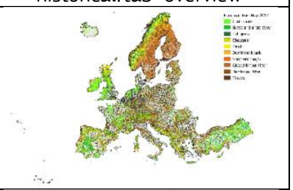
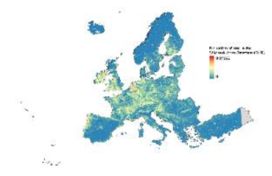
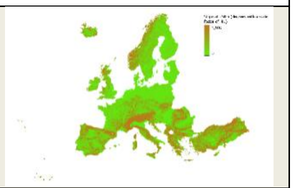
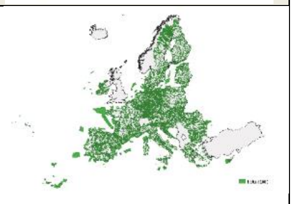
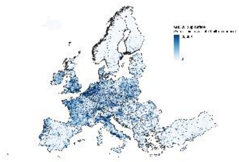
Data (original)	Temporal Resolution	Spatial Resolution	Maps
MODIS thermal anomalies	Daily for 2003-2020	1000m	
Fire Intensity (based on MODIS thermal anomalies FRP values)	Daily for 2003-2020	1000m	
EFFIS burned area	Daily for 2003-2020	250m	
Corine Land Cover	2000;2006;2012;2018	25ha	
FWI, BUI, ISI	Daily for 2003-2020	0.25° (approx. 27 Km at the equator)	https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-fire-historical?tab=overview
Fuel map	2017	250m	
WUI	2012	EURO-CORDEX (approx. 11 km)	
Slope	2018	250m	
Natura 2000	2021	Vector data, scale 1:100000	

Table 3 (cont.). Resume of the data used in wildfire risk (version 1) with the temporal and spatial resolution (grey boxes are variables that are not included in this version, being still the object of exploratory research).

WDPA	2021	The data comes from a wide range of sources which use different scales and techniques to generate the data.	
GHS-built-up surface	2020	1000m	
Global Water Layer	2020	0.00025°	

Methodology

To identify areas where vegetation fires could occur, a high-resolution mask was developed and designated as "Potential Burnable Area", PBA) (Figure 21). This mask refers to any type of vegetation that could burn, so also including cropland, with the goal to act as a filter to avoid false alarms, detecting observations that do not correspond to vegetation fires. The Global Human Settlement Layer (GHSL) built-up product (Corbane *et al.*, 2018) jointly with the JRC's Global Water Layer (Pekel *et al.*, 2016) and the Normalized Difference Vegetation Index (NDVI) time series generated by the Global Land Service of Copernicus from the PROBA-V 333m NDVI product were used as input. The data processing was implemented with spatial resolution of ~30 metres, and then aggregated at the spatial resolution of the WCRP[4]. A pixel was masked, i.e., considered as non-burnable pixel if the maximum annual value of NDVI was lower than 0.2, so below that value would correspond to areas where there is little or no vegetation to burn.

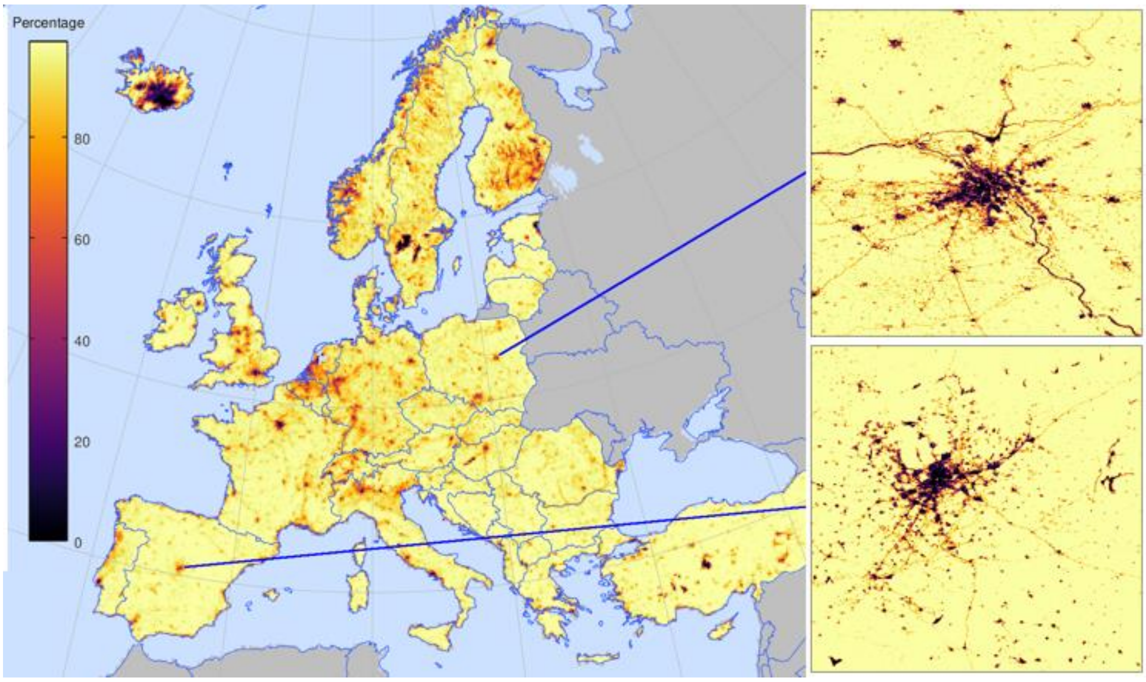


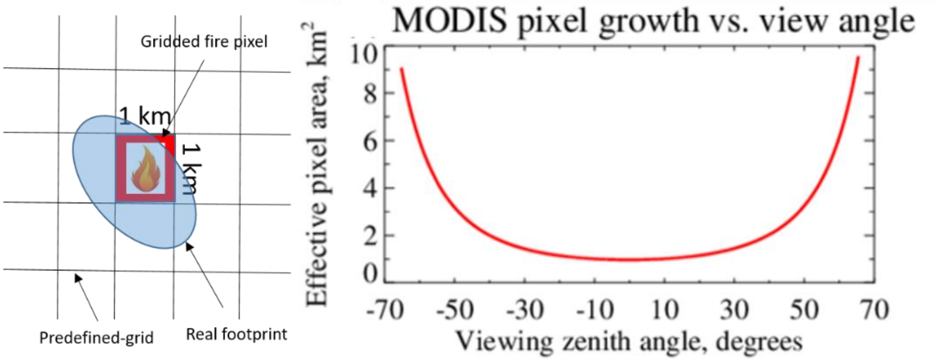
Figure 21. Potential Burnable Area proportion (PBAP, in the range 0-100 %) in each 12.5 km cell. Right inside are examples of the cities of Madrid and Warsaw.

Thermal anomalies weighting/ranking

Considering all the available information on areas with detectable fires (where thermal anomalies are detected from satellites), a detailed assessment can be made at the continental scale. However, not all the detected thermal anomalies may be referred to actual wildfires. A fraction of false positives refers to industries, smokestacks, gas flares, volcanoes, or other sources of thermal activity not related to wildfires. Another fraction (in some areas, quite large) of thermal anomalies may be associated to agriculture fires. Therefore, this key source of information on fires requires careful tuning to become useful (see Figure 22 and the corresponding section). In this section, an overview of how fires can be detected by satellites is briefly offered. Then, the methodology will be outlined for filtering out non-wildfire related thermal anomalies and ranking the remaining anomalies to prioritise those more clearly related to wildfires, against those more likely to refer to other fires (e.g., cropland fires).

[4] European grid of the Coordinated Regional Climate Downscaling Experiment (CORDEX) by World Climate Research Programme (WCRP). Archived at https://tinyurl.com/y85nxfdw. The standard grid EUR-11 is used (grid cell resolution of approximately 0.11 degrees, or about 12.5 km).

A) **How thermal anomalies by fires are detected remotely –** MODIS sensor could detect flaming and smouldering fires around 1000 m^2, however, under excellent observation conditions, fires around 50 m^2 could also be detected (Giglio *et al.*, 2020). The location of the fire is the centre of the nominal MODIS ~1km pixel, not necessarily the coordinates of the actual fire. The actual fire size pixel is usually larger than the one provided in a pixel grid-based product (Figure 22a). The MODIS pixel size varies with the scan and track exhibiting a large distortion at the end of scan, growing in size from nadir with increasing view zenith angles (VZAs). This increase could go from ~1 km nominal size to ~2.01 km and ~4.83 km in the along-track and along-scan directions, respectively (Wolfe *et al.*, 1998) (Figure 22b). The scan and track values (in metres) were used to define the "real" footprint area (size of the thermal anomalies pixel), for each one of the 3 785 732 MODIS thermal anomalies.



(a) (b)

Figure 22. (a) Illustration a MODIS observation cell in the gridded products (the "fire" square represents the 1km grid cell with fire, whereas the ellipse represents the 'real" footprint) and (b) representation of how the area of nominal 1km×1km size increase as ta a function of viewing zenith angles (VZA) (from Sayer *et al.*, 2015).

B) **Filtering satellite observations and ranking thermal anomalies to prioritise wildfires over other types of fires –** For each MODIS fire pixel footprint, the proportion of the PBA (PBAP), burned area (with 1km buffer around each burned area), CLC classes and WL and NWL classes were calculated. Figure 23 shows an illustration of the intersection between the MODIS thermal anomaly (TA) "real" footprint (in orange) with the burned area (dashed polygon) and the WL/NWL land cover.

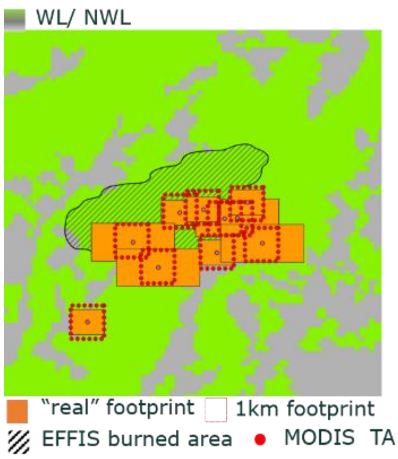


Figure 23. Illustration of the method of thermal anomalies classification based on the EFFIS burned area and CLC landcover classes aggregated in Wildland vs non-Wildland areas.

The goal for these statistics is twofold. First, thermal anomalies whose footprint lies outside any potential burnable vegetation fuel are filtered out as non-wildfire activity (either linked with industries, smokestacks, gas flares, volcanoes, or other sources of satellite-detectable thermal anomalies which however cannot be linked to any vegetation-fuel burning). After this filtering to remove false detections, the second goal is to analyse whether a threshold can be defined to discriminate the fire typology, i.e., to assess if the thermal anomaly is related with agriculture practices (cropland fires), or instead potentially related with a legitimate wildfire. Rather than a drastic binary classification (where thermal anomalies marked as likely “cropfires” would have been simply discarded), a more robust fuzzy classification is introduced, so that the level of fuzzy-confidence may be assessed to rank thermal anomalies as wildfire-related in a way more tolerant to data uncertainty and misclassification. Around 5 % of the total thermal anomalies where the proportion of WL was lower than 5 % and not allocated to any burned was flagged. As shown in Figure 24 and Figure 25, a considerable number of thermal anomalies have high proportions of CLC classes related with agricultural activities or non-wildland classification type. Without an appropriate modelling strategy to better discriminate between thermal anomalies, in the working spatial grid (Coordinated Regional Climate Downscaling Experiment, 2015, see footnote 4) the problem would be clearly visible (Figure 26a).

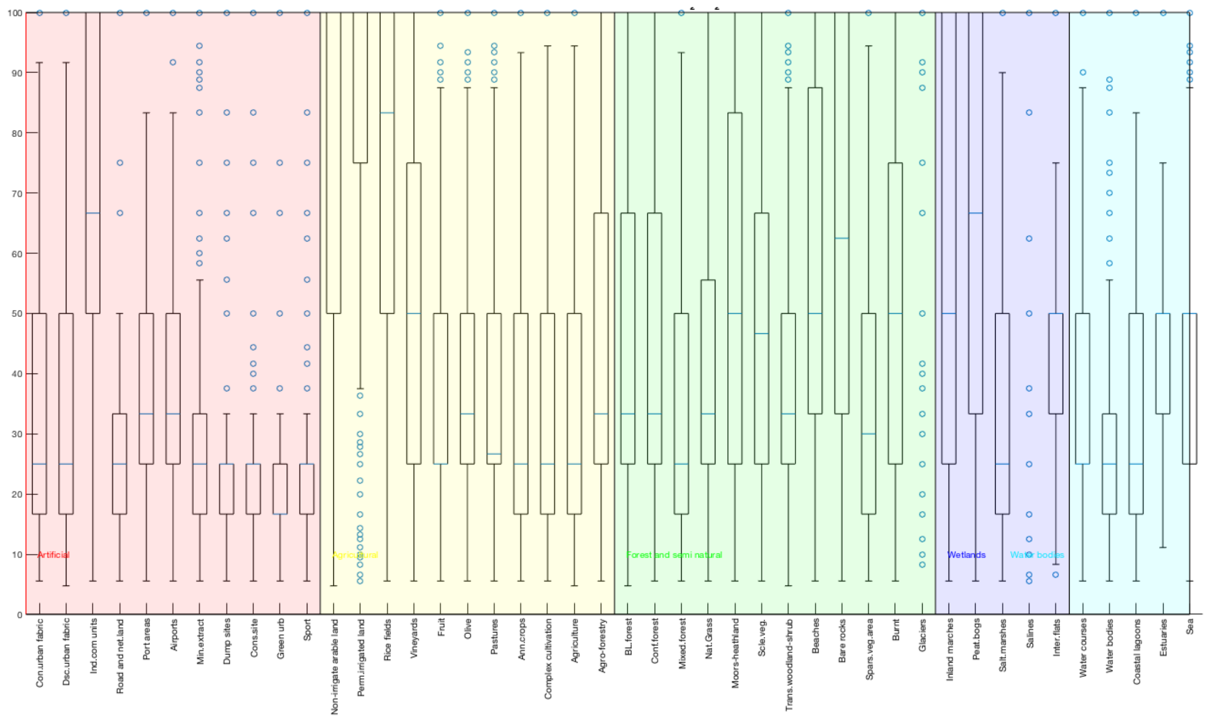


Figure 24. Boxplots of the proportion of each Corine Landcover class for all the MODIS fire pixel footprint (2003-2020). Different colours represent the aggregated 5 classes of CLC- see Figure 16 (red-artificial areas, yellow-agricultural areas, green-forest and semi-natural areas, blue-wetlands, cyan-water bodies).

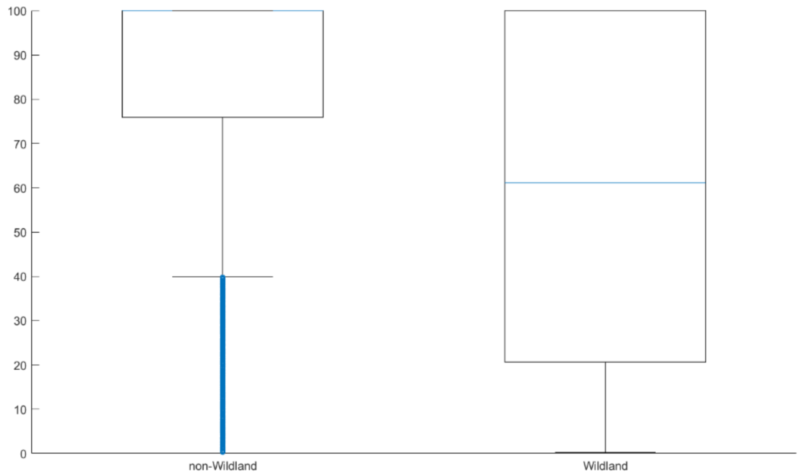


Figure 25. Boxplots for the Wildland/non-Wildland aggregation for all the MODIS fire pixel footprint (2003-2020).

This problem was discussed together with the Countries' representatives participating in the WRA, and the ranking discussed at the end of this section was introduced. Before outlining the mechanism of the fuzzy ranking for the thermal anomalies, a visual overview may be useful to appreciate qualitatively the distribution and prevalence of cropland fires in Europe. An illustrative example of the comparison between an initial version of "Danger by fire thermal anomalies", and the improved current "Danger by wildfire thermal anomalies" after the thermal anomalies ranking procedure is shown in Figure 26(a and b) The patterns in the improved version are matching better the historical series of burnt areas in EFFIS (Figure 26c). In addition, a key element is the estimate of biomass burning emissions (even for their relevance for climate change). The total carbon in aerosols, estimated by the Global Fire Assimilation System (GFAS, v1.2) (Kaiser *et al.*, 2011) is shown in Figure 26d, highlighting the maximum daily values in the years 2018-2021.

In Romania, where the relatively flat land along river channels offers a terrain suitable for farming, promoting the use of fire to burn crop residues, or in Central Turkey, where fire is used as an agriculture tool for stubble burning in the central part of the country are just a subset of the European areas where the thermal anomalies ranking procedure revealed major changes (Figure 27).

Two aspects were considered in the ranking of thermal anomalies (TA) to qualitatively estimate their (fuzzy) possibility to originate from wildfires. First (criterion A), for each TA footprint (see Figure 23) the percentage of overlap with known historical wildfires was assessed. For each year, this was done by applying an uncertainty buffer to the wildfire perimeters manually classified within EFFIS, and by estimating its intersection with each TA footprint. Second (criterion B), the percentage of overlap with *burnable* wildland fuel (i.e. the fraction of wildland area occupied by potentially burnable vegetation fuel) was assessed. Since wildfires in EFFIS include at least 5 % of wildland in their final perimeter, the same percentage of burnable wildland was considered as the minimum for a TA to be labelled as wildfire according to this secondary criterion. Thermal anomalies with higher overlap with known wildfires were prioritised. If two TA had the same overlap with known wildfires, then the TA labelled as wildfire (at least 5 % burnable wildland in its footprint) was prioritised over TA without intersection with wildland. Intermediate percentages of burnable wildland (between 0 and 5 %) were accordingly ranked. The mathematical mechanism for this ranking relies on standard long-established lexicographic sorting algorithms (Fishburn, 1974; Ben-Tal, 1980; Weber *et al.*, 2002): first, ranking by criterion A, then secondarily ranking by criterion B all the TA with the same value in the criterion A. After the ranking procedure, the danger by wildfire TA (Figure 26b) was estimated as an improved version of the initial danger by fire (either wildfire, or cropland fire) TA (Figure 26a).

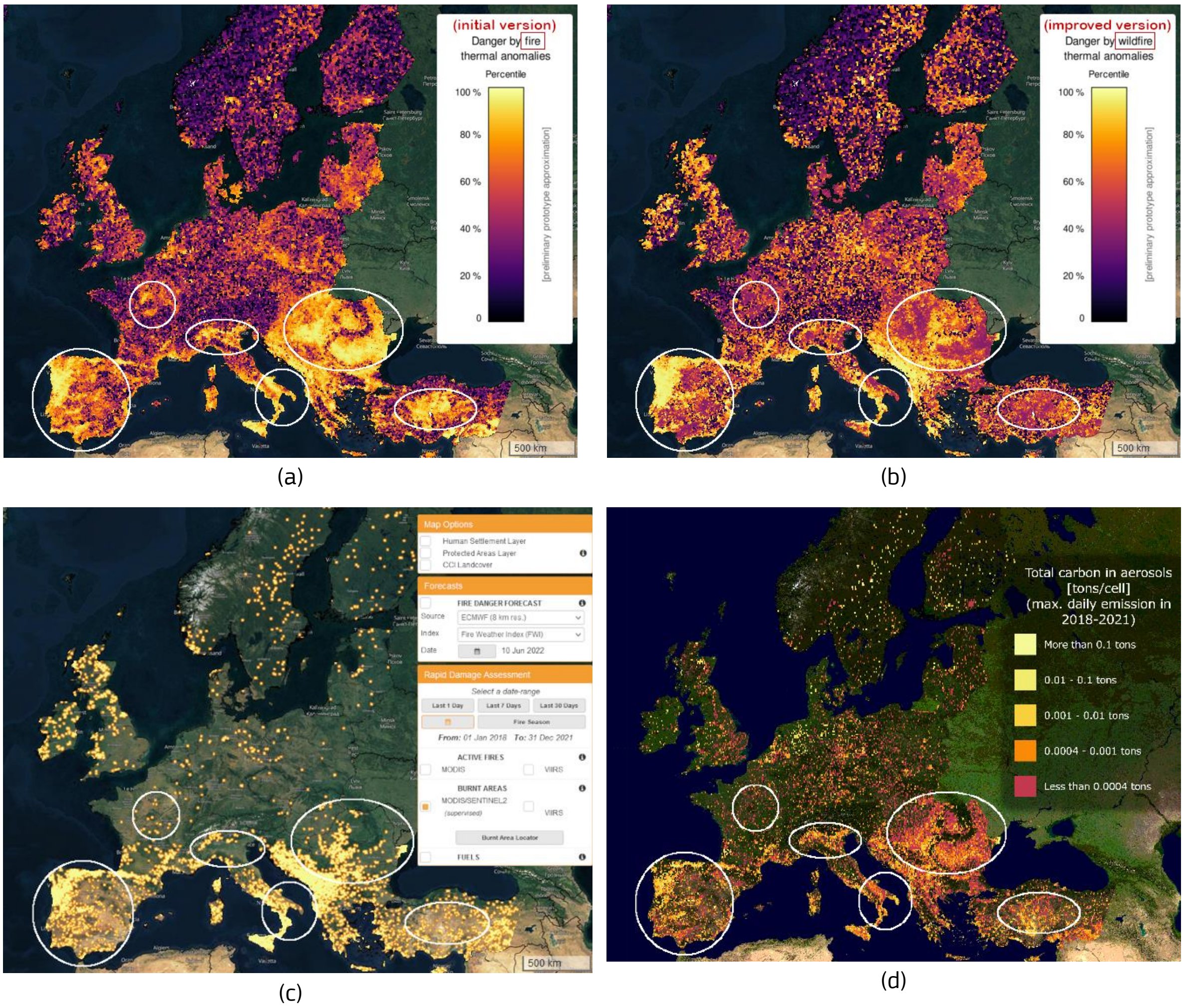


Figure 26. (a) Comparison between an initial version of "Danger by fire thermal anomalies", and (b) the improved current "Danger by wildfire thermal anomalies". The initial version (a) shows the central value (median of 100 bootstrap runs) percentile of each spatial cell c compared with the other cells. This is the percentage of cells with less danger than the cell c, when assessing the whole set of recorded thermal anomalies. In (b), this initial estimation is refined by ranking the thermal anomalies as explained in the text, to account for their relevance as indicators of wildfires. In (c) the MODIS/Sentinel2 burned areas mapped by EFFIS are shown for the latest complete years (2018-2021). White ellipses highlight some of the areas where major differences can be observed between the two versions. In (d) the max daily value in 2018-2021 of total carbon in aerosols [tons] derived after GFAS v1.2 (spatial cell 0.1 °).

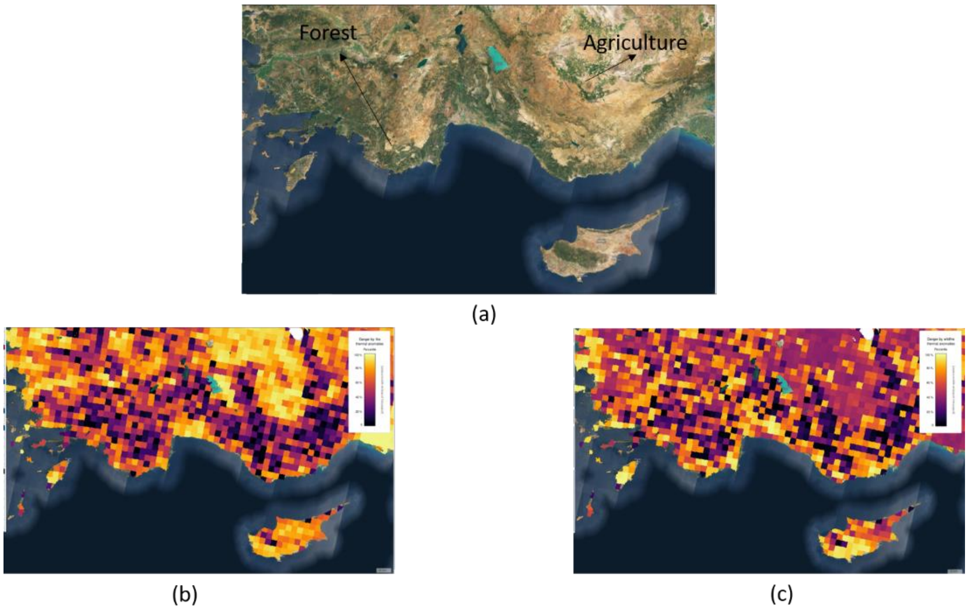


Figure 27. Example of southern part of Turkey where the use of fire in (a) Forest and Agriculture areas led to different results when comparing the (b) initial version of "Danger by fire thermal anomalies", and (c) the improved current "Danger by wildfire thermal anomalies".

Uncertainty, multiplicity, and prioritising risk for human lives

Virtually all the layers discussed in Table 2 as components of the wildfire risk are associated with an intrinsic, ineliminable uncertainty, so that their non-linear integration (Figure 6) to estimate the final risk magnifies the cumulative aggregated uncertainty.

Therefore, this structural uncertainty is at the basis of a robust method for identifying the areas to prioritise, where the estimated risk is consistently higher than in other areas. This robust risk assessment is computed by considering multiple simulations of the uncertainty – as explored in a corresponding set of multiple model instances (where each instance, or model run, is a bootstrap statistical resampling repeated for all the uncertain components). The degree of agreement between model instances can be easily estimated, thereby identifying the high-priority areas where most instances agree on these areas being at high risk. Analogously, areas with relatively low risk (lower priority areas) can also be identified, where most instances agree on the same low-risk classification. The model instances do not always agree, because in some areas the extent of bootstrap uncertainty might generate a higher noise in the model instances. In the worst case (un-assessable areas), the risk level in some areas may be too uncertain to assess: this happens if the model instances classify these areas with contradictory levels of risk. This risk-level ranking yields a robust method for integrating the noisy signal provided by the various components considered in the wildfire risk assessment, offering users a robust estimation of the WRA stability (or conversely its potential fragility) in each area.

However, it should be underlined how the proxy layers available in a harmonised way at the European scale supply, of necessity, less detailed and accurate information compared with that available only at the national or sub-national scale. Therefore, a trade-off exists between the aim of offering a European-wide harmonised WRA, and its potential degree of fitness for many specific purposes at national/sub-national level. Although some of the available European-wide components do not provide a proper assessment on their uncertainty, a distribution of equi-possible instances of each of the uncertainty-aware components can be modelled. This is the case of data displaying a marked variability in different years. Examples are weather data, and their derivative estimates of fire danger by weather, the fire weather index (De Groot, 1987; Van Wagner, 1987; Vitolo *et al.*, 2020) and the observed historical fire activity including large fires mapped in EFFIS (Sedano *et al.*, 2012) and MODIS thermal anomalies (Giglio *et al.*, 2020). Figure 28 visually illustrates how the intrinsic uncertainty in several components of the overall approach to assess wildfire risk in Europe (Figure 6) is integrated within the bootstrap statistical resampling described above. A robust risk assessment is computed by considering multiple simulations of the uncertainty, each of them based on a corresponding bootstrap run of all the components for which uncertainty was possible to estimate with the available data.

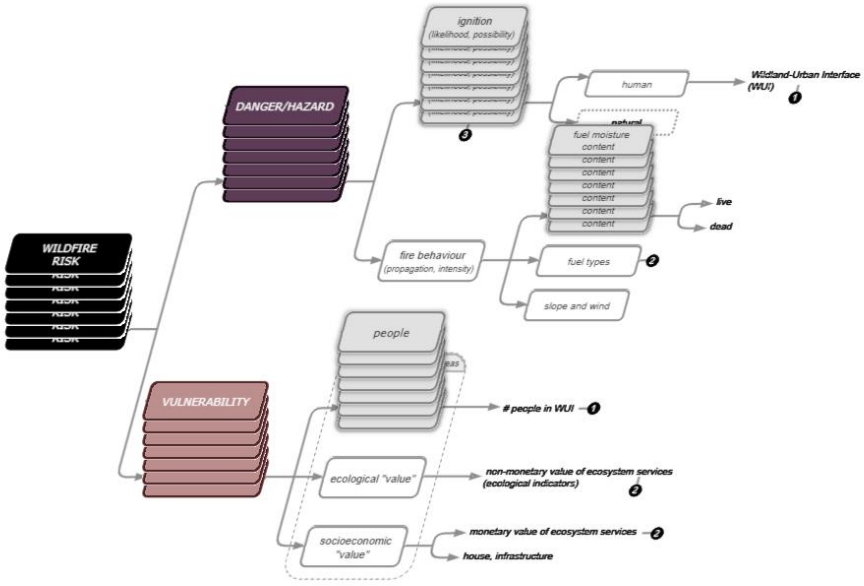


Figure 28. Several components in the overall approach to assess wildfire risk in Europe (Figure 6) are characterised by noticeable, intrinsic uncertainty. For example, the information related to the ignition patterns (see Figure 7) is subject to inter-annual variability so that even the uncertainty envelope of a simple multi-annual linear prevents a trend analysis. Analogously, Figure 8 depicted the variability of burned areas, and similar uncertainty affects other quantities such as in the weather driven assessment of fire danger, and in the assessment of the people exposed in the vulnerable interface between wildland and settlements. A statistical resampling (bootstrap) was used to account for the overall uncertainty propagation of these components in the resulting risk ranking.

Wildfire risk may be assessed by considering the vulnerable areas where people, ecological, and socioeconomic values are exposed to fire danger. An aggregated wildfire risk index is proposed, which prioritizes the risk for human lives, while also considering ecological and socioeconomic aspects. This is done by ranking as high-risk areas those where people may be exposed to wildfires, and secondarily other areas where ecological and socioeconomic aspects are at stake. Even for this ranking, the mathematical mechanism relies on standard long-established lexicographic sorting algorithms (Fishburn, 1974; Ben-Tal, 1980; Weber *et al.*, 2002), already used for the ranking of thermal anomalies (see previous section).

Looking at Figure 6, in some branches of the WRA tree graphical representation, proceeding from right to left, more than one input component needs to be aggregated into a single output. In these cases, a classical Pareto ranking aggregation (Ben-Tal, 1980; Fonseca and Fleming, 1993; Tracey *et al.*, 2018) is used, so that a semi-quantitative prioritisation can be derived, irrespective of any particular preference on how input components could be weighted. This may subjectively vary depending on political and society values which are inherently non-technical and cannot be delegated to others than policy makers – with decision makers in different countries and sub-national regions being able to display a very diverse range of preferences. Pareto ranking is a standard methodology to derive a robust ranking (invariant for *any* monotonic transformation of the input components) where the Pareto frontier between the values in each area of two or more components defines higher priority areas, and iteratively the Pareto frontier of the remaining areas defines progressively lower priority areas. For example, aggregating the danger components from (a) the observed historical fire activity, and (b) the monitored fire danger by weather, a Pareto ranking would de-prioritise areas where negligible or no fire activity was historically observed, *and* a time series of fire danger by weather was locally monitored verifying it to be much lower compared with the danger by weather in other regions. An illustrative example on the ranking of each spatial cell by assessing the local ecosystems exposed in vulnerable areas (ecological vulnerability) is shown in Figure 29. In this example (Figure 29 top), two dimensions of the problem are considered in each spatial cell: the fraction of protected area (y axis); and their irreplaceability (x axis). A cell with no protected areas, and very common ecosystems, is de-prioritised (Pareto dominance) when compared with a cell with a vast share of protected areas; but also, when compared with a cell with a smaller fraction of protected areas, yet whose ecosystems are very rare. By assessing how many other cells show a Pareto-dominance compared with a given spatial cell, a Pareto ranking is obtained (Figure 29 bottom). The ranking would not change for any change of units, or even for any non-linear monotonic transformation of the dimensions.

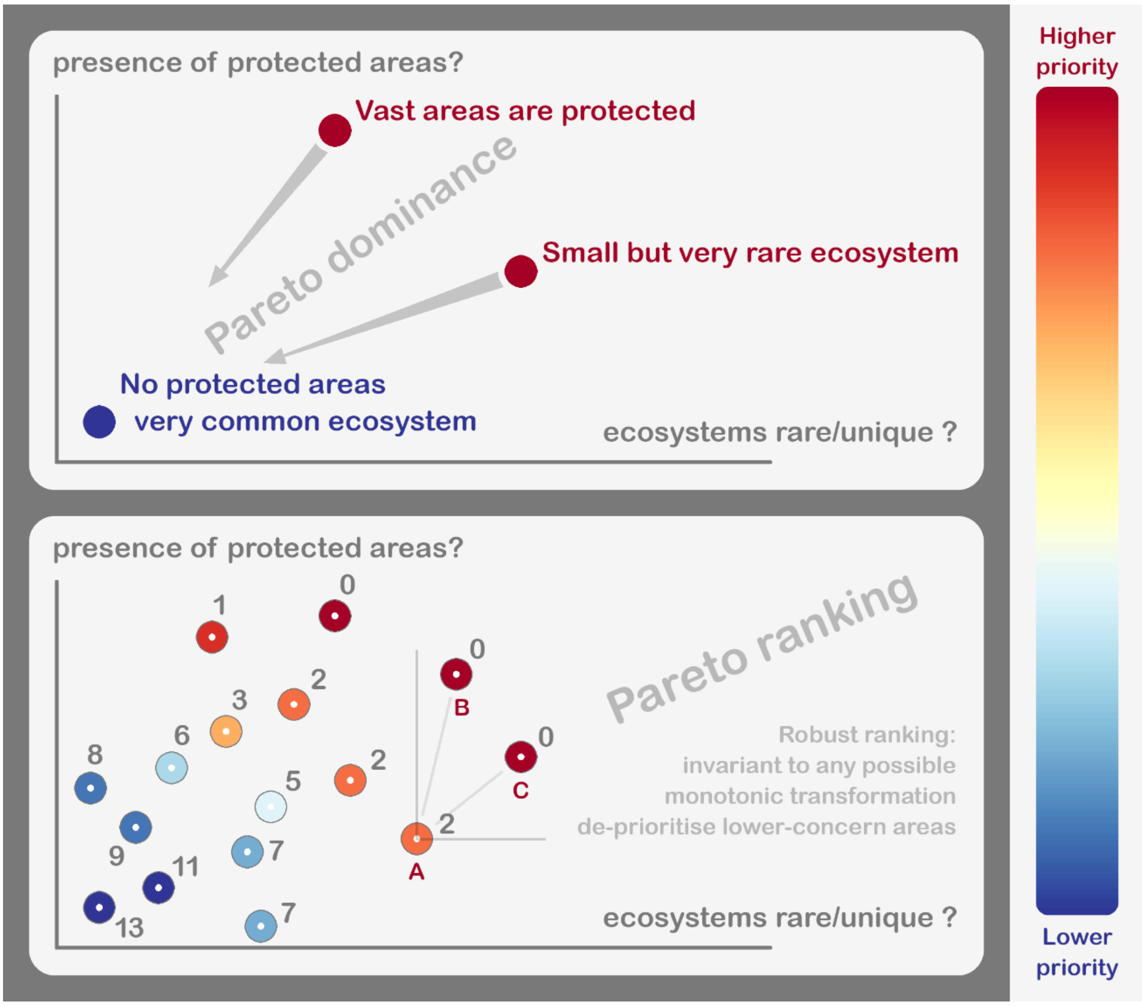


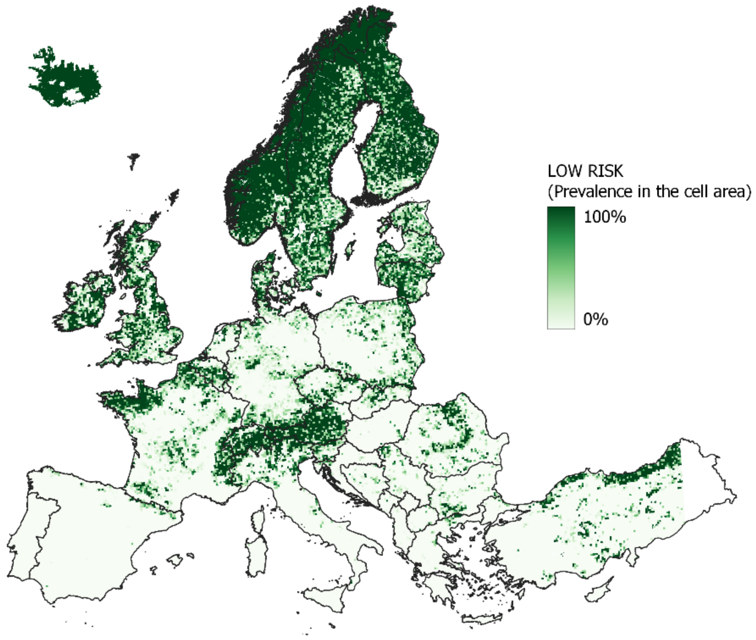
Figure 29. When multiple dimensions characterise the same conceptual component, a Pareto ranking is applied. Top: exemplifying with the ecological vulnerability, two dimensions are considered in each spatial cell: the fraction of protected area (y axis); and the irreplaceability of their ecosystems (x axis). A cell with no protected areas, and very common ecosystems, has less priority on both dimensions (i.e. is Pareto dominated). Bottom: Pareto ranking, based on how many other spatial cells (points) show Pareto-dominance on a given cell (e.g., A is Pareto-dominated by B and C).

A computational trade-off exists between combining the robust aggregation ranking of multiple component dimensions, and the robust estimation of the agreement among model instances, each based on a corresponding statistical run of the uncertain variables. A smaller amount of model instances/runs would make it possible to approximate more accurately the Pareto ranking, at the price of a higher instability in accounting for the uncertainty, given the higher impact within the statistical resampling of random stochastic fluctuations. Therefore, as a trade-off compromise to maintain acceptable accuracy in both multiplicity and uncertainty processing, a set of 100 model instances was processed, with each corresponding run based on an independent statistical resampling of the components with modellable uncertainty. Each of these runs separately processed a set of statistical-resampling instances of the uncertain components in the WRA scheme (Figure 6) up to obtain a final risk ranking. The agreement between the 100 runs is shown in Figure 30 (prevalence in each cell area of each risk class).

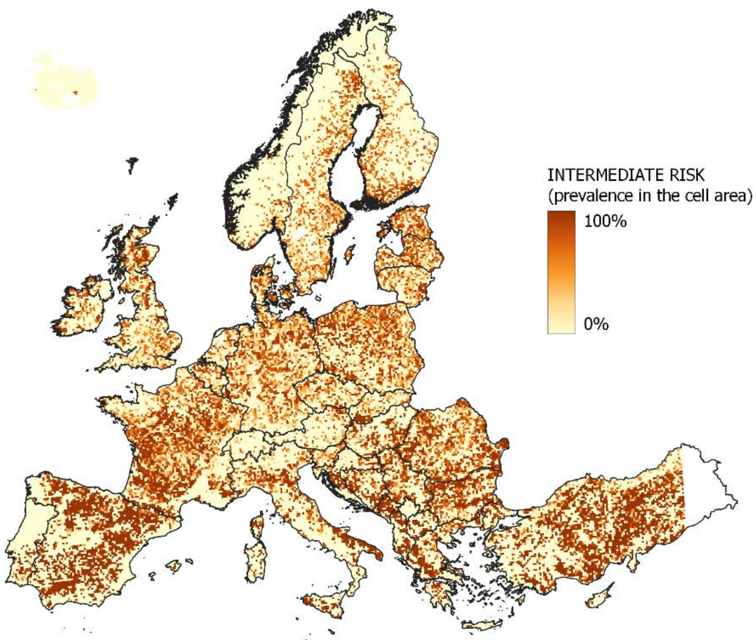
Overall, the proposed WRA approach is designed to respect the semantics of the arrays of proxy data sources and their inherent uncertainty (Figure 6, Table 2) through their intermediate data-transformations, up to aggregate them in a final risk-class ranking. The robust semi-quantitative modelling integration is based on the semantic array programming paradigm (de Rigo, 2012; 2015), and explicitly designed to ease the support for a future climate change analysis (de Rigo *et al.*, 2017b; Costa *et al.*, 2020).

Wildfire Risk index (version 1)

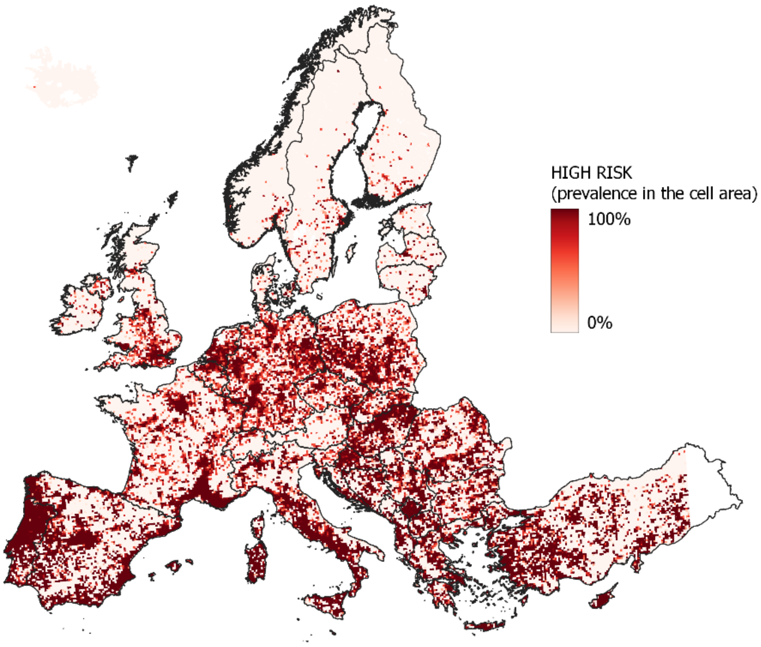
A wildfire risk map was generated – as prototype version 1 – as an index to summarize the combined effect of wildfire danger and vulnerability. An aggregated wildfire risk index is proposed, which prioritizes the risk for human lives, while also considering ecological and socioeconomic aspects. This is done by ranking as high-risk areas those where people may be exposed to wildfires, and secondarily other areas where ecological and socioeconomic aspects are at stake. The format of the risk map allows risk classes (from low to high risk) to be identified, with a simple score ranging from 0 % to 100 %, which could then be aggregated in three levels of risk: low, intermediate and high (Figure 30). High risk may be expected where high wildfire danger affects the most critical areas for people, and secondarily for the other ecological and socioeconomic aspects.



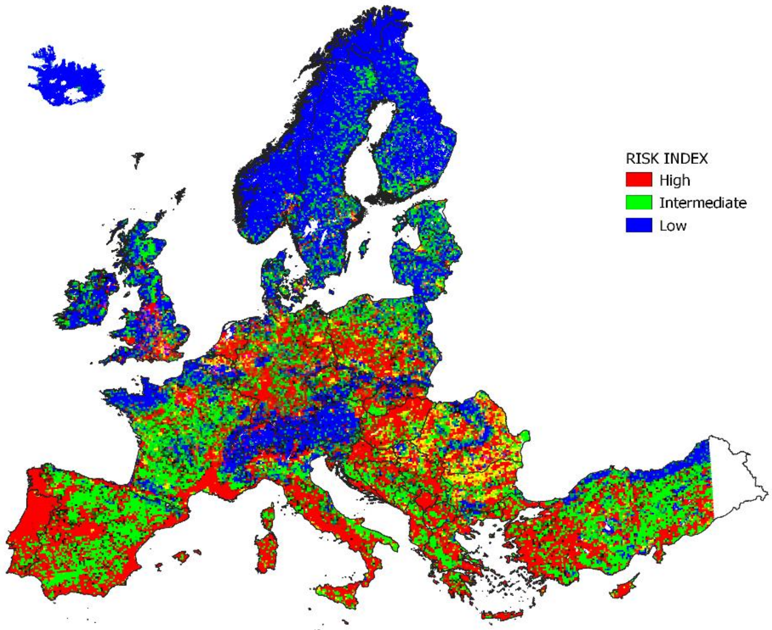
(a)



(b)



(c)



(d)

Figure 30. Final aggregated wildfire risk by pixel level. Prevalence of the (a) lower-risk class, (b) intermediate-risk class and (c) higher-risk class in each EURO-CORDEX spatial cell. Percentage based on the risk classification in each EURO-CORDEX cell of 100 equi-possible model runs, to integrate the uncertainty sources. The (d) is a simple RGB composition of the risk classes (Red-High, Green-intermediate, Blue-Low) which is only qualitatively illustrative of the main patterns in Europe (as the information in the three classes of risk a, b, c cannot be fully represented in a single aggregated view).

The prevalence of high-risk class is mainly located in the southern European countries, such as Portugal, Spain, France, Italy, Greece, and Turkey, where more than 70% of all burned areas from 2003 to 2020 were mapped (Figure 31). Northern parts of Portugal are one of the big clusters where the prevalence of the higher risk class is clear.

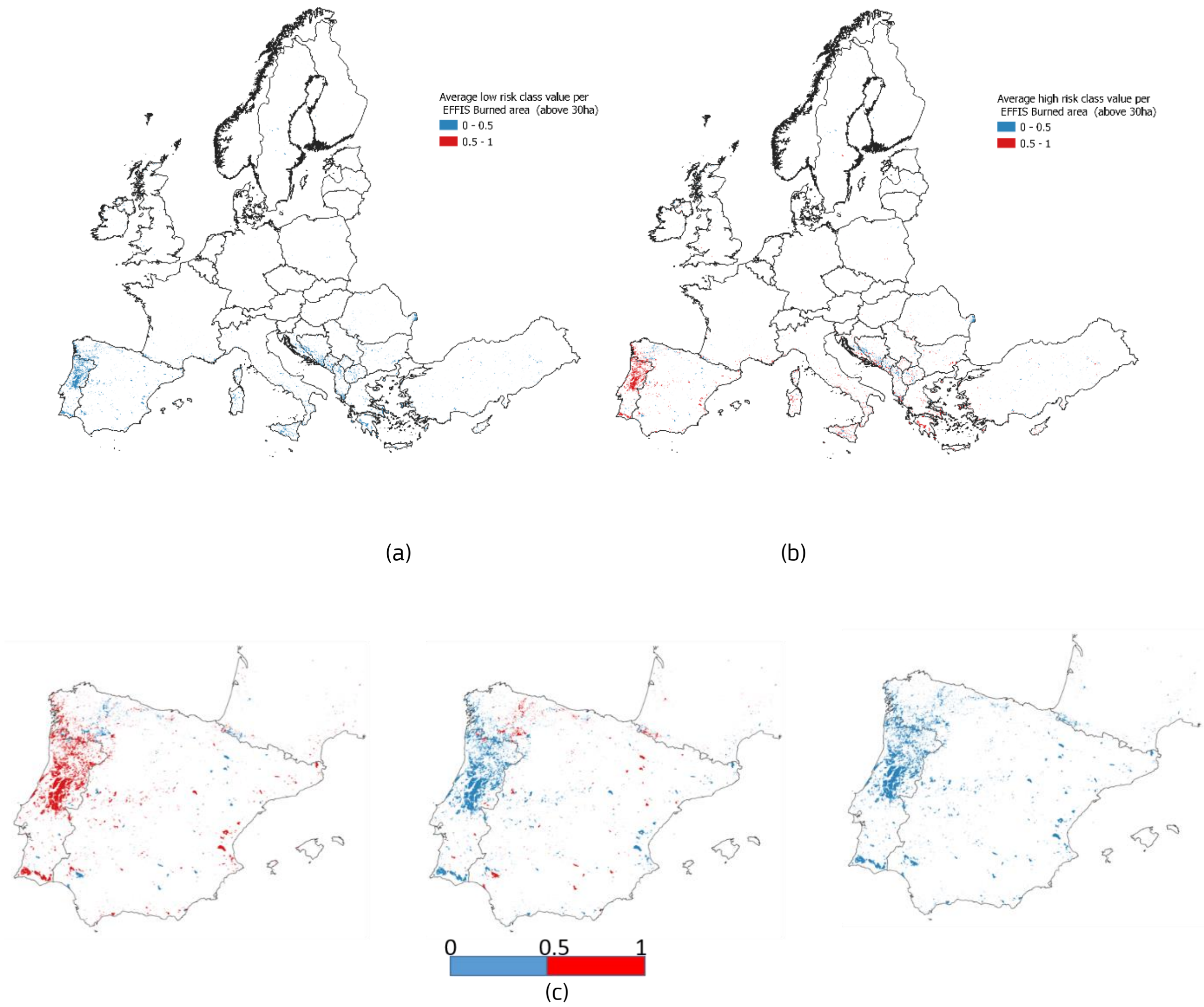


Figure 31. Average prevalence (values between 0 and 1: less than 50 % per each fire event, blue; otherwise, red) of the (a) low risk, (b) high-risk and (c) the three risk classes (left: prevalence of the high-risk class within burned areas; middle: intermediate risk; right: low risk) for Iberian Peninsula for each EFFIS burned area above 30 ha for the period between 2003 and 2020.

Figure 32 shows the average values of the three levels of risk for all the burned areas mapped by EFFIS by each country and the average values of the three levels of risk for each country respectively for the period between 2003 and 2020. We can see clearly that the southern countries are not only the most affected by burned areas, but they also present higher proportion of the territory classified as high risk. It can be further noted that even in some countries where most of the land is classifies as low risk (e.g., Norway), the majority of burned areas may still fall under the highest risk class.

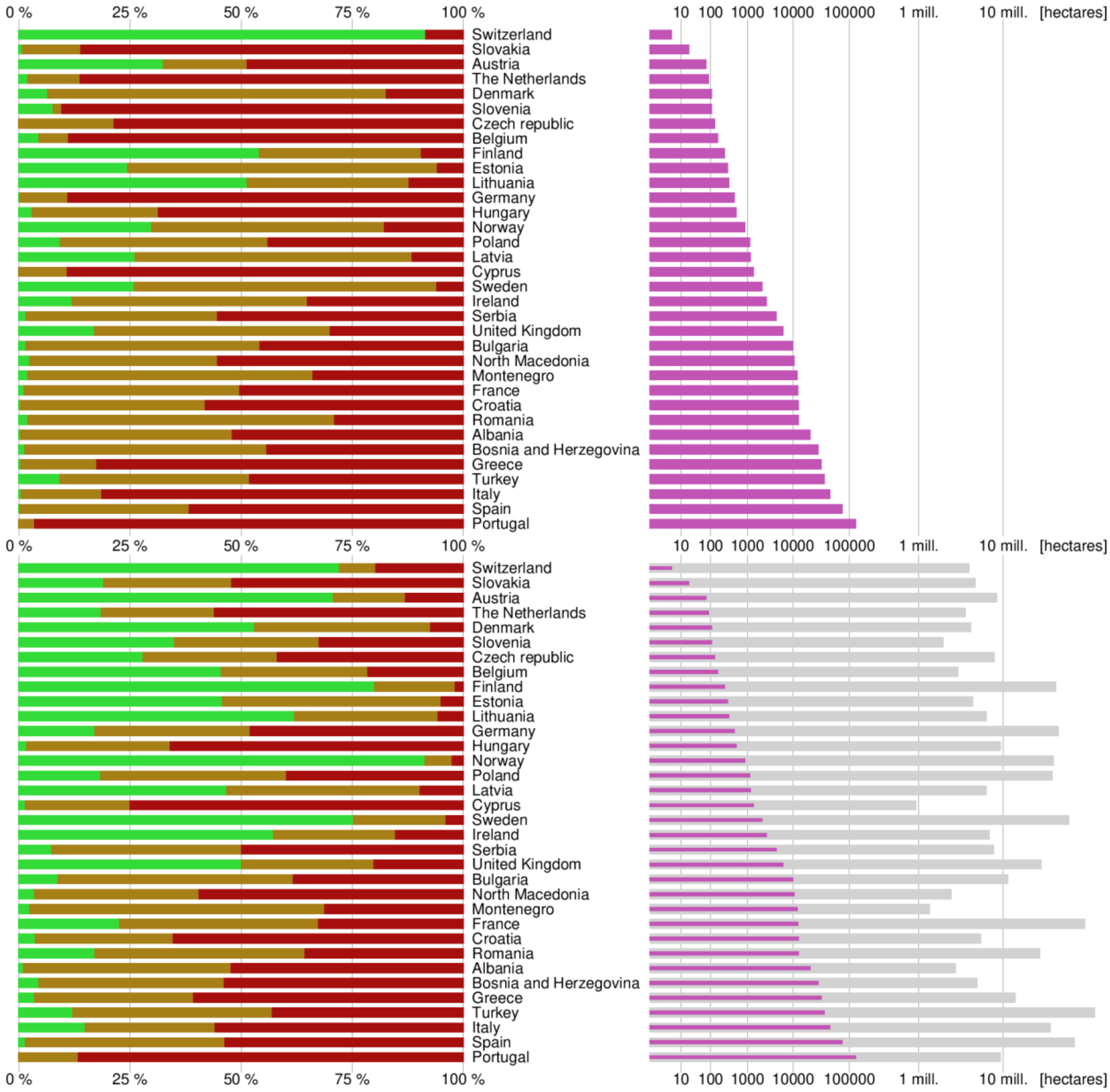
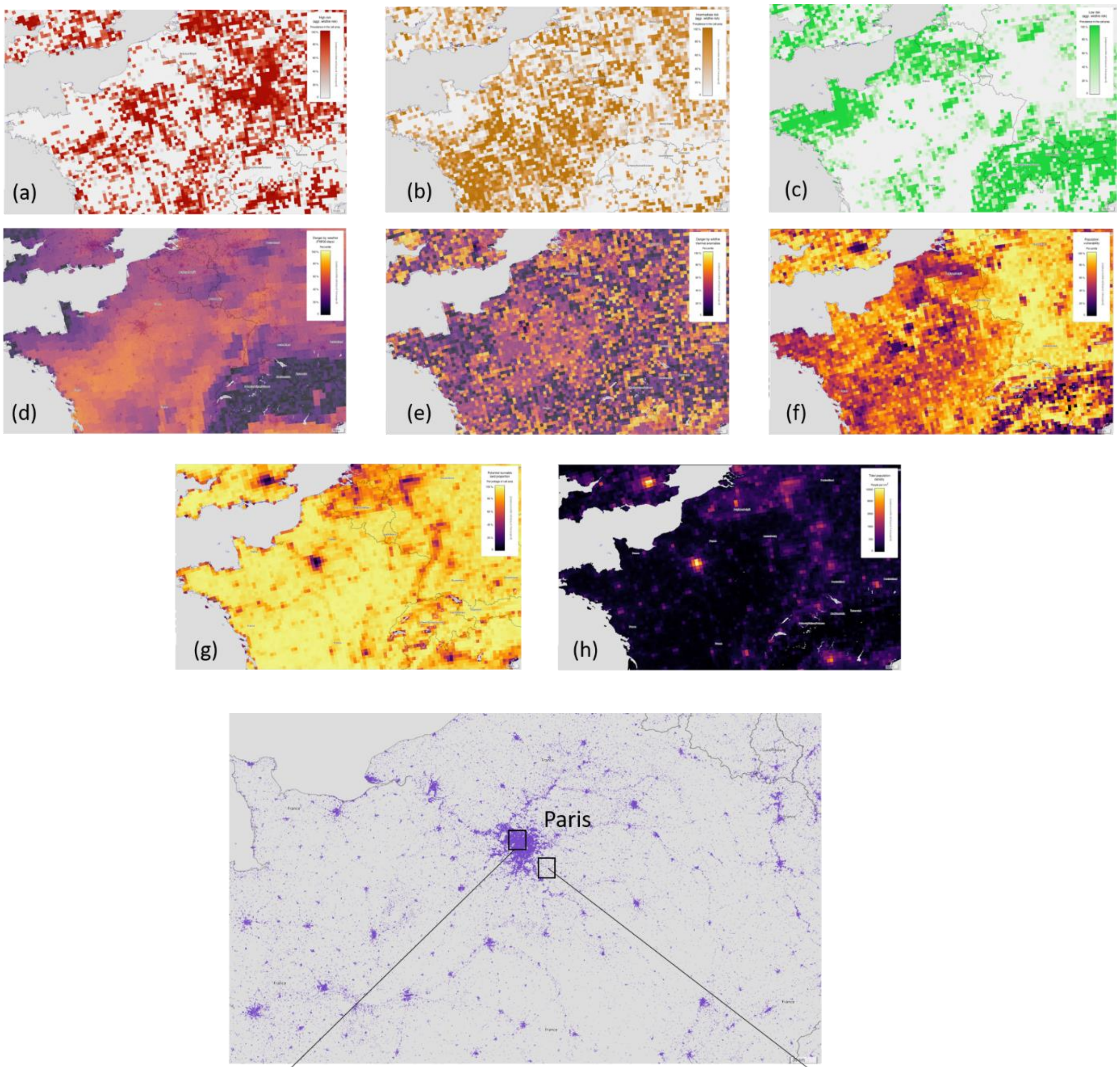


Figure 32. Top: average risk values distribution by burned area for each country. Top left: percentage for each risk class (green: low; dark yellow: intermediate; dark red: high risk) inside the wildfires larger than 30 ha as mapped by EFFIS in 2003-2020. Top right: average annual burned area by country. Bottom: average risk values by country. Bottom left: percentage for each risk class in the whole country (also outside wildfires). Bottom right: grey, country areas (for better comparison, the smaller fuchsia bars report the same average annual burned area as above).

In cities such as Paris or Milan, the risk is lower than in their surrounding areas where the high percentage of burnable area and the population density in the WUI is much higher, so being more vulnerable to fire events and consequently with a higher risk. Figure 33 shows two pixels in the Paris region, one inside the city (P1) perimeter and the other outside (P2). From the values for both pixels presented in the tables, the difference in the area that is potentially burnable (P1-11 %: P2-93 %) and in the population density in the vulnerable interface (P1-0.2; P2- 29 people/Km^2) is clear. The weather and thermal anomalies danger (Figure 33d and e) are similar in both regions (the fire danger part of the risk), so the variable that affects the risk class most would be the population vulnerability (Figure 33f) and the population density in vulnerable WUI (Figure 33h).



Lat/Lng	48.926898 / 2.296143		Lat/Lng	48.438711 / 2.488403
High risk (aggr. wildfire risk) (Prevalence in the cell area)	0 %	(a)	High risk (aggr. wildfire risk) (Prevalence in the cell area)	99 %
Intermediate risk (aggr. wildfire risk) (Prevalence in the cell area)	58 %	(b)	Intermediate risk (aggr. wildfire risk) (Prevalence in the cell area)	1 %
Low risk (aggr. wildfire risk) (Prevalence in the cell area)	42 %	(c)	Low risk (aggr. wildfire risk) (Prevalence in the cell area)	0 %
Danger by weather (FWI30-days) (Percentile)	56.794 %	(d)	Danger by weather (FWI30-days) (Percentile)	63.037 %
Danger by wildfire thermal anomalies (Percentile)	75.641 %	(e)	Danger by wildfire thermal anomalies (Percentile)	86.56 %
Population vulnerability (Percentile)	23.948 %	(f)	Population vulnerability (Percentile)	84.911 %
Potential burnable land proportion (Percentage of cell area)	10.867 %	(g)	Potential burnable land proportion (Percentage of cell area)	93.361 %
Population density in vulnerable WUI (People per km²)	0.288 [people / km²]	(h)	Population density in vulnerable WUI (People per km²)	28.697 [people / km²]
Total population density (People per km²)	8908.015 [people / km²]		Total population density (People per km²)	98.788 [people / km²]

Figure 33. Example for Paris region high-risk, (b) intermediate-risk, (c) low-risk, (d) Danger by weather, (e) Danger by thermal anomalies, (f) Population vulnerability, (g) Potential burnable land, (h) Population density in WUI maps depicted from the EFFIS Wildfire Risk Analysis Viewer. The values for a pixel within the city perimeter (48.92N; 2.29E) and outside (48.43N; 2.48E) are presented in the tables displayed.

EFFIS Wildfire Risk analysis viewer

A preliminary version of the pan-European Wildfire risk map viewer (https://effis.jrc.ec.europa.eu/apps/fire.risk.viewer/) was built to include all the input data and the final risk on a pixel (circa 12.5 km) and administrative level basis. This version is displayed in Figure 34 with two examples of the layers included in the viewer.

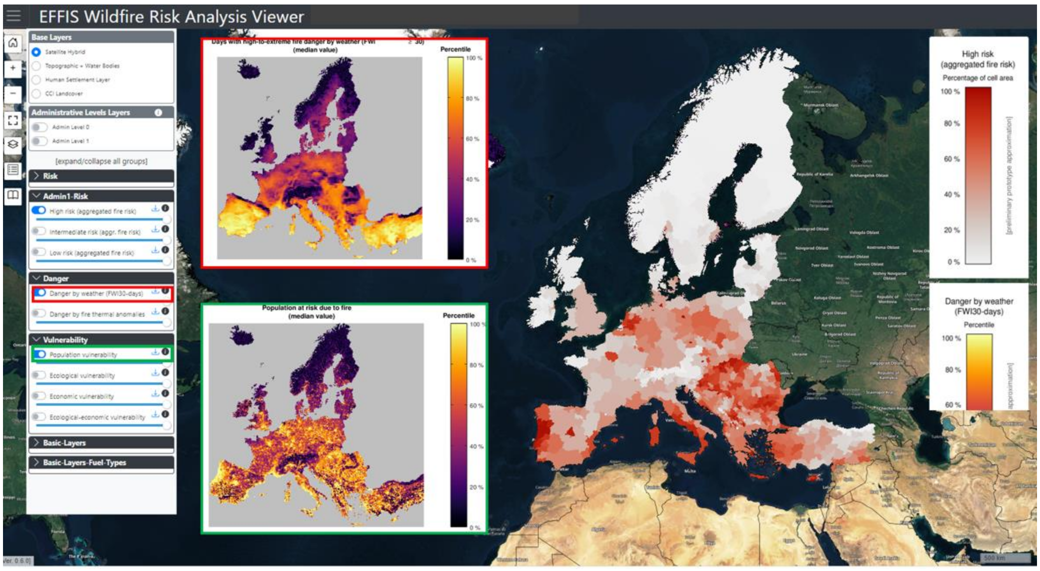


Figure 34. EFFIS Wildfire Risk Viewer (preliminary version). Values displayed in the map correspond to the high-risk class at administrative levels, based on GADM (https://gadm.org/index.html). As an example of some of the layers included on the viewer, the inside boxes display the Danger by Weather (red frame) and the aggregated index of population vulnerability (green frame).

Four groups of layers are displayed and downloadable (as maps in GeoTiff format) in the viewer) (Table 4):

Table 4. Layers incorporated in the EFFIS Wildfire Risk analysis viewer

Layer name	Group	Units
Potential Burnable Land Proportion	Basic Layers	Percentage of cell area (%)
WUI proportion	Basic Layers	Percentage of cell area (%)
Protected area irreplaceability	Basic Layers	Percentile (%)
Protected area fraction	Basic Layers	Percentile (%)
Population density in vulnerable WUI	Basic Layers	People per Km^2
Total population density	Basic Layers	People per Km^2
Fuel types	Basic Layers	Percentage of cell area (%)
Aggregate land-cover	Basic Layers	Percentage of cell area (%)
Land-cover	Basic Layers	Percentage of cell area (%)
Danger by Weather	Danger	Percentile (%)
Danger by thermal anomalies	Danger	Percentile (%)
Population vulnerability	Vulnerability	Percentile (%)
Ecological vulnerability	Vulnerability	Percentile (%)
Economic vulnerability	Vulnerability	Percentile (%)
Ecological/economic vulnerability	Vulnerability	Percentile (%)
High risk (aggregated fire risk)	Wildfire-Risk	Prevalence in the cell area (%)
Intermediate risk (aggregated fire risk)	Wildfire-Risk	Prevalence in the cell area (%)
Low risk (aggregated fire risk)	Wildfire-Risk	Prevalence in the cell area (%)

The full description of all the layers is included in the users' guide that is also available for download at:
https://effis-gwis-cms.s3-eu-west-1.amazonaws.com/apps/fire.risk.viewer/effis.fire.risk.viewer.user.guide.pdf .

Concluding remarks and perspective

This report contributes to a harmonised wildfire risk assessment over wide spatial areas, by presenting a first consistent methodology and set of data for the pan-European region, acting as a starting point for a more comprehensive risk assessment. Wildfires are here understood in terms of coupled human and natural systems (Fischer *et al.*, 2017; Liu *et al.*, 2007a; 2007b). The integration of multiple intertwined social, environmental and economic dimensions is recognised as key for any inclusive assessment, to avoid the negative impacts of simplistic quantifications (Masood, 2022; Pascual *et al.*, 2022; Victor, 2020). Given the inescapable complexity and the non-linear interplay between the components of wildfire risk, a mere aggregated risk ranking – isolated from basic contextual information – may be difficult to understand alone. This is why the proposed approach is explicitly designed to provide not only the final risk ranking, but also to complement it with a rich set of spatial quantities, either directly used to estimate the risk, or useful as basic layers to ease a contextual comparison with selected background data. We hope the information in this first prototype of pan-European wildfire risk could be informative to identify the areas where the risk is higher, providing a baseline for understanding the risk and helping with the development of efficient fire management strategies across the pan-European scale. However, as we have not yet developed a full comprehensive risk including all the fire risk components (on-going research), the information is meant to be indicative at the continental scale, while it should be carefully used when applying it to local, specific real-world situations. Users should be aware of the essential use in this structural risk assessment of historic data, and how the past fire risk may diverge more and more from the risk under future climate change conditions. Nevertheless, lessons learned from previous critical fires must be taken into consideration (San-Miguel-Ayanz *et al.*, 2013a), as these episodes are becoming more frequent in Europe and worldwide (Moreira *et al.*, 2020).

The next steps foreseen would be the development and incorporation of enhanced datasets and methods such as fire intensity, information on fuel classification incorporating the new data derived under the FireEuRisk project, funded by the European Union's Horizon 2020, socio-economic components, or live fuel moisture content, and continue testing and validating the pan-European wildfire risk map in close collaboration with the Expert Group on Forest Fires.

In addition to the natural climatic variability between different years (which, as we have seen in Figure 8 and Figure 9, is a primary uncertainty factor), the changing climate adds complexity to the study of structural wildfire risk. While human aspects are dominant in the vulnerability components in Figure 1 and Figure 6, so that their future evolution is extremely challenging (if not impossible) to estimate, the hazard/danger components are clearly connected with the changing wildfire danger by weather (de Rigo *et al.*, 2017b; Costa *et al.*, 2020). This means that while the complete evolution of the structural wildfire risk cannot be fully projected in future, a key part of its components (related to weather and climatic aspects) can be analysed. In this respect, the WRA working spatial grid is already the standard one for pan-European climatic studies (Coordinated Regional Climate Downscaling Experiment, 2015, see footnote 4).

The spatial extent of this first prototype version of the risk ranking was carefully selected to ensure the broadest possible spatial coverage, given the limits and gaps of the currently available data, and at the price of some sub-optimal approximations. In some cases, the available data only covered most of the region of interest (so that some included areas have partial data gaps and cannot yet rely on an optimal data coverage) and may be complemented in future by national datasets, provided that these more accurate local data can be assimilated to the European datasets in terms of format and information content. It is essential to note how the availability, quality and harmonisation of the input data is decisive for a reliable final ranking of wildfire risk. At the same time, the presence of multiple regions with a broad diversity in their sensitivity/response to wildfires is important for the final risk ranking to be representative of the rich diversity of local conditions. Therefore, a trade-off exists between the widening of the study area (too small an area would be biased to over-specific local conditions, and not comparable to other regions), and the availability of minimum-quality data to cover the whole spatial extent (otherwise, poor quality proxy data would propagate their negative impact over the whole risk ranking, making it useless). These scientific and technical aspects will play a core role in the potential expansion of the spatial and temporal coverage the European wildfire risk assessment.

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