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LUÍS MÁRIO RIBEIRO

Pan-European Wildfire Risk Assessment- preliminary version

Duarte Oom[1]*; Daniele de Rigo[2,3]; Hans Pfeiffer[4]; Alfredo Branco[2]; Davide Ferrari[4]; Rosana Grecchi[2]; Tomás Artes-Vivancos[1]; Tracy Houston Durrant[4]; Roberto Boca[2]; Pieralberto Maianti[2]; Giorgio Liberta[1] and Jesús San-Miguel-Ayanz[1]

[1]*European Commission, Joint Research Centre (JRC), Ispra, Italy,*
{Duarte.Oom, Tomas.Artes-Vivancos, Giorgio.Liberta, Jesus.San-Miguel}@ec.europa.eu
[2] *ARCADIA SIT s.r.l, Vigevano (PV), Italy {Daniele.De-Rigo,*
Alfredo.Branco, Rosana.Grecchi, Roberto.Boca, Pieralberto.Maianti}@ext.ec.europa.eu
[3] *Maieutike Research Initiative, Milano, Italy*
[4] *Engineering Ingegneria Informatica S.p.A., Roma, Italy*
{Hans.Pfeiffer, Davide.Ferrari, Tracy.Durrant}@ext.ec.europa.eu

**Corresponding author*

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Abstract

Wildfire, as a global phenomenon, is an integral part of the Earth system that affects different regions in diverse ways resulting in variable levels of long-lasting impacts to environmental, social, and economic systems. In a context where extreme and high severity events are becoming more frequent, it is crucial to respond with a more robust preparedness and planning, identifying the risks posed by wildland fires, fostering better fire management policy tools, and developing mitigation strategies accordingly. However, scope and methods for wildfire risk assessment vary widely among countries leading to different regional/national approaches not always comparable, although wildfires are often transborder events and may affect several countries simultaneously. The elaborateness of these assessments is often related to the impact of fires in the corresponding regions, with countries more often confronted with wildfires being more prepared by having more elaborated and detailed wildfire risk maps at country/regional level, although based on 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 the 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, is currently under development in close cooperation with the EC Joint Research Center (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 to assess 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.

1. Introduction

Given the projected increase of fire risk 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 as a key element to disentangle the complex relationships between fire occurrence, drivers, and impacts caused by fires at different levels (Oliveira et., 2021; Moreira et al., 2020). Many countries have customized approaches to assess wildfire risk, widely varying based on different variables and methodologies (San-Miguel-Ayanz et al., 2003, 2017). Usually, these different approaches are not only related to the frequency/impact of fires, level of preparedness, and data availability, but also to how 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, for very different territories and specific purposes has led to different regional/national approaches, difficult to compare at the European scale, although 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 et al., 2005). A noticeable share of published fire risk systems only considers wildfire likelihood and behaviour, usually ignoring the damage caused by fire impacts in operational fire danger assessment systems (San-Miguel-Ayanz et al., 2003). Some other systems integrate fire danger and vulnerability, as two essential risk components (Calkin et al., 2010; Chuvieco et al., 2010, 2012; Tutsch et al., 2010; Thompson et al., 2011; Oliveira et al.,2020). However, much work is still needed to converge on a clear and concise terminology and harmonise quantitative risk analysis in the context of wildland fire management and of disaster risk management (Bachmann et al., 2001). The main goal of this work is to describe the development of a pan-European wildfire risk assessment (WRA) based on the definition of risk adopted by UNISDR (2009) which was also followed by the European Commission (EC) Joint Research Centre (JRC) reports (San-Miguel-Ayanz et al., 2017, 2019; Oom et al., 2021) by presenting a first set of data that would enable the implementation of the proposed assessment. Quantitatively, wildfire risk is defined as the product of the probability of wildfire occurrence/propagation (hazard) and the damage potentially caused (exposure and vulnerability) (Finney, 2005; Scott et al., 2013). This involves three main fire research areas: fire ignition/occurrence, fire behaviour/propagation, and fire effects (exposure and potential loss of assets/resources in vulnerable wildfire-prone areas). The harmonised WRA will support the inter-comparison of methods and needs among countries and be complementary to existing national WRA. Additionally, it can serve as a first approach to assess wildfire risk in those countries that have not yet performed a national WRA.

1.1. Pan-European risk assessment in the context of EFFIS

The development of the pan-European approach follows from a series of EU regulations that require the EC to have a wide overview of the wildfire risk 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 (Figure 1).

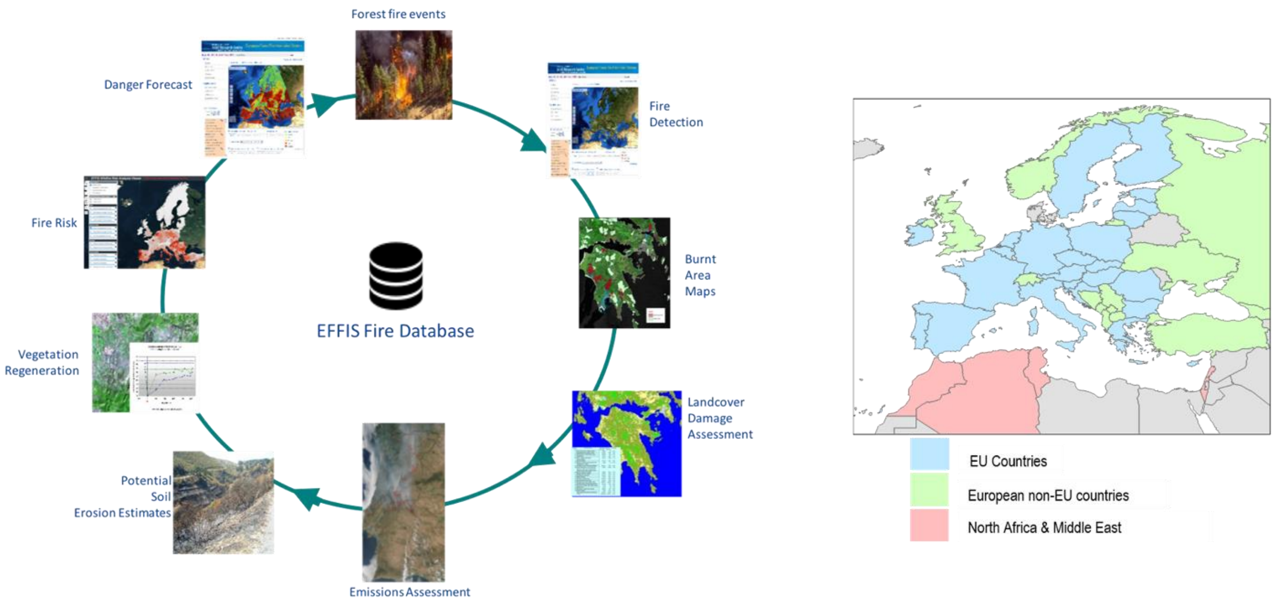

Figure 1- European Forest Fire Information System (EFFIS) services (left); map of countries that are currently part of the Expert Group on Forest Fires (EGFF) (right).

1.2. Wildfire risk scheme

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 2 illustrates the WRA scheme here proposed, 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.

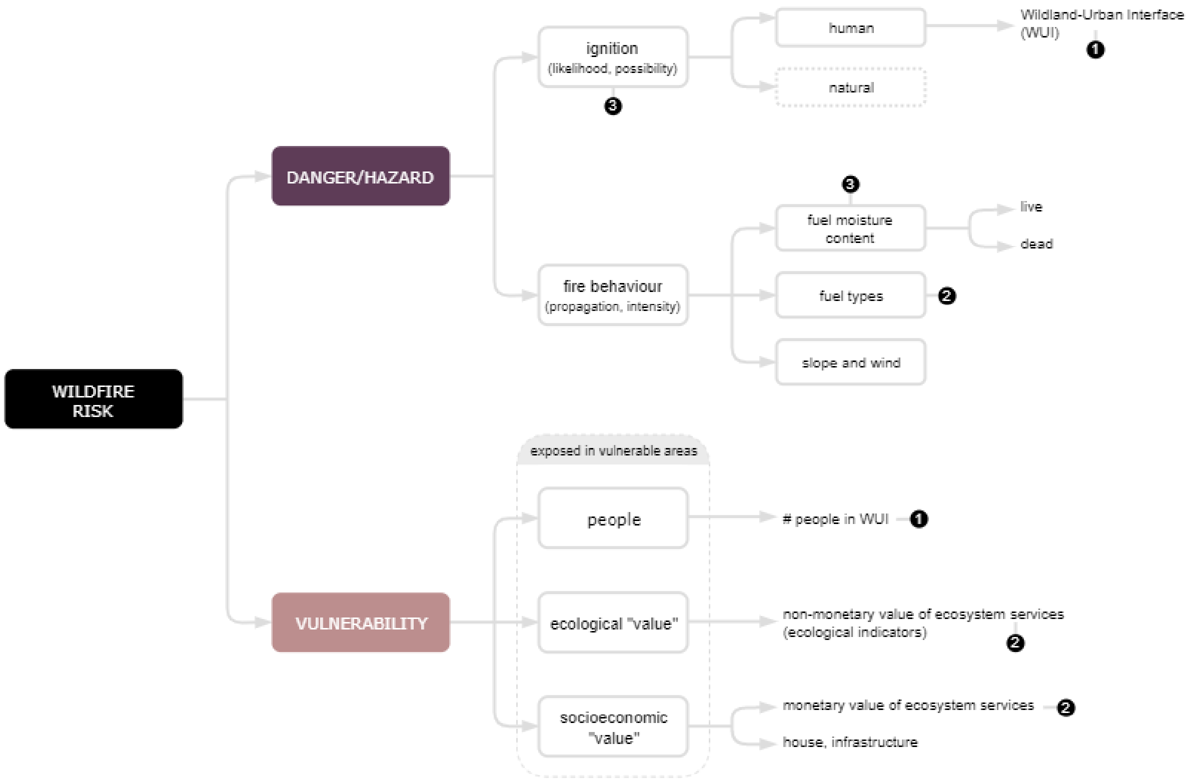

Figure 2- Basic components of the Pan-European Wildfire Risk Assessment scheme (from Oom et al., 2021).

The scheme follows a classic quantification of "risk", based on the probability or possibility (P) of negative outcomes (damage, D)

$$R = P \times D \qquad (1)$$

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 is linked to human causes, either deliberate or due to accident/negligence (de Rigo et al., 2017). 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, assets exposed in vulnerable areas (D, vulnerability) refer to the susceptibility to suffer damage by fire: "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" (UNISDR, 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).

2. Data

The development of an operational fire 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 1 describes the datasets for each component in the WRA.

Table 1- Datasets for the components of the fire risk assessment system (grey boxes are variables that are not yet operational, 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 behavior	Fuel moisture content	Live Fuel Moisture Content (LFMC)	[4]
			Dead Fuel Moisture Content (DFMC)	Fire Weather Index system[5,6,7]
		Fuel types	vegetation types	Corine Land Cover[3] Fuel Map of Europe[8]
		Climatic conditions	- wind, humidity, precipitation and temperature	Fire Weather Index system[5,6,7]
		Terrain	slope, aspect	Elevation data[9]
VULNERABILITY	People	# People in WUI	wildland–urban interface (WUI)[10]	Population density[11,12] Built-up areas[13]
	Ecological "value"	Ecological indicators	- irreplaceability score[14] - protected area - potential burnable land	Nature 2000[15] Protected area[16]
	Socioeconomic "value"	Monetary value of land cover and vegetation	Wildfire-damage restoration costs [17,18,19]	Corine Land Cover[3], vegetation age (restoration time) [17,18,19] restoration costs [17,18,19]
		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] Yebra et al., 2013
[5] CEMS, 2019
[6] Vitolo et al., 2020
[7] Herbach et al., 2018
[8] EFFIS, 2017
9 Amatulli et al., 2020
[10] Costa et al., 2020
[11] Freire et al., 2016
[12] Schiavina et al., 2019
[13] Corbane et al., 2018
[14] LE Saout et al., 2013
[15] The European network of protected sites, Natura 2000, https://www.eea.europa.eu/data-and-maps/data/natura-12
[16] The World Database on Protected Areas (WDPA), https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA
[17] Mavsar et al., 2011
[18] camia et al., 2017
[19] Oehler et al., 2012

3. Methodology

To identify areas where vegetation fires could occur, a high-resolution mask was developed ("Potential Burnable Area", PBA) (Figure 3) acting as a filter to avoid false alarms, avoiding 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)[1] and PROBA-V 333m Difference Vegetation Index (NDVI) product generated by the Global Land Service of Copernicus[2] were used as input. The data processing was implemented with spatial resolution of ~30 meters, and then aggregated at the spatial resolution of the WCRP[3].

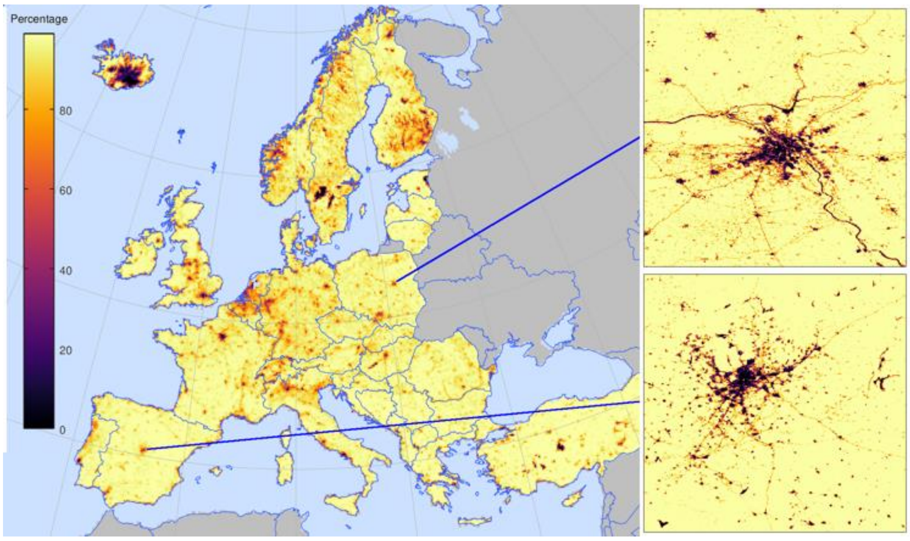

Figure 3- Potential Burnable Area proportion (0-100%) in each 12.5 km cell. Right inside are examples of the cities of Madrid and Warsaw.

The WRA was assessed through a semi-quantitative approach by using the available quantitative data presented in Section 2, as proxy information for the wildfire danger and vulnerability components, along with a qualitative aggregation of them in classes of importance (from low to high importance).

Virtually all the layers discussed above (Table 1) as components of the fire risk are associated with an intrinsic uncertainty, so that their non-linear integration (Figure 2) 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 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. Not always the model instances 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

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[1] https://global-surface-water.appspot.com/
[2] https://land.copernicus.eu/global/products/ndvi
[3] 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).

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 forcefully supply 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 at al., 1987; Wan Wagner et al., 1987; Vitolo et al., 2020) and the observed historical fire activity including large fires mapped in EFFIS (Sedano et al., 2012, 2013) and MODIS thermal anomalies (Giglio et al., 2020).

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. The mathematical mechanism for this ranking relies on standard long-established lexicographic sorting algorithms (Fishburn et al., 1974; Ben-Tal, 1980; Weber et al., 2002).

Looking at Figure 2, 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 et al., 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[4]. 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. Overall, the proposed WRA approach is designed to respect the semantics of the arrays of proxy data sources and their inherent uncertainty (Figure 2, Table 1) 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 (deRigo et al., 2012, 2015) and explicitly designed to ease the support for a future climate change analysis (de Rigo et al., 2017; Costa et al., 2020).

4. Preliminary results

A wildfire risk map was generated as an index to summarize the combined effect of wildfire danger and vulnerability. 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, medium and high (Figure 4). 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.

[4] as 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.

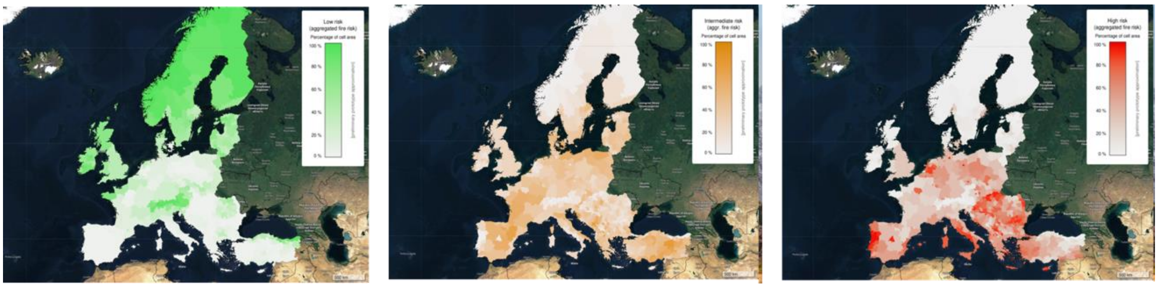

Figure 4- Final aggregated wildfire risk by administrative units. Prevalence of the lower-risk class (left); intermediate-risk class (centre); and higher-risk class (right) in each EURO-CORDEX spatial cell. Percentage based on the risk classification in each EURO-CORDEX cell of 100 equi-possible model runs, to integrate the uncertainty sources. Average aggregation by administrative units, expressing the prevalence of each risk class at the administrative level.

A preliminary version of the pan-European Wildfire risk map 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 5 with two examples of the layers included in the viewer.

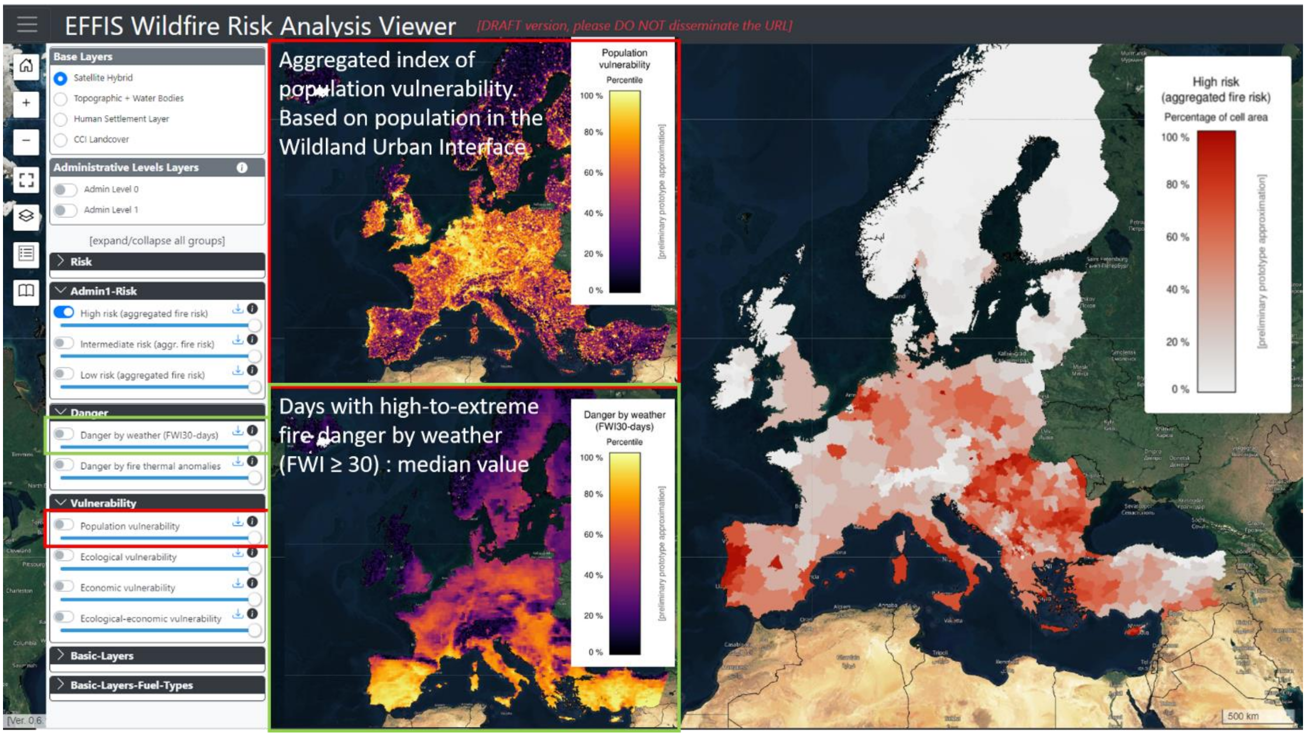

Figure 5- EFFIS Wildfire Risk Viewer (preliminary version). Values displayed in the map correspond to the high-risk class at administrative levels, based on GADM (https://gadm.org/index.html). As an example of some of the layers included on the viewer, the inside boxes display the Danger by Weather (green) and the aggregated index of population vulnerability (red). On the left panel are displayed the layers available in the viewer and on the right inside the legend for the two examples aforementioned.

5. Ongoing research

The above sections set the input data and the basic criteria for the WRA. Also, lessons learned from previous critical fires must be taken into consideration (San-Miguel-Ayanz et al., 2013), as these are becoming more frequent in Europe and worldwide. Next steps foresee testing and validating the WRA and will be undertaken in close collaboration with the EGFF. At the same time, research is ongoing on both deriving enhanced datasets and methods such as fuel classification, socio-economic components, or live fuel moisture content.

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