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Fires at the wildland-industrial interface. Is there an emerging problem?

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A R T I C L E I N F O

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A B S T R A C T

Over the past years, wildfires have raged with unprecedented intensity across the world, becoming a growing problem, as weather conditions conductive to wildfire ignition and spread will increase in frequency and severity worldwide. This, coupled with a growing human expansion, leads to an increase in wildfire risk and in the threat to wildland-urban interface (WUI) communities. Commonly, definitions for WUI areas consider homes, commercial facilities, office and public buildings. This excludes industrial installations, where wildfires can trigger accidents or cascading events leading to extremely dangerous situations for the population causing enormous economic losses. In this paper, the problem associated to the wildland-industrial interface (WII) is analyzed. A methodology to obtain a global WII map is described, and the first WII maps for Europe and Asia are provided. Results show that, in Europe, 2.5% of the land and 6% of vegetated areas are WII, while in Asia these are respectively 0.24% and 0.5%. An analysis of how wildfire triggered industrial accidents can be considered when performing quantitative risk assessments (QRA) in industrial sites is also performed, identifying the current state of the art and research gaps, with the aim of helping industry, public authorities and policy makers, for better accident prevention, preparedness and response.

1. Introduction

Forest fires, and more particularly extreme wildfires and megafires, are a growing problem across the world [1]. Over the past few years, wildfires have raged with large intensity across many world regions, as never seen before. Even though most wildfires do not pose significant risk to society and often contribute to ecosystems health, wildfires affecting communities (urban, suburban or rural) have increased rapidly over the past few decades, in both frequency and severity, and the number of structures lost each year has increased significantly worldwide [2–4].

Since 1990, wildfire events declared as disasters[1] have globally killed 2700 people, injured 11,700 and displaced 182,000 from their homes, with economic losses reaching 167.2 billion US$ [5]. Worldwide loss data of all wildfires are not available but we can expect they will probably increase the previous figures considerably. A closer look to the time evolution of the economic losses due to wildfire events at global level (see Fig. 1) shows a significant increase in the last decade (2013–2022) as compared to the two previous ones (1993–2012), as the mean value raised from 17 to 44 billion US$ (nearly 160% increase).

This tendency is expected to continue or even worsen due to climate change [6–9]. Global climate projections show that weather conditions conductive to the ignition and spread of wildfires, commonly known as *fire weather*, will increase in frequency and severity due to increases in global mean annual surface temperature, global frequency and intensity of heatwaves and regional frequency and severity of droughts [10].

The wildland-urban interface (WUI) is commonly defined as the area where houses and other structures are built within or close to wildland vegetation [11–13]. This definition is used to qualitatively identify settlements that are potentially at risk due to wildfires. Nevertheless, when one wants to quantify or map the risk, or perform an analysis on WUI areas and their dynamics, this simple definition is not enough and more details are needed. In general, to quantitatively define the WUI three main variables are considered [14–16]: a) the presence of structures (usually measured as a function of the house density); b) the presence and distribution of the vegetation (usually measured as a function of vegetation type, density and continuity), and c) the buffer distance between vegetation and houses, measured as a conservative

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[1] Disasters that registered more than 10 deaths and/or more than 100 people affected/injured/homeless, or that required the declaration of the estate of emergency and/or an international appeal [5].

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distance representing how far on average a firebrand can fly ahead of the fire front. The specific values considered for each of these three variables as well as the data sources to obtain them, varies across the world, among countries and even regions [17–25] making any comparison at global scale difficult.

Depending on how the WUI is defined, it can include or not industrial structures, but in general industrial facilities are not taken into account when mapping or analyzing the WUI problem. This in spite of the fact that wildfires can not only destroy them but can also trigger severe disasters by initiating cascading events leading to toxic spills, fires or explosions that further complicate the emergency management, or force the industry shut-down with the consequent revenue losses [26]. The areas where industrial facilities meet or are dispersed within the wildland vegetation are named wildland-industrial interface (WII) [27]. Even though several countries already consider wildfires as an additional source of risk for industries that needs to be regarded [28–30], to the best of our knowledge, only Canada has quantitatively defined and mapped the WII areas as a first step to identify and characterize this problem and to help risk modelling and fire management and mitigation [27].

The study of the impact of natural hazards on industrial installations is not new. Accidents triggered by the impact of a natural hazard are called Natech events [31–33]. Natural events triggering technological accidents have been a growing concern for regulatory authorities and industry during these last years [34]; in particular in areas prone to natural disasters, due to the potential overall consequences of the impact of these events on the population and on the environment, involving also severe economic losses. In addition, the impact and recurrence of natural disasters is aggravated due to climate change [35].

Natech events can be classified into four main categories following the commonly used taxonomy for natural disasters [36] as shown in Table 1. According to recent surveys [37,38] meteorological events such as storms, extreme temperatures and lightning are found to be the main trigger of Natech scenarios (86%), even though Natech events caused by earthquakes and floods are the most studied ones, as they are usually characterized by more severe consequences and escalation of events.

Even though in many countries there is a legal framework for the prevention and mitigation of industrial accidents, only in few cases this extends to address the control of hazards caused by Natech scenarios. In the European Union for instance, according to the Seveso III Directive [28], since 2012 it is required to include Natech scenarios in the safety reports of industrial installations that store or process relevant quantities of hazardous substances. However, there is still limited information on how Natech risk management has to be performed and many steps of the risk management process still lack data, models and methodologies to be fully applicable in a quantitative way [39,40].

Table 1
Taxonomy of natural events triggering technological accidents [37].

Natural event category	Natural event type
Geophysical	Earthquakes, landslides, tsunamis, volcanic activity
Meteorological	Storms, extreme temperatures, lightning, fog
Hydrological	Flooding, wave action
Climatological	Wildfires

As previously explained, wildfires are a natural event frequent in many parts of the world with a growing impact on urban settlements. Although industrial sites are common around urban communities, wildfire-triggered Natech events are still rare. However, several accidents have occurred worldwide during the last years [41,42], which lead to a raising concern about the consequences they may have in the future. These are a typical example of potential high-impact low-frequency (HILF) type of accidents [43], as they occur with a low degree of frequency, usually in an irregular and unpredictable way but, when they happen, they usually cause a significant degree of damage and disruption.

The purpose of this paper is to analyze the problem that wildfires can pose to industrial installations and review the available methods and tools that can help industry, public authorities and emergency managers for better accident prevention, preparedness and response. First, a review of past Natech events triggered by wildfires is performed. Then a methodology to obtain a global WII map is explained and the results obtained for Europe and Asia are provided and analyzed. An analysis of how wildfire-triggered Natech events can be considered when performing quantitative risk assessment (QRA) in industrial sites is later performed, identifying the current state of the art and research gaps. Finally, we provide a summary of the main findings.

2. Past wildfire-triggered accidental scenarios in industrial sites

A survey of past events in which a wildfire has threatened and/or impacted industrial installations or infrastructures was performed. There is no one single database containing this information. Wildfire impact on the WUI and, even to a lesser degree, on the WII is not currently being collected in wildfire statistics at country level. Databases collecting information on industrial accidents record those originated by wildfires only if there have been significant consequences. Thus, main sources of information used here were the ARIA (Analysis, Research and Information on Accidents) database from French Bureau for Analysis of Industrial Risks and Pollution (BARPI) [44] and the NRC (National Response Centre) database from the US EPA [45]. ARIA contains accidents from all over the world but most of them are from Europe, while the NRC database only includes accidents from USA. Other less formal

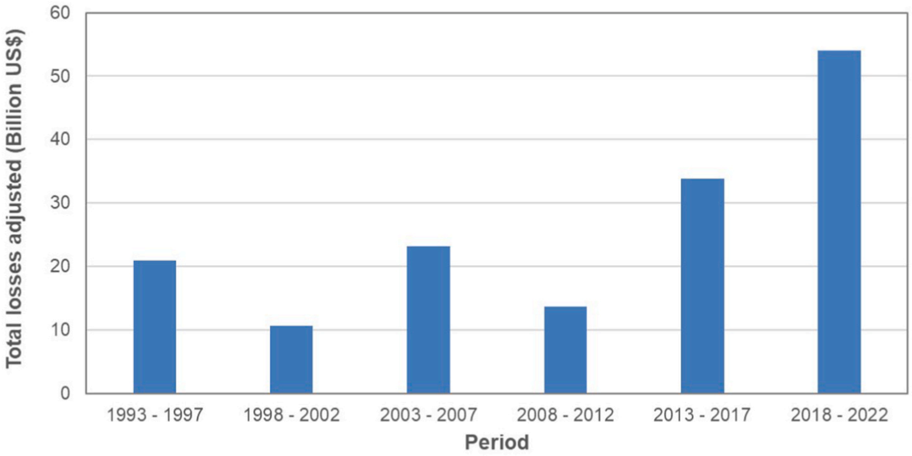

Fig. 1. Evolution of economic losses associated to wildfire events declared as disasters for the period 1993–2022, in billion US$ adjusted to the 2021 US$ value [5].

sources of information, such as articles from newspapers or other news media, have also been used occasionally to find events that have threatened or damaged an industrial installation, even if there have not been significant consequences.

The survey compiled in Table 2 gathers events occurred between 1997 and 2022 in different types of industrial facilities like landfills, biogas parks, decommissioned hazardous sites, nuclear power plants, storage facilities, chemical and petrochemical plants and pipeline infrastructures, the latter being the most affected type of installation. Regarding the consequences, the number of accidents that resulted in casualties were found to be limited. The construction type, site preparation, and professional management of industrial sites undoubtedly contribute to a lower incidence of wildland fire-related losses in comparison to alternative construction types, such as residential structures. However, a significant amount of records involved indirect effects (e.g. power shut downs) leading to business disruption and environmental pollution with important economic losses. A significant increase in the number of events during the last decade is observed in Table 2, following the tendency also shown by Fig. 1. It should be noted that it is probable that more cases exist around the world, which were not registered in a database nor were found by the authors in English mass media.

3. Mapping the wildland-industrial interface

The first step to better understand the problem associated to the WII and its future potential risks is to be able to identify those areas in which industries are close to or within wildland areas. Therefore, mapping the WII is key to identify the most vulnerable zones and prioritize management actions. As previously stated, only one attempt has been done so far to map the WII [27], even though many different countries in the world are highly industrialized and have also wide vegetated areas. Although this does not necessarily mean that they are in close contact, the probability of having WII areas is surely higher in these cases. If we look for instance at the countries with larger number of chemical facilities (using the number of employees as a proxy) and look at those with the largest forested areas (Fig. 2), we can see that the top 5 chemical producers are also within the top 10 most forested countries. And this is only considering the chemical companies, other types of industry such as the ones linked to energy production, mining, etc. can also pose a significant risk when threatened by a wildfire.

A recent study related to chemical accident prevention in the USA [47] identified more than 350 facilities in areas with high or very high wildfire hazard potential [48]. This represent 3% of the total USA risk management plan (RMP) facilities according to the EPA's classification, emphasizing the need to foresee in advance the risks that this issue may entail in the future.

Therefore, to look at the problem from a worldwide perspective, a first step is to create a global WII map. The strategy to do so follows the one used for the mapping of the WUI, as explained in the introduction, but considering industrial structures instead of houses, as was also done by Johnston and Flannigan [27] in Canada. This consists in obtaining a vegetation map and a map of the structures of interest, then defining a buffer distance between both, and finally combining the three to obtain the interface. The main challenge when trying previous approaches at a global scale, is data availability. Typically, country-level information is substantially more precise and comprehensive compared to the data accessible at the global level; however, there can be significant variations among different countries. This would require different approaches for each country, making the creation of a global map quite difficult.

The following subsections describe the methodology followed to come up with the WII global map. For the sake of simplicity only the results for Europe and Asia are shown and discussed (full resolution WII maps for the whole world cannot be reproduced here but are available at the following website: https://certec.upc.edu/en/research/wii-world-map).

Table 2
Wildfire-triggered Natech past events (updated from Ref. [42]).

Date (dd/mm/yyyy)	Location	Main wildfire triggering event	Type of impacted/threatened infrastructure
25/12/1997	Bintulu (Malaysia)	1997 Indonesian forest fires	Air distillation unit explosion [46]
11/07/2003	Castellbisbal, Catalonia (Spain)	Castellbisbal fire	Industrial area, threat to chemical industries
16/07/2003	Constantí, Catalonia (Spain)	Constantí fire	Industrial area, threat to chemical industries
26/07/2004	Alès (France)	Forest fire in Rochebelle and Mont Recato districts	Two spoil heaps of washery shale and ashes from coal mines
14/05/2011	Slave Lake, Alberta (Canada)	Slave Lake wildfire	Oil and gas industries shut-down
09/02/2014	Hazelwood, Victoria (Australia)	Hernes-Oak fire	Hazelwood coal mine burned
02/01/2012	Ranquil, Biobío (Chile)	Ñuble province wildfire	Cellulose panels production plant burned
01/07/2015	Fairbanks, AL (USA)	Aggie Creek Fire	Threat to Alyeska Trans-Alaska Pipeline
12/09/2015	Lake County, CA (USA)	Valley Fire	4 power plants in The Geysers geothermal complex affected. Damage to cooling towers, telecommunications and other infrastructure
01/05/2016	Fort McMurray, Alberta (Canada)	Fort McMurray Fire	Oil sands plants and pipelines shutdowns
07/04/2017	Cleveland, OK (USA)	Grass fire	Oil pipeline release
01/11/2017	Santa Rosa, Ca (USA)	Tubbs fire	Benzene pipelines release into water supply system
28/07/2018	Redding, CA (USA)	Carr fire	Natural gas pipeline burned
01/10/2018	Esmeraldas (Ecuador)	Brush fire	Threat to a refinery
01/10/2018	Bay point, San Francisco, CA (USA)	Grass fire caused by a fallen power line	Threat to natural gas pipeline, forced evacuation
01/10/2018	Goyang (South Korea)	Grass fire caused by a lost sky lantern	Oil storage facility. Gasoline tank exploded.
01/11/2018	Agoura, Los Angeles, Ca (USA)	Woolsey fire	Landfill. Gas collection system burned
01/11/2018	San Clemente, CA (USA)	Woolsey fire	Threat to decommissioned nuclear generation station
01/06/2019	Flegentreu, Brandenburg (Germany)	Brandenburg fires	Former military training ground and biogas plant affected
19/08/2020	Glenwood Canyon, CO (USA)	Grizzly Creek Fire	Hydroelectric power plant shut-down
09/09/2020	Mill City, OR (USA)	Beachie creek fire	Big Cliff and Detroit Dams threatened. Log boom and transmission lines destroyed.
13/09/2020	Linn, OR (USA)	2020 Oregon Wildfires	Threat to a warehouse/distribution Center
15/09/2020	Salem, OR (USA)	2020 Oregon Wildfires	Threat to a warehouse/distribution Center
17/09/2020	North Fork, Madera, CA (USA)	2020 Creek fire	Explosion of explosive materials stored in China Peak Mountain Resort Turbine from power plant (San Joaquín Valley Energy) released oil into the river.
12/04/2021	Osage, OK (USA)	Grass fire	Oil pipeline (Release of crude oil into the river)
14/04/2021	Pawhuska, OK (USA)	Grass fire	Brine pipeline (release of brine into the river)
20/07/2021	Rustic, CO (USA)	Forest fire	Pipeline, release of oil

(*continued on next page*)

Table 2 (*continued*)

Date (dd/mm/yyyy)	Location	Main wildfire triggering event	Type of impacted/threatened infrastructure
04/08/2021	Turkevleri, Mugla (Turkey)	2021 Turkish wildfires	Kemerkoy Thermal Power plant shutdown
04/03/2022	Uljin and Samcheok, Gangwon (South Korea)	Uljin wildfire	Nuclear Power Plant, LNG Storage facility, transmission lines threatened
23/03/2022	Chernobyl, Ukrania	Forest fire	Chernobyl Nuclear power plant exclusion zone was affected. Radionuclide emitted to the atmosphere.
26/07/2022	Estepona, Andalucia (Spain)	Estepona fire	Several warehouses burned in the industrial area of Estepona
10/12/2022	Esmeraldas (Ecuador)	Nuevos Horizontes wildfire	Threat to Esmeraldas refinery

3.1. Materials and methods

3.1.1. Vegetation map

The map of vegetated areas for Europe has been obtained from the 2018 Corine Land Cover (CLC) dataset [49], while for the rest of the world the 2018 Copernicus Global Land Cover (CGLC) dataset has been used [50]. Both datasets have a spatial resolution of 100 m but classification of vegetation types is slightly different, as CLC distinguishes 44 land cover classes while CGLC only 23. To simplify, homogenize and take into account the potential fire hazard associated to each type of vegetation, these were grouped into five fuel categories representing the potential fire behavior and suppression difficulty (see Table 3) [27]. The resulting map of fuel category for Europe and Asia is shown in Fig. 3. Russia was not included in either Europe or Asia, as it was treated separately, and the results are therefore not shown here.

Vegetation patches obtained after this classification can be of any size. It is clear though that polygons do not pose the same level of threat if they are small and/or there is no connectivity with other vegetation patches. In order to consider the potential capability of the landscape to propagate an eventual fire, an additional classification was performed. We used as a proxy for the fire propagation capability, the vegetation continuity [51] measured as a function of the Aggregation Index (AI) computed in each polygon of any given vegetation category [52]. Then, each vegetation patch was classified into a continuity category (see Table 4) following the work of Johnston and Flannigan [27].

A final map of vegetation distribution is obtained with 7 different fuel hazard categories by summing the fuel category and the continuity category values in each polygon, where 1 corresponds to the most hazardous category (obtained when adding fuel category 1, i.e. coniferous forests, with continuity category 0, i.e. largest AI values) and 7 to the lowest one (see Fig. 4).

This methodology is applied directly to all patches of the CLC data set, which are defined as polygons in vector format. For the CGLC data set that is delivered as raster, the fire hazard classification is made for each industrial site by running a polygonization of the locally cropped raster data at the time of the WII calculation. At the current stage of development of the methodology, continental map of fuel hazard category is therefore not available for Asia.

3.1.2. Industrial installations map

CLC and CGLC products do not have a specific category for industrial installations. CGLC provides only a single category for the land covered by buildings and other man-made structures (50-Urban/built-up), while CLC has category 1 (artificial surfaces) subdivided into four sub-classes one of them including industrial units (12-Industrial, commercial and transport units) but which cannot be separated from commercial units. Therefore, in this case the industrial areas map has been extracted from the latest version (March 2023) of the Open Street Map (OSM) dataset [53], considering the tag landuse = industrial, which has been filtered to keep only those polygons greater than 1 ha. The obtained industrial areas, for Europe and Asia, are given in Fig. 5.

3.1.3. Interface definition

The WII is defined here as the area of wildland vegetation surrounding any industrial installation area. To delimit and map the WII, a buffer distance between the vegetation and the industrial areas is defined depending on the final 7 hazard categories of the vegetation. The maximum buffer distance corresponding to vegetation hazard category 1 is 2400 m, which is an accepted standard in the USA (and WUI mapping literature) for the distance that a firebrand can travel from a wildfire and ignite a structure [16], while the values for the other categories correspond to this maximum divided by the value of the vegetation hazard category, as proposed by Johnston and Flannigan [27]. Then the WII is computed for each industrial polygon as the intersection between the vegetation polygon of a given hazard category and the buffer area around the industrial polygons corresponding to this fire hazard category (see Fig. 6).

The maximum distance traveled by a firebrand during a wildfire depends on factors such as the vegetation type, fire behavior and prevailing weather conditions [54]; therefore, the buffer distances used might be too large for some countries while being too small for others, according to the specific values associated with these parameters in each respective country. Nevertheless, this is a first attempt to provide a global WII map, which can later be refined at continental or country

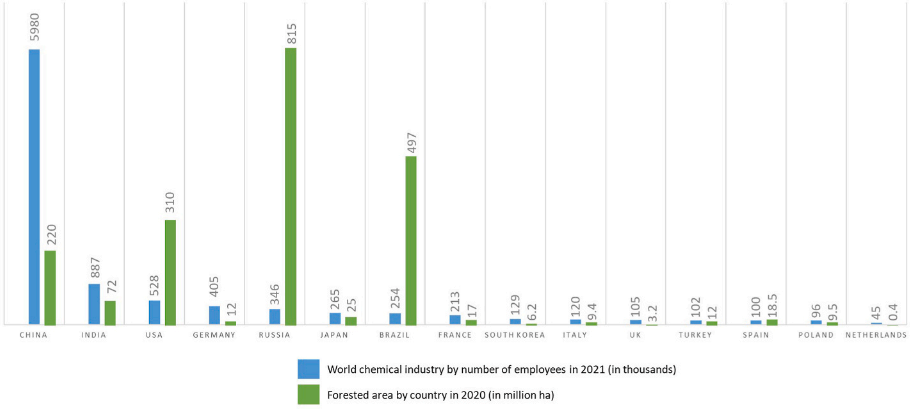

Fig. 2. World ranking of leading countries in the chemical industry sector based on number of employees (in blue) and corresponding forested area of the country (in green) (Source: statista.com). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Vegetation classification from CLC and CGLC and their corresponding fuel category, used here to map the WII areas. Fuel category values from 1 (most dangerous) to 5 (less dangerous).

CLC vegetation cover type	CGLC vegetation cover type	Fuel category
312-Coniferous forest	111-Closed forest, evergreen needle leaf 113-Closed forest, deciduous needle leaf 121-Open forest, evergreen needle leaf 123-Open forest, deciduous needle leaf	1
313-Mixed forest	115-Closed forest, mixedo 116-Closed forest, unknown 125-Open forest, mixed 126-Open forest, unknown	2
311-Broad-leaved forest 321-Natural grassland 323-Sclerophylous vegetation 324-Transitional woodland/shrub	112-Closed forest, evergreen broad leaf 114-Closed forest, deciduous broad leaf 122-Open forest, evergreen broad leaf 124-Open forest, deciduous broad leaf 20-Shrubs 30-Herbaceous vegetation	3
322-Moors and heathland	90-Herbaceous wetland	4
411-Inland wetlands	100-Moss and lichen	5

level. Fig. 7 shows the WII map for Europe and Asia. It has to be highlighted that these maps do not provide a risk measure, i.e. do not provide the probability of an industrial accident due to a wildfire, but they provide a measure of the vegetated areas that are close enough to industrial areas, so that in case of a wildfire it may potentially trigger an industrial accident. These are therefore the areas where risk assessments and prevention and mitigation actions have to be prioritized.

3.2. *Results*

In the case of Europe, there are 15 Mha of WII, which represent 2.5% of the European land and 6% of the wildland fuel areas (see Table 5). These numbers are larger than those obtained in Canada, which has 10.5 Mha of WII covering 1.3% of the land area and 1.9% of fuel areas [27], mostly due to the fact that Europe is more industrialized and has less percentage of fuel areas (specifically 43%, while in Canada wildland fuel areas represent 67% of the country area).

The ratio WII/wildland fuel area percentage gives an idea of how much of the wildland fuel areas are near industrial installations, while the ratio WII/industrial area (not percentage in this case) gives an idea of how much the industrial areas are surrounded by vegetation. In broad terms, Europe exhibits a relatively more uniform distribution of industries across its vegetation, whereas Asia demonstrates a higher concentration of industries in limited locations. This disparity primarily accounts for the larger ratio of WII/industrial area and WII/wildland fuel area observed in Europe.

If we look at country level in Europe, we can see that Germany is the European country with the largest WII area, 3.2 Mha representing 9% of its land area (see Table 6), followed by Sweden, Poland, France, Finland, Spain and Czechia. In some countries, such as Turkey or Romania, even if there are significant large industrial and wildland areas, the WII areas are relatively small, which means that industrial areas are generally located far from the vegetated areas and/or are more concentrated. Moreover, in very small countries such as Liechtenstein or Luxembourg, even if the total industrial and wildland fuel areas are small, the WII

Table 4
Vegetation classification into continuity categories depending on the Aggregation Index.

Aggregation Index (AI)	Continuity category
AI > 90	0
0 < AI ≤ 90	1
AI = 0	2

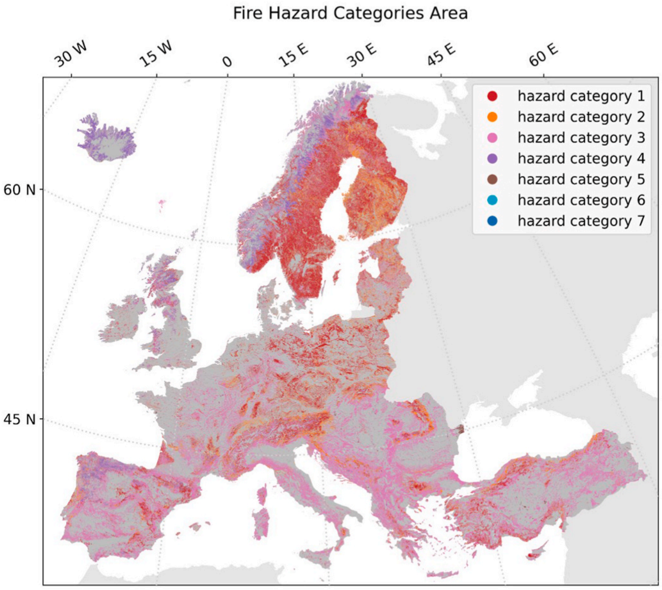

Fig. 4. Areas covered by the final seven fuel hazard categories after taking into account the AI for Europe.

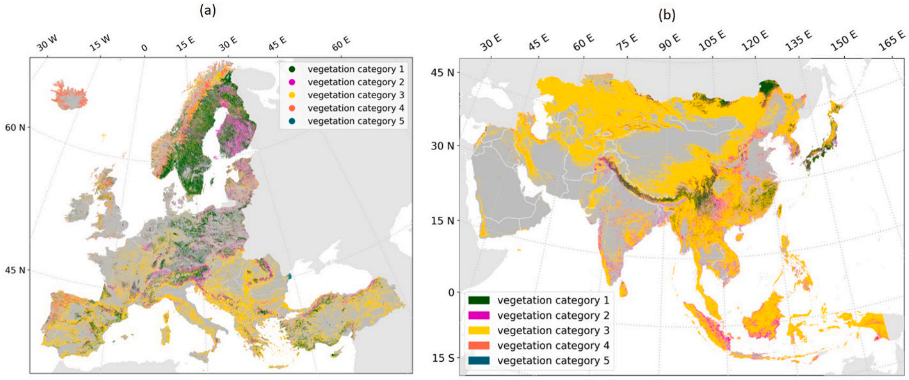

Fig. 3. Vegetation map showing the areas covered by the five fuel categories of vegetation. a) Europe obtained from the CLC; b) Asia obtained from the CGLC.

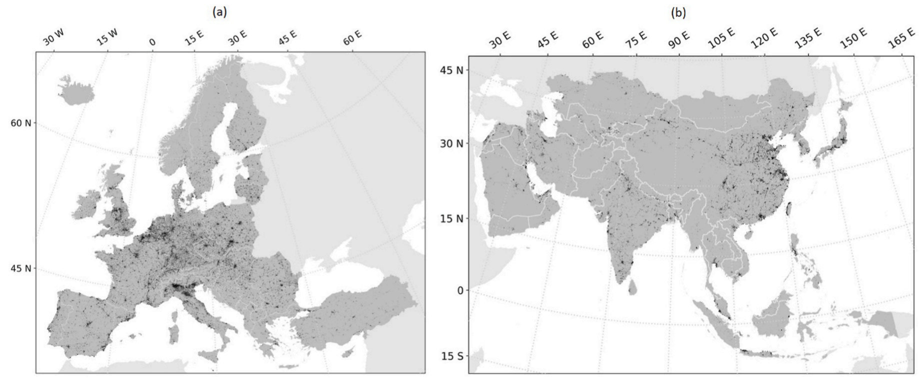

Fig. 5. Industrial areas map obtained from Open Street Map (March 2023 version). a) Europe, b) Asia.

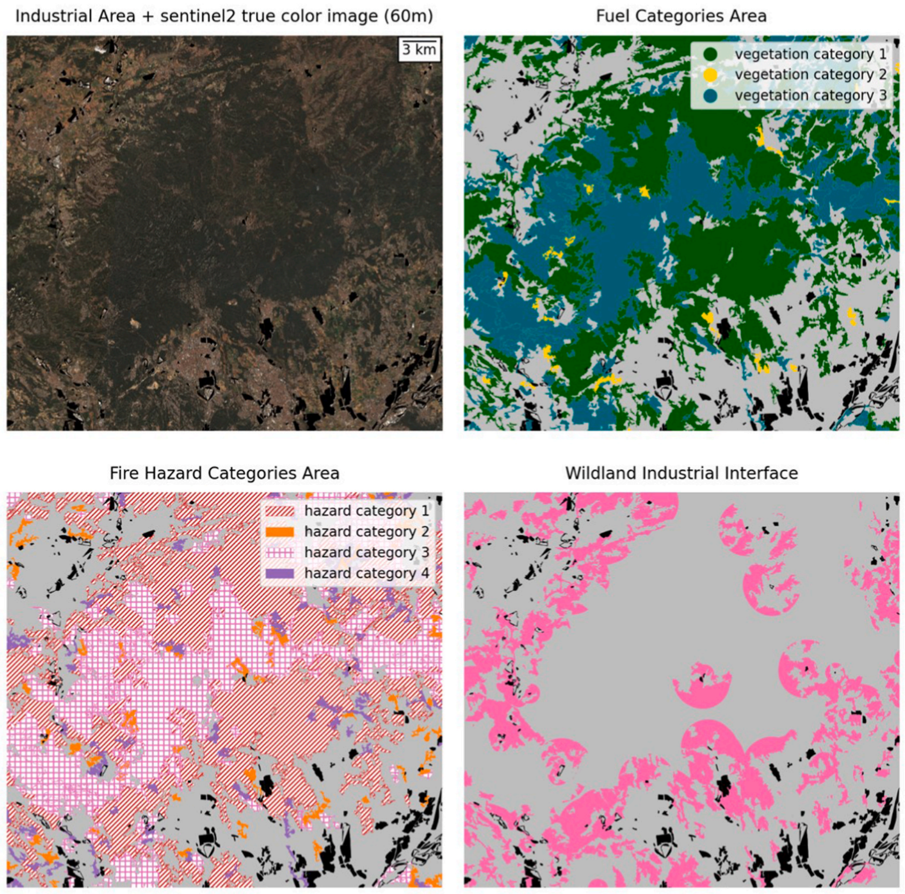

Fig. 6. Procedure followed to map the WII shown in an area of 50 × 50 km^2 located in Europe. Top left) Polygons corresponding to the industrial areas (in black) extracted from the Open Street Map (March 2023 version) overlapped with satellite imagery. Top right) Areas covered by wildland fuels (only the three first categories according to Table 3 are shown). Bottom left) Distribution of vegetation according to the fuel hazard categories (only the first four categories are shown) together with industrial areas. Bottom right) WII area is shown in pink colour, after intersecting the fuel hazard areas and the buffer distances around the industrial areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

represents a large percentage of its wildland fuel area (20% and 16% respectively), which means that their industrial areas are homogeneously distributed among the vegetated areas. When we look at percentage of WII with respect to the wildland fuel areas, some highly industrialized and highly vegetated countries with a significant WII area, such as Spain, are not located high in the ranking. This is generally because industrial areas are concentrated only in some regions (while in Germany, for instance, industrial areas are evenly distributed all over the country's surface). In the case of Spain, if we look at the Catalonia region (in the northeastern part of Spain), which is highly industrialized (see Figs. 5 and 8), 10% of its vegetated area is WII, which means it would be located after the Netherlands according to the ranking in Table 6.

In the case of Asia, with a total area over 5 times larger than Europe, the total WII area is 7.4 Mha (see Table 5), half that of Europe, even if the total industrial area is nearly the double and the vegetated areas are six times larger than in Europe (although the percentage of vegetated areas in Asia, 50%, is only seven percentage points larger than in Europe). This means that in general, industries in Asia are not as close to vegetation as in Europe. In any case, these results must be looked at also at country level, as they provide more useful information. China is the country with the largest WII area (3.5 Mha), followed by Japan (0.8 Mha), India (0.49 Mha), Kazakhstan (0.46 Mha), Indonesia (0.3 Mha), Iran (0.22 Mha), Malaysia (0.21 Mha) and South Korea (0.19 Mha), these eight countries count for nearly 84% of the Asian WII area. In terms of WII with respect to the wildland fuel areas (see Fig. 8), some small industrialized countries, such as Singapore (24%), Hong Kong (18%), Israel (10%) or Bahrain (8%), appear high in the ranking because they have small

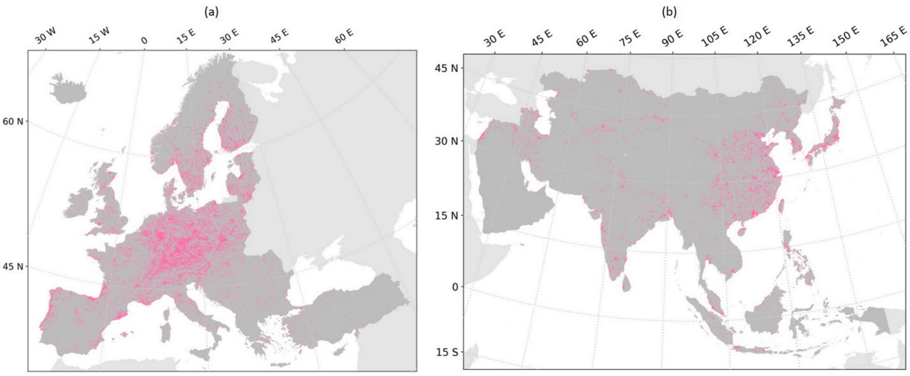

Fig. 7. WII map. (a) Europe. (b) Asia.

Table 5
Global results at continental level for Europe and Asia.

	Europe	Asia
Total land area (Mha)	583.8	3030.7
Wildland fuel area (Mha)	252.4	1512.1
Industrial area (Mha)	2.2	4.0
WII area (Mha)	14.8	7.41
Wildland fuel/land area (%)	43.2	49.9
Industrial area/land area (%)	0.4	0.13
WII/land area (%)	2.5	0.24
WII/wildland fuel area (%)	5.9	0.49
WII/industrial area	6.9	1.86

vegetated areas, are small countries and industries are close to these vegetated areas. Other highly industrialized countries such as Japan or South Korea have similar values (around 3%) but well below most European countries mostly because their vegetated areas are much larger (the case of Japan) or the industry is concentrated in some areas of the country (the case of South Korea). In these cases, results may have large differences among provinces (i.e. Busan province in South Korea has 30% of WII/wildland fuel areas, ten times the country value). For the largest countries, such as China, India or Kazakhstan, results would have to be analyzed at province level to obtain more useful information.

When analyzing the obtained results, we should take into account the limitations of the data used when producing the maps and the errors that may consequently arise. First, the maps may be out-of-date (e. g. new industries may have not been considered or some that have been considered, may have disappeared, vegetated areas can change with

Table 6
Ranking of the first fifteen European countries by area covered (Mha) by industrial installations, wildland fuel and WII, and percentage (%) of WII over wildland fuel, WII over industrial area and WII over country area.

Rank	Industrial Area (Mha)		Wildland Fuel Area (Mha)		WII Area (Mha)		WII/Wildland fuel area (%)		WII/Country Area (%)	
1	Germany	0.305	Sweden	32.5	Germany	3.24	Germany	28.5	Liechtenstein	11.8
2	France	0.286	Turkey	29.4	Sweden	1.70	Czechia	25.7	Czechia	9.2
3	Italy	0.206	Finland	25.0	Poland	1.66	Liechtenstein	19.8	Germany	9.0
4	Spain	0.167	Spain	23.5	France	1.25	Belgium	18.4	Austria	7.7
5	UK	0.151	France	17.8	Finland	1.11	Poland	15.9	Switzerland	6.0
6	Poland	0.123	Norway	16.1	Spain	0.78	Malta	15.7	Luxembourg	5.7
7	Turkey	0.117	Germany	11.3	Czechia	0.72	Luxembourg	15.5	Poland	5.3
8	Romania	0.114	Italy	10.9	Austria	0.65	Austria	14.2	Lithuania	4.5
9	Netherlands	0.099	Poland	10.4	Italy	0.54	Switzerland	13.3	Belgium	3.9
10	Sweden	0.063	Romania	8.5	Norway	0.50	Lithuania	12.8	Sweden	3.8
11	Belgium	0.059	Greece	7.0	Lithuania	0.29	Denmark	12.7	Slovenia	3.4
12	Czechia	0.056	UK	5.7	UK	0.28	Netherlands	11.0	Finland	3.3
13	Finland	0.052	Bulgaria	4.7	Switzerland	0.25	France	7.1	Netherlands	3.2
14	Hungary	0.045	Austria	4.6	Portugal	0.23	Portugal	5.8	Portugal	2.6
15	Bulgaria	0.041	Portugal	4.2	Turkey	0.22	Slovenia	5.6	Estonia	2.5

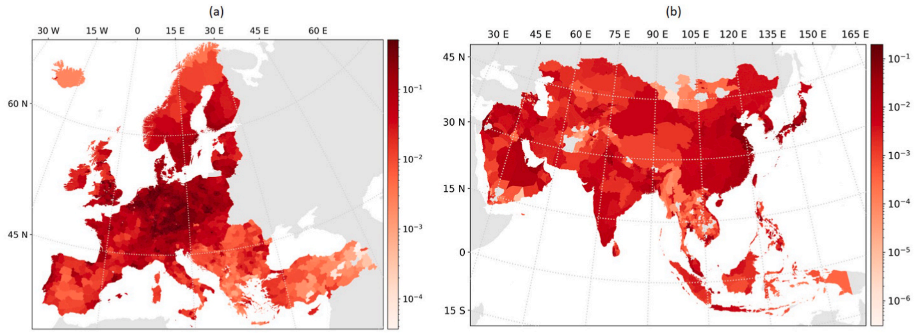

Fig. 8. Map providing the ratio of WII area over total fuel area at province level. (Left) in Europe; (Right) in Asia.

time) or have errors (e. g. some industrial polygons may be overlapped with vegetation, some areas may be wrongly classified or other areas may lack the information). Second, all categories of industries according to the OSM classification have been included in the analysis due to the limitations of this classification, which does not allow for the distinction of hazardous industries. While it is acknowledged that certain industries may not possess hazardous substances and consequently carry no risk of triggering a Natech event, it is important to note that significant economic losses and environmental impact could still arise if an industrial facility were to burn or sustain damage due to a wildfire. Third, the fuel hazard classification and buffer distances that have been used may not be adequate for some countries, if lower values were used, the WII areas would decrease as well. When using the WII map on a country or regional scale, it is advisable for users to ensure the satisfactory accuracy of the provided WII map for the intended purpose. Additionally, careful consideration should be given to adapting the proposed methodology to accommodate the local vegetation characteristics and anticipated fire behavior.

Further work can be done to develop these results by combining them with wildfire-related data, i.e. with respect to past fires (i.e. number of fires and perimeter location, ignition probability, area burnt, etc.), current data (i.e. wildfire hazard assessed according to the Fire Weather Index) or future projections.

4. Quantitative risk assessment (QRA) of wildfire risk in industrial sites

The WII map can be combined with the information on the hazardous industries present in a given country, to locate and identify those that should consider the wildfire risk as an external event that contributes to the overall risk of the installation. In this section, we provide an analysis of how this could be done and what tools and methods currently available could be used to include wildfire risk in traditional QRA.

The framework of the risk management process of any organization is well defined by the ISO 31000:2018 [55], and is commonly followed to manage risk in the context of hazardous installations. The core of the risk management process is the risk assessment process (see Fig. 9), which in turn is constituted by three main steps: (1) risk identification, (2) risk analysis and (3) risk evaluation.

Risk identification refers to the process of finding, recognizing and describing hazards with the objective of determining which unwanted events can occur, as well as the mechanisms that can trigger them. Risk analysis is the process of characterizing the identified risks, either through qualitative and/or quantitative risk analysis techniques. At this stage, the consequences of undesired events and their probability of occurrence are analyzed. Finally, risk assessment is the stage where we assess the risk against predefined thresholds of acceptability and tolerability. Risk assessment helps to determine if, in addition to existing systems and controls, additional mitigation treatments or measures are required to contain risk to acceptable levels.

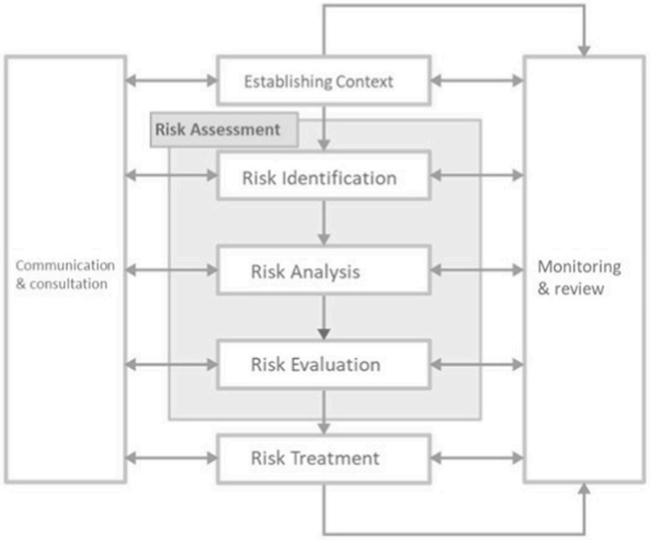

Fig. 9. Risk management process according to ISO 31000:2018 [55].

Although all the stages of the risk management process are important, the central part, corresponding to the risk analysis, is the one that entails the greatest complexity and at the same time requires the knowledge and application of different techniques and models, especially if the risk is to be analyzed quantitatively [56].

QRA for process industries has been developing for several years now and a solid knowledge base exists, providing diverse and multiple methodologies, models and techniques [56–60]. It is also a common practice in developed countries in which it is often a law requirement [28,29,61]. Although, as science evolves, improvements are continuously being applied [62], the fact is that QRA can be nowadays performed with good confidence to produce useful information to better manage the risk associated to hazardous substances. Nevertheless, the same cannot be said when talking about Natech risk management and even less if we focus specifically on Natech risks triggered by wildfires.

A recent report from the Joint Research Centre of the European Commission [40] provides technical guidance on how to conduct a Natech risk assessment and it points out the main challenges that currently impede its accurate implementation. It is mainly focused on the general framework for QRA traditionally performed in the process industry, as explained before, in which accidents are commonly caused by the loss of containment of a hazardous substance directly due to an equipment failure. When applied to Natech events, the natural hazard considered would be the cause of a given equipment failure leading to the accident. Nevertheless, past events have shown that often accidents caused by Natech events happened not due to the direct impact of the natural hazard on equipment but due to the indirect impact caused by the failure of plant utilities, safety barriers or auxiliary systems; and this would require a new assessment framework [63].

Following the general procedure proposed by Necci and Krausmann [40] for Natech risk assessment and adapting it to wildfires, the following steps would need to be followed.

1. Wildfire scenario identification and characterization
2. Identification of the critical equipment that, when affected by a wildfire, can lead to hazardous situations
3. Identification of the damage modalities that wildfires can cause to critical equipment
4. Wildfire hazard identification due to both direct and indirect causes
5. Wildfire consequences analysis
6. Wildfire risk calculation

4.1. Wildfire scenario identification and characterization

Wildfires have certainly the potential to trigger an accident at an industrial installation directly due to heat radiation and/or flame contact from the main fire front (if wildland vegetation is close enough to the industrial site) or by ember attack, but also indirectly by damaging safety systems (in any of the layers of protection) or essential auxiliary systems or utilities (such as power or water supply).

At least two wildfire scenarios should be identified, heat radiation/flame contact and ember attack, which can be the most likely or worst-case scenarios, but that have to be reasonable and well-justified. A description of the characteristics of each scenario will then be required. For heat radiation, the expected flame geometry for the wildland fuel involved, as well as the residence time and fire emissive power will be needed [64]. For ember attack, it is necessary to estimate the expected spotting distances, number and distribution of firebrands. In both cases, wildfire changes in frequency and intensity due to future climate projections, as well as potential future land-use changes that could affect these scenarios would have to be taken into account. Information on historical wildfire events occurred near the industrial site can also be very useful to help their characterization. Many wildfire-prone countries in the world have wildfire hazard and/or frequency maps providing the spatial distribution of wildfires return periods or probability [65–68].

In addition, the potential effect of smoke (and ash) and of the fire environment (i.e. high wind velocity and temperatures due to atmospheric winds and fire-induced in drafts) on the equipment and personnel of the industrial site has to be analyzed as well, as it could have both direct and indirect impacts on the plant equipment and operation, and on the people's ability to work, compromising the whole plant safety.

4.2. Identification of critical equipment in a wildfire situation

The second step after identifying and characterizing the wildfire scenarios to be considered is to identify all installations containing hazardous materials that can potentially be damaged by these wildfire scenarios, which may lead to a hazardous situation for people, property or the environment (such as a release of a toxic or flammable substance, an explosion or a fire).

Certain equipment may be particularly vulnerable to wildfire exposure; this is the case of storage equipment, as large quantities of flammable and/or toxic substances can be released if the tank fails. For instance, floating roof tanks widely used to store low boiling point flammable liquids could be specially threatened by flying embers as large numbers of burning particles might accumulate around the rim seal and ignite the stored substance. Another example is those areas in many industrial sites classified as ATEX, i.e. zones that can produce explosive atmospheres due to the presence of mixtures of air with flammable gas/vapors or combustible dust/fibers, in which heat radiation, flame contact and flying embers can act as ignition sources. Processes and equipment involving heat sensitive substances may also be affected by smoke and the fire environment, leading to extremely dangerous situations. Furthermore, it is also important to consider nuclear power plants and other nuclear installations, as they rely on uninterrupted mechanical ventilation, which can be compromised in the event of a wildfire due to the filters becoming clogged with smoke particles.

Although most of the equipment, pipes and instrumentation in industrial sites are made of diverse metallic non-combustible materials (e.g. steel), polymers are also present as substitute material in corrosion sensitive applications and can hence be vulnerable to wildfire exposure, either by thermal radiation, flame impingement or ember attack.

All identified critical equipment can be even more vulnerable during shutdown and start-up operations, as the risk of equipment failure or uncontrolled accidental release of hazardous substances is higher in these situations. Emergency shutdown is often connected to flaring, venting or rapid depressurization of process equipment to create safe conditions, but in case of a wildfire this might lead to further accident escalation.

4.3. Wildfire damage to critical equipment

Once all critical equipment potentially vulnerable to the wildfire impact has been identified, the main damage modalities for each of the identified equipment have to be defined. The most typical failure modes in Natech scenarios were identified by Necci and Krausmann [40], the following should be considered in case of wildfire.

- Ignition and sparking. Process plants dealing with hazardous substances may have areas that contain flammable or explosive atmospheres, which in case of a near wildfire can be easily ignited. Moreover, recent studies show that lightning can be severely enhanced by wildfires [69], and lightning strikes are already the most common natural ignition source of tank fires.
- Floating roof failure. The most probable situation during a wildfire is the ignition of the tank contents at the rim seal between the roof and the shell wall of the tank due to embers accumulation. However, in some cases, if the roof is damaged, it can sink into the liquid and expose the whole surface, leading to the release of toxic and/or flammable vapors into the atmosphere, and a tank fire, if they ignite.
- Rupture of fixed tank roof. The roof is the weakest part of a fixed roof tank and therefore strong winds generated by the wildfire environment could damage it. Even though this does not necessarily mean there would be a loss of containment, if the content of the tank is flammable, its further exposure to flying embers can lead to ignition.
- Buckling damage. Deformation of metal enclosures due to load effects, debris impact or wind on the structure. In case of a wildfire this could be due to the strong fire induced winds and debris falling from the fire's convection column.
- Rupture of pipes and fittings. Strong winds induced by a wildfire can cause objects to fall onto pipes and racks, breaking them. In industry, different kind of materials can be used to transport liquids and gases and some of them can melt under high temperatures or due to flame contact or ember attack.
- Tearing of metal shell. When a vessel deformation is sufficiently large, the metal shell may fall apart, exposing the insulation layer (which may be combustible, and therefore ignite due to wildfire impact) or causing a loss of containment.
- Detachment of the shell-to-bottom connection. This is a special case of buckling damage to atmospheric storage tanks, when bucking affects the lower part of the tank.
- Support leg failure. Many equipment have legs to support their weight. Legs can fail under strong heat radiation or flame contact, causing the collapse of the entire equipment on the ground.
- Puncturing damage. Strong winds associated to wildfires can carry sharp objects that can impact and puncture low shell thickness equipment, leading to a loss of containment.

Apart from the direct damage that wildfires can cause to critical equipment, they can also disrupt the correct functioning of process plant auxiliary and utility systems (i.e. power, water, steam, compressed air, control systems, pumps, etc.) and safety barriers (i.e. detection and alarm systems, emergency shutdown, pressure relief valves, flares, sprinklers and water deluge systems, etc.), which can indirectly trigger or enhance the consequences of an accident. During a wildfire event, particular attention has to be paid to the emergency management procedures and firefighting crews' intervention, as the need for simultaneous suppression in the wildland and at the urban and industrial interface may lead to criticalities in term of available resources and water. Even though, auxiliary systems and utilities may have high redundancy in installations dealing with hazardous substances, past Natech accidents have shown that often, both the principal and the redundant systems are damaged simultaneously by the natural hazard.

Currently, there is a lack of systematic data and methods to accurately quantify all the direct and indirect damages caused by wildfires to critical equipment. However, initial efforts are underway to address this gap [64,70].

4.4. Hazard identification due to both direct and indirect causes

After analyzing the critical equipment that can potentially be affected by a wildfire and evaluating the diverse failures modes that can lead to an equipment loss of containment or the direct ignition of flammable substances, all the initiating events (defined as a deviation from a process condition with the potential to develop an accident with adverse effects) potentially leading to accidental scenarios have to be identified. Tools such as Hazard and Operability Analysis (HAZOP), Failure Modes and Effect Analysis (FMEA), Layers of Protection Analysis

(LOPA), etc., typically used in traditional QRA to identify specific initiating events can also be used here. In this case though, taking into account the wildfire impact on the system and the fact that in Natech events the simultaneous failure of systems −unlikely in normal conditions− cannot be discarded unless the detailed analysis of the conditions during the wildfire event show that no dangerous situation can arise from it.

In the case of the direct damage of the wildfire on equipment, the considered initiating event should include the eventual loss of containment (LOC) description (i.e. instantaneous release of the equipment full content, continuous release from a hole in a vessel, full bore rupture of a pipe, etc.) while in the case of ignition of flammable substances there will not always be a LOC, and the initiating event and final accident outcome are more directly linked (i.e. ignition of a flammable liquid in a tank, ignition of a flammable vapor cloud, etc.).

For each identified initiating event, the evolution from the initiating event to the final accidental scenario has to be determined. In traditional QRA this is usually done by means of Event Tree Analysis (ETA), which could also be used for wildfire triggered initiating events. Frequencies of the final accidental scenarios are computed from the initiating event frequency taking into account the probabilities assigned to each branch of the event tree. We have to consider though that probabilities used in generic event trees commonly used in traditional QRA [71], may no longer be applicable in a wildfire situation. For instance, delayed ignition probability of flammable clouds in process areas with possible ignition sources is taken as 0.7, but in case of a wildfire, this would have to be increased to 1 due to the presence of flying embers.

Determination of the frequencies associated to these wildfire specific initiating events would be required if a QRA has to be performed. This could be done by carrying out Fault Tree Analysis (FTA). Some attempts to do so have already been implemented at the WUI [72,73], nevertheless to the knowledge of the authors very few attempts have been performed at the WII [30,74,75]. Moreover, no information is available on the LOC scenarios to be considered for specific wildfire initiating events. For other Natech events, a relationship between damage state as a consequence of natural hazard impact and the LOC scenario is often considered, which could also be applied for the wildfire case.

The indirect effect of wildfires on utility systems and safety barriers also needs to be considered. In the case of safety barriers, the easiest way is to not take them into account, i.e. even if safety barriers are present, the mitigating effect on the potential outcome of the accident will not be considered as a worst-case scenario. The indirect effect on utility systems can be considered when performing a HAZOP, but of course it requires a deep analysis and thorough understanding of the process operations.

4.5. *Consequences analysis*

Once the list of potential final accident scenarios (i.e. tank fire, jet fire, pool fire, vapor cloud explosion, toxic cloud dispersion, vessel explosion, etc.) has been identified, modelling the physical effects they may cause (thermal radiation, overpressure, toxic concentration) and their consequences on people, environment or installations, does not differ from what is traditionally done in QRA (i.e. using Probit functions to obtain the probability of death due to thermal radiation, overpressure or toxic exposure) and many resources are already available [58,59,76].

In traditional QRA, simultaneity of accidents and their overlapped consequences are not considered because they have extremely low probabilities of occurrence and only the potential domino effect (i.e. the case in which an explosion or a jet-fire at a given industrial installation can trigger another accident such as a toxic release) is taken into account. In case of domino effect, the frequency of a given initiating event that can occur by itself or as a consequence of domino effect is multiplied by 2 [77]. Nevertheless, in the case of wildfires, apart from the domino effect that can happen as well, the possibility of having two or more initiating events at the same time turning into simultaneous accidents is something that needs to be considered carefully and cannot be discarded easily, as demonstrated for other Natech events [78]. Moreover, very little research has been done on how to compute the consequences of simultaneous accidents on people and equipment [79,80], as in traditional QRA only one accident is considered to occur and the probability of death from an accident is independent of the other accidents that can eventually happen. The best way to address these issues in a QRA certainly needs further research.

4.6. *Risk calculation*

When performing a QRA in industrial installations, the individual risk at a given location ($IR_{x,y}$) is computed by multiplying the frequency of a given accidental scenario (f_i, in year^{-1}) by its consequences in terms of probability of loss of human lives (see Eq. (1)), and summing this for all the accidental scenarios considered [76].

$$IR_{x,y,i} = f_i \bullet P_{F,i} \tag{1}$$

$P_{F,i}$ is the probability of that the accidental scenario i will result in a fatality at location x,y. The frequency of a given accidental scenario, f_i, is computed from the frequency of the initiating event leading to the accidental scenario ($f_{LOC,i}$) and the global probability of the event sequence leading to the accidental scenario ($P_{sequence,i}$) (obtained usually by event tree analysis), as shown in Eq (2).

$$f_i = f_{LOC,i} \bullet P_{sequence,i} \tag{2}$$

As explained in section 4.4, there is no data available yet on the frequencies associated to the initiating events in case of wildfire. Moreover, LOC events considered in traditional QRAs are associated to failure of the industrial installation itself (due to equipment failures, maintenance problems, human error, etc.) and these frequencies are commonly obtained from reliability databases. In the case of LOC events originating from a wildfire, there is not enough statistical data available to directly obtain these frequencies. In addition, when estimating frequency, both the probability of a wildfire near the industrial installation (linked to the presence of WII and to the probability of wildfire ignition and spread) and the probability that a wildfire (by radiation, impingement, ember attack or smoke) impacts directly or indirectly critical equipment should be considered. Very few attempts to compute the frequency of initiating events in case of wildfire have been found in the literature so far [64,74,81], and all of them considered only ignition by radiation. Therefore, significant research has still to be performed to be able to account for wildfire Natech events into QRA.

5. Conclusions

Due to climate change wildfire's frequency, severity and fire season's length is expected to increase in many regions of the world. At the same time, the world population is progressively occupying spaces that are closer, or even inside, vegetated areas. In recent years, there has been a significant increase in the impact of wildfires on the WUI, causing damage to people and infrastructure with important economic losses. Industrial sites are part of urban communities and are often close to vegetated areas, with the consequent risk of being affected by wildfires. In addition, some industries have processes that require the storage and handling of large inventories of hazardous substances, which requires a strict control of the risk they can pose for the population. In these cases, wildfires may trigger industrial accidents, increasing the magnitude of the consequences and the difficulty of the emergency management.

The analysis of past accidents affecting the WII has shown that even if many different industrial installations have been impacted by wildfires, only a few industrial accidents have been triggered, while plant shut-down and economic losses have happened in most cases. In addition, the number of events has been increasing with time, which is worrying. The first step to understand how big this problem might be in the future is to identify how many areas in the world are WII areas.

A methodology to map the WII worldwide has been presented and the results for Europe and Asia have been given as example. Even though it has limitations and can be further improved, it allows for the identification of high-risk areas that require focused attention from authorities. It assists in planning preventive measures and enhancing the understanding of risks at specific industrial sites, thus contributing to improved emergency management and land-use planning. A variety of mitigation measures to protect industrial facilities from wildfires should be implemented, including the maintenance of a buffer zone with little vegetation or constructing a ring road around the facility to provide defensible space for emergency response crews.

When performing QRAs for industrial areas in general, the impact of wildfires should be included. This is particularly important for the areas in which wildfires can trigger severe accidents, such as explosions, fires, or toxic releases. How to do this quantitatively is not clear yet. A review of the state of the art of methodologies and tools that can help take wildfire risk into QRA has been provided. Several stages within the QRA process necessitate further research before achieving complete implementation. Among these stages, the identification of wildfire-specific initiating events and their corresponding frequencies, attributed to both direct and indirect causes, is likely the aspect that demands the utmost attention. This step holds significant importance within the QRA process, as it is a key step and precisely where a scarcity of information currently exists.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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