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Review paper

A review of forest fire research directions: Different approaches for one goal

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Forest fires cause environmental and economic damages every year, especially in the southern part of Europe. Approaches to estimate the fire risk vary from practical to scientific, since different professions as firefighters, meteorologists, soldiers and foresters are involved. The Internet of Things enables to connect different sources of information in one place, however, the understanding of usage and processes that caused the disaster sometimes is missing. The aim of this article is to give a comprehensive overview of nowadays possibilities for fighting with the fires and categorization of different methods, techniques and approaches. Considering the timeline of the information about fires we are dealing with, we propose three categories: *past* which mostly refers to analysis, *present* which encompasses monitoring and *future* covering forecasting. Each of the categories is described in detail, confirmed with related work and examples, and enriched with challenges and future directions. Dealing with forest fires is very complex, therefore it is difficult to deal with all proposed categories at the same time. However, due to the growing amount of available information and increasing interest of scientists from different research fields, there are more examples of intertwined areas dealing with forest fires. It is expected that in the future it will be possible, in real time, to handle various sources of data and forecast fire danger and risk with high spatial and temporal resolution.

Keywords: forest fire, EFFIS, FWI, forest fire modelling, forest fire forecast

1. Introduction

Forest and wooded land cover represent more than 40% of the total European land area and about 182 millions of hectares (European Parliament, 2020). European Union (EU) forests absorb 417 million tonnes of CO_2 equivalent which corresponds to around 9% of total greenhouse gas emissions. Although forests play important role in reducing greenhouse gasses and are an important factor in mitigating climate change, forest fires do just the opposite. Forest fires cause environmental and economic damages every year. For example, Germany for their own country estimated cost per hectare burned over 1137 EUR/hectare in 2018. Reading news from media from all over the world, one can wonder is it even possible to compare European fires with wildfires in California in the USA or with those in Australia? What is the most efficient way of fighting with fires? Is there anything that can be done or is it all up to the weather?

Global Wildfire Information System (GWIS) and European Forest Fire Information System (EFFIS) provide insight into burnt area and number of fires (Global Wildfire Information System, 2021; European Forest Fire Information System, 2021). Both systems use sensors placed on satellites that identify areas on the ground that are hotter than their surroundings and mark them as active fires. GWIS divides the world into six categories by continents while EFFIS differs between EU and non-EU countries. GWIS data time period is 2001–2019, while EFFIS covers more recent time period 2008–2020. Comparing data between continents, one can see that, in multi-annual average, almost two thirds of all burnt area in the world between 2001 and 2019 refers to Africa, while Europe stands in the last place with only 1% (Fig. 1). Australia is a country with the highest multi-annual average burnt area of 48 mil. ha. Although Europe ranks the last, its 3.4 mil. ha in average make up 0.2 % of the European area. European countries with largest burnt areas are traditionally Mediterranean countries Portugal (115,700 ha), Spain (62,400 ha) and Italy (40,800 ha) which make up to 55% of European burnt area.

Comparing share in total number of fires with the share in total burnt area provides an information about average size of each fire by continent – the higher number of fires indicates the smaller burnt area. Europe, Asia, North and

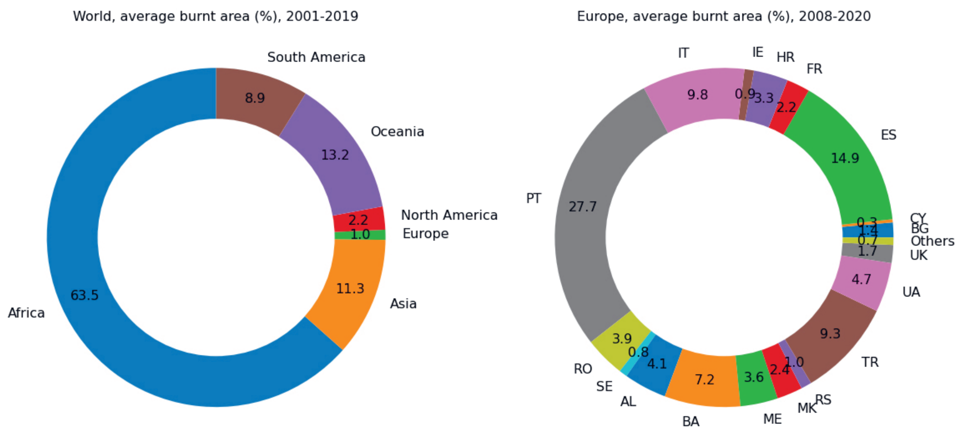

Figure 1. World multi-annual average burnt area (%) for time period 2001–2019 from GWIS (*left*) and European multi-annual average burnt area (%) for time period 2008–2020 from EFFIS (*right*).

South America have decrease in their share of total number of fires in comparison to burnt area (*cf.* Figs. 1 and 2). On the other hand, Africa and Oceania show an increase which means that, in multi-annual average, their fires have larger burnt areas. However, information about average burnt area that is destroyed in fire is not enough to assess and quantify the harm – determining the value between property, human life and disruption of the ecosystem is a very ungrateful task with regard to ethical and moral principles. Although Europe has only 1% share in total number of fires, experience and efforts in fighting the fires are great. European countries with highest average number of fires are again Mediterranean countries: Italy (224), Portugal (222), and Spain (168), which make up to 50% of European number of fires.

Ubiquitous fires forced people to define a period in the year when fire risk is significant (*i.e.* fire season) and protection preparedness has to be increased. Fire seasons are different between countries. For example, Norwegian fire season is from March to September, Italian fire season is from mid-June to mid-September, but there are also countries like Portugal which has the highest fire risk in Europe with fires all over the year (Joint Research Centre, 2019). EFFIS seasonal trend shows that, on average, mid-February is time when 30 fires in Europe with more than 7,000 ha of burnt area already have occurred. Despite the used definition of fire season, the main factors for fire protection preparedness include current weather conditions together with conditions of previous seasons. Due to climate change and expected hotter and drier conditions in the future, the main part of the fire season and fire season in general are expected to be longer.

Although EFFIS provides information for Europe, Middle East and North Africa in one place, it should be emphasized that only burnt areas of approxi-

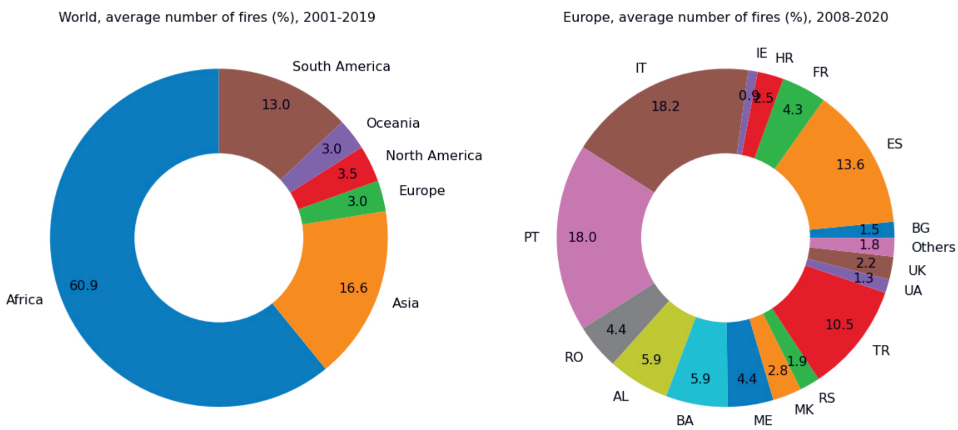

Figure 2. World multi-annual average number of fires (%) for time period 2001–2019 from GWIS (*left*) and European multi-annual average number of fires (%) for time period 2008–2020 from EFFIS (*right*).

mately 30 ha or larger are mapped, therefore, mapped burnt area corresponds, on average, to around 75% to 80% of the total burnt area in Europe each year. Approach to fighting with the fire varies from practical to scientific since different professions as firefighters, meteorologists, soldiers and foresters are involved. The Internet of Things put us in the position to connect different sources of information in one place, however, the understanding of usage and processes that caused the disaster sometimes is missing (Singh et. al., 2021). The aim of this article is to give a comprehensive overview of nowadays possibilities for fighting with the fires and categorization of different methods, techniques and approaches is proposed.

The paper is organized as follows. Section 2 explains complexity of forest fire research and gives an overview of proposed categories. Each category is briefly described as well as its sub-categories. Section 3 gives a detailed description of each category, data sources and their comparison. The possibility of intertwining between categories is explained as well as summarizing challenging research and development issues. Finally, Section 4 concludes with suggestions of possible future directions in forest fire research.

2. Categorization of different methods, techniques and approaches

The purpose of this review article is to give a categorisation of different methods, techniques and approaches related to forest fires. Considering the timeline of the information about fires we are dealing with, we propose three categories: *past, present* and *future*. Roughly speaking, category *past* refers to analyses, *present* to monitoring and category *future* to forecasts. The timeline of dealing with forest fires shows that each category can be divided into subcategories (Fig. 3).

Category *past* refers to forest fires that happened in the past. That could be an analysis of historical forest fires that happened in nature, fires that were intentionally induced in the laboratory or simulated with different numerical models. Category *present* refers to fire detection: a multitude of ways that forest

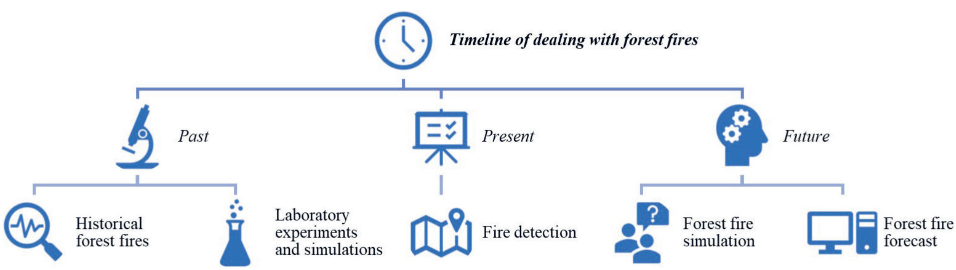

Figure 3. Timeline of dealing with forest fires divided into three categories, and each category in subcategories.

fire could be detected are in real time or near real time. Third category, *future*, refers to forest fire forecast and to forest fire simulation, which is performed after the fire has progressed in order to track its behaviour.

2.1. Category past

The *past* category is dedicated to historical forest fires that have occurred in the nature, fires that have been intentionally induced in the special laboratories or simulations of past forest fires. Researchers from different professions conducted detailed analyses after great forest fires or after fires that were important because of human losses or forest devastation. It is interesting that plenty of professionals such as meteorologists, foresters, firefighters, engineers, soldiers and rescuers can be involved and contribute to the analysis. Since fighting with fire is a widespread issue, there are a multitude of ways in the struggle with this problem.

More details about historical forest fires and their link with laboratory experiments will be presented. The solution that is imposed after detailed analysis led us to think about prognosis – the better we draw conclusions from history, the better we will act now and the better we will be prepared for the future.

2.2. Category present

Detecting of forest fires nowadays draws more and more attention because of available and cheap sensors, especially when Internet of Things was experiencing rapid growth. Unfortunately, it is often the first and the only way to fight with the fire, but usually incomplete. Combining information from different data sources for forest fire detection increases the likelihood of prompt reaction and putting out the fire at the very beginning. The moment when a fire is detected is a trigger for the start of firefighting procedures and all additional actions connected with fire suppression and extinguishing.

2.3. Category future

Our last category, *future*, comprises the possibility of forecasting the fire occurrence or further development of fire after its occurrence is reported. It should be emphasised that considering forest fires (as well as considering other disasters or catastrophes) forecasting means estimating the risk for the fire to occur, not the fire itself.

Forecasts could differ regarding the time scale on which it is performed. Time scale could vary from next few hours, next 3–7 days, next month, season, decade or till the end of the century. Due to numerical limitations, time scale affects spatial resolution and the type of output data. For example, numerical weather prediction model for next few hours enables calculation of many output variables with high spatial resolution of a few kilometres or even less than one kilometre.

On the other hand, forecast for next season will give us information on lower spatial resolution, with fewer variables and their values will be expressed like a deviation from the average with a given probability. In the end, forecast till the end of the century, in order to be feasible, will be limited containing information about very few variables, such as temperature and rainfall, as well as their deviations from the average with a given probability.

However, it can be expected that computing power will increase in the future, which will lead to an increase in spatial and temporal forecast resolution as well as to a decrease in time required for the calculation. A review of existing models and techniques for future forest fires will be discussed in Section 3.3.

2.4. Intertwined categories

In the transition from one category to another, it turned out to be easy to use the same method, technique or approach in different categories. It can be concluded that one could not deal with all categories at the same time. However, it is not possible to ignore the other two categories while dealing with only one. The best way would be to determine the goal of forest fire research, have expert knowledge in that field and look for the available data. At the end of the article in Section 3.4., examples of intertwining in categories will be listed.

3. Sources of each category and potential combination

3.1. Sources of category past

In most fire seasons, weather conditions had a crucial impact on the number of fires, burnt area and intensity (Joint Research Centre, 2019). For example, if the area had lower summer temperatures and more periodically distributed precipitation, the chance to have a less endangered area is higher. This section gives a more detailed explanation of category *past* that is dedicated to historical forest fires and laboratory experiments, where historical forest fires can be divided into two other approaches: case study and forest fire dataset (Fig. 4).

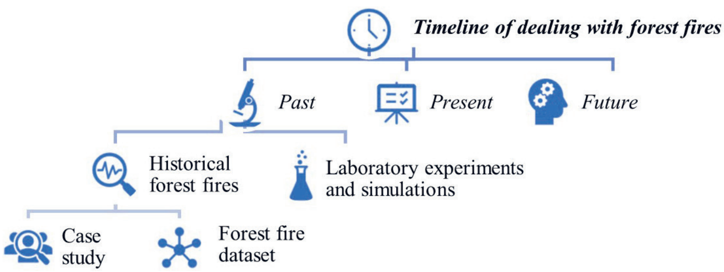

Figure 4. Timeline of dealing with forest fires divided in three categories, with a detailed division of category *past*.

3.1.1. Historical forest fires analysis

The first studied historical example in this article comes from Croatia. Although Croatia is territorially small in comparison to other Mediterranean countries, it has long experience in forest firefighting and forest fire research of about 40 years published in journals such as *Croatian Meteorological Journal*[1] (before *Rasprave-Papers*) (Vučetić, 1987; Strelec Mahović, 2007), journals in Croatian like *Šumarski list*[2] (Dimitrov and Jurčec, 1989), *Vatrogastvo i upravljanje požarima*[3] (Mifka and Vučetić, 2012; Miklić, 2013; Kuraži and Vučetić, 2015) and *Vatrogasni vjesnik*[4] (Vatrogasni vjesnik, 2020), and also in the proceedings of international conferences, books and thesis (Dimitrov i Jurčec, 1987; Vučetić et al., 2007; Čavlina Tomašević et al., 2019). There is an important example of co-operation between different professions dealing with forest fires. On the Kornati islands 12 firefighters lost their lives in 2007. Detailed analysis tried to explain the role of meteorological conditions in this specific fire. Vučetić et al. (2007) showed that not only the weather on the day of fire occurrence was important, but also the preceding month as well as the climate of the affected area. The authors also found two meteorological indicators that can be an indication of a specific behaviour in forest fire: a low-level jet and the approaching cold front. This type of analysis requires knowledge and skills enabling deep understanding of surface and upper-level synoptic, mesoscale and local conditions, the use of satellite images and numerical weather prediction model products, surface data from ground meteorological stations as well as upper-air data from sounding stations. Apart from different data sources, such comprehensive analysis includes recognition of climatic types, presence and severity of drought, state of the atmospheric boundary layer and finding regularities between fluid dynamics and observed data. Besides meteorological conditions, Stipaničev et al. (2008) included terrain configuration and vegetation with the aim to explain the fire. Another independent investigation tried to explain aerodynamics and thermodynamics aspects of the accident on the Kornat island (Klarin et al., 2008). Another group of authors performed independent investigation in order to expand the aforementioned analysis with several model simulations of the fire propagation (Viegas et al., 2008). They described in detail one possible explanation connected with eruptive fire behaviour and pointed out that nature combination of terrain, vegetation and weather conditions could be stronger than human and our technology. Due to climate changes, Croatia, which has a variety of climate types, experienced an extended fire danger risk spatially and temporally where

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[1] Website of *Croatian Meteorological Journal*: http://www.meteohmd.hr/en/journal/

[2] Website of *Šumarski list*: https://www.sumari.hr/sumlist/

[3] Website of *Vatrogastvo i upravljanje požarima* https://hrcak.srce.hr/vatrogastvo

[4] Website of *Vatrogasni vjesnik* https://vatrogasni-vjesnik.spis.hvz.hr/vatrogasni-vjesnik-arhiva-2007-2021

not only coastal parts of the country were endangered. Guided by earlier conclusions, case studies were conducted, from the northern Adriatic (*e.g.*, Miklić, 2013) to the mid-Adriatic (*e.g.,* Strelec Mahović, 2007; Mifka and Vučetić, 2012; Trošić Lesar and Mokorić, 2018; Čavlina Tomašević et al., 2019), even in the continental part of Croatia outside the fire season (*e.g.*, Kuraži and Vučetić, 2015). Some of them tried to provide an additional analysis of Fire Weather Index (FWI), to include soil temperatures and to find a physical link between fire behaviour and Low Level Jet (LLJ), a narrow region in the lower troposphere associated with extremely strong winds (Blackadar, 1957). These analyses and conclusions drawn enable better understanding of the forest fires, not just in the Mediterranean countries, but also in others with similar weather conditions or with the potential for a future threat posed by climate changes.

The aforementioned authors approached the problem of fire by detailed analysis of only one fire case in Croatia. However, extensive analysis and use of a large amount of data, helped them to understand the behaviour of the fire more deeply. Performing detailed analyses of each forest fire could help in recognizing the common weather conditions associated with fires. Obtained knowledge may be useful for future fire alerts. Since such kind of analysis is very detailed, it requires a lot of time just for one case study.

Kassomenos and Paschalidou (2017) pursued a different approach for analysis based on fire dataset from Greece that corresponds to the 18-year period 1985–2002. They considered 727 fire events including a fire with total burnt area exceeding 200 ha. In their approach, there was no distinction between naturally and anthropogenically induced events. Fires were classified in different schemes with the help of software that provides a number of pan-European synoptic classification schemes based on various well-established grouping techniques. They linked burnt areas to synoptic circulation patterns in order to reveal the most fire-prone large scale conditions in Greece. These patterns could be used in the future by wildfire managers and improve the wildfire prediction accuracy. An example with a different approach is presented in Trigo et al. (2016) for the Iberian Peninsula. The authors analysed 22-year long period (1980–2001) of forest fires in Portugal and Spain. They created a dataset consisting of fires that occurred on the Iberian Peninsula in order to find the relationship between burnt area and both long-term climatic pre-conditions and short-term synoptic forcing. They found relationship between burnt area, temperature and precipitation from 2 to 7 months in advance to fire peak. They also found a relationship between burnt area and synoptic weather patterns derived from 11 distinct weather types classification. Although their conclusions differ depending on the region of Iberian Peninsula, general conclusion is that weather types tend to better reproduce annual burnt area time series than those with only pre-conditioning climatic information. The best results are of course if both synoptic and climatic predictors are considered.

Although the highest number of fires occurs in the Mediterranean area, wildfires have become more often in the northern countries as well. Thus, in the summer season of 2018, Finland had three months when more than half of Finland had 11–20 days with forest fire warnings (Joint Research Centre, 2019). In the same year, Norway recorded the occurrence of high air temperature and low precipitation together with a number of fires that were never experienced in previous 17 years. In mid-June 2018, Sweden experienced forest fire where they received an international support consisting of staff and vehicles from Denmark, Norway, Finland, France, Poland and Germany. It was the first time that a member country had used the EU civil protection mechanism to raise its own preparedness even before having a major event to deal with. Moreover, four years before the aforementioned Swedish fire, in summer 2014 Sweden experienced the largest forest fire in its modern history. This is an example showing that forest fires have started to occur in places where people never experienced them before. Despite facing a new natural disaster that requires vehicles and staff, the Swedes met a new situation where having large forest fire had negative and positive consequences. Lidskog et al. (2019) provided a complex picture of how the Swedes that were affected by the wildfire understood the wildfire, its causes and consequences. The authors tried to explain how their organizations performed during the fire and how people can learn something from the events and future wildfire risks in Sweden.

3.1.2. Laboratory fire experiments and simulations

In addition to real forest fires, we can also learn about fire behaviour from laboratory experiments where is possible to artificially induce and observe different impacts on fire in the controlled environment. It is also an opportunity to separate different effects what we could never do in nature. Such experimental analysis does not depend on the synoptic weather condition, country and does not need a fire database. Therefore, obtained results and conclusions could be generally valid for any fire if limitations and simplifications of experiments are considered. Viegas (1998) described the role of convection for fire propagation and discussed it for different weather and terrain conditions. He also explained fire behaviour in canyons. Canyons have a geometrical terrain configuration which produces the chimney effect. The fire spread is very complex and intense creating a difficult situation for fire suppression. Consequently, canyons are associated with a large number of fires with fatal accidents. Further analyses led the author to the next intuitive step – the development of a theoretical model which describes the interaction of the convection effects induced by the wind and topography with a uniform slope (Viegas, 2004). The author has improved the model with a practical range of parameters for different fuel types and explained the importance of time as a factor in fire behaviour which had previously been neglected (Viegas, 2006). This resulted in a model which has a possibility to predict time change in the rate of spread of the fire. He confirmed modelled results with both experimental results obtained in the laboratory and observed field data. It should be emphasized again that a better understanding of relatively simple cases that he considered is the first step of generalization for more complex situations (Viegas, 2004).

Except for learning about fire behaviour from laboratory experiments, simulations are widely accepted and used. Every detailed analysis about historical forest fire can be simulated in order to reconstruct past fire event. Since such simulations can also be used when fire has already occurred in the present in order to predict future fire behaviour and spread, an expanded description of forest fire simulations is given in Section 3.3.2. An example of intertwining between proposed categories *past* and *future* is explained in Section 3.4.

3.2. Sources of category present

Although, as mentioned above, the category *present* refers to relatively short time period which is dedicated to forest fire detection, importance of this category is noteworthy because of multitude of ways the fire could be detected (Fig. 5). These comprise the use of unmanned aerial vehicles (UAVs), fixed cameras and sensors that are nowadays available and have a broad purpose. Also, remote sensing via satellites provides additional and valuable information in fire detection.

3.2.1. Detection with Unmanned Aerial Vehicles (UAVs)

UAVs as a technological solution for detecting, monitoring and fighting with forest fires can be equipped with different onboard cameras, engine power, payload capacity and wings (Yuan et al., 2015). The first regulated use of UAV in Europe for detecting forest fires in fire service was done in Hungary in 2004. The authors also described the use of single or fleets of UAVs guided by a central ground station. This station can be used for detection of actual fire in progress, make fire diagnosis and fire prognosis with the prediction of fire evolution, but also for monitoring the environment for possible occurrence of fire before it has

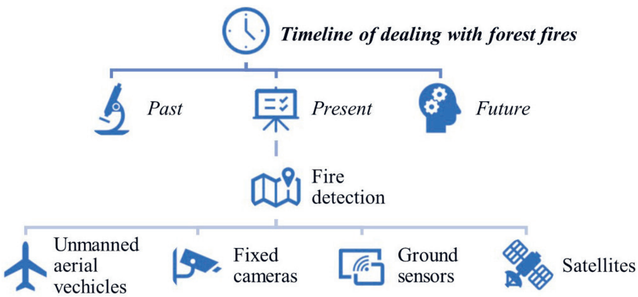

Figure 5. Timeline of dealing with forest fires divided in three categories, with a detailed division of category *present*.

occurred. There are different approaches for fire detection systems. For example, vision-based fire detection technologies can generally be classified as either visual or infrared fire detection system. Fire detection could also be divided into either flame detection or smoke detection.

The complexity of fire detection is emphasized by Cruz et al. (2016) who demonstrated how smoke and flame presented on UAV's images depend on background colours. These colours represent different vegetation types and vegetation conditions which can be detected using RGB images. They also compared UAV images of different sizes and numbers of figures in one second. They reported that for image sizes of 960 × 540 pixels at a processing time of 0.0447 s, where they process 22 f/s, detection precision was 96.82%. Despite UAVs can fly close to the fire and do not endanger people, air turbulence and vibrations can affect camera's position, image quality and lead to detection failure. Also, report of four pilot projects confirmed that UAVs, unlike satellites, could be useless during unfavourable weather conditions like low visibility, fog, heavy rain or strong wind (O'Brien et al., 2016).

3.2.2. Satellites for forest fire detection and vegetation monitoring

Unlike UAVs, satellites cover wider area but with less frequent sampling in time and space. Nowadays, satellites have an important role in detecting and monitoring fires. Near real-time active fire detection is provided by National Aeronautics and Space Administration Fire Information for Resource Management System (NASA FIRMS) which uses multispectral sensors (NASA Fire Information for Resource Management System, 2021). They compare land cover temperature with an area of higher temperature above a given threshold and mark them as an active fire or "hotspot". Thus, "hotspot"/active fire is associated with one or more fires or other thermal anomalies (*e.g.* volcanoes). The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, onboard Terra and Aqua satellites, can detect active fire with a spatial resolution of 1 km and temporal resolution of 1 day. Using one dimension in spatial resolution refers on horizontal dimensions of one pixel of 1 km × 1 km where the fire is often less than the size of the pixel. Each "hot spot" or active fire detection represents the centre of a pixel flagged. The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor onboard Suomi-National Polar orbiting Partnership (S-NPP) and National Oceanic and Atmospheric Administration (NOAA-20) satellites are successors of MODIS. The difference between VIIRS sensor and MODIS sensor is in better spatial resolution of 375 m and better temporal resolution of twice daily. Active fires detected with MODIS and VIIRS are also represented on EFFIS web site.

Sentinel-2 satellites, from Copernicus Program, are two polar-orbiting satellites that monitor variability in land surface conditions (European Space Agency, 2021). Each of them carries a multispectral sensor with 13 bands. With two satellites, under cloud-free conditions, data are accessible every 5 days at the equator or every 2–3 days in mid-latitudes, available typically within 3–24 hours of being sensed by the satellite. Their spatial resolution is not uniform: four spectral bands are at 10 m, six bands are at 20 m and three bands are at 60 m. Within the domain of forest fires, these satellites are useful for the detection of smoke, flames and burn scars. De Simone et al. (2020) described how to detect and quantify burn scars and how to monitor the short-term vegetation dynamics in different 'burn severity' classes. They used two multispectral indices: Relativized Burn Ratio index (RBR) for detection of the burnt surface by severity classes and Normalized Difference Vegetation Index (NDVI) which discriminate vegetation from other surfaces. With applied methodology, they proved it was possible to detect and quantify different burn severity classes as well as vegetation recovery dynamics after forest fires. Turco et al. (2019) compared four satellite-based burnt area datasets (FireCCI51, GFED4, GFED4s and MODIS) in Mediterranean Europe with a ground-based EFFIS dataset emphasizing that users need to carefully consider the limitations of the satellite products. They confirmed that temporal correlation between the datasets decreases at finer aggregation scales, with reasonably good scores at resolution coarser than 1°. Regarding spatial resolution, they found spatial patterns become more similar at a lower resolution and that satellite datasets generally show good agreement with EFFIS data considering aggregation of at least 1°.

3.2.3. Ground sensors and fixed cameras in comparison with satellites and UAVs

Surveillance of forest fires with UAVs and satellites for flame and smoke recognition, as well as vegetation condition, can be enhanced with in-situ cameras or sensors. Although cameras' fixed location, height and area width, they offer continuous monitoring where pre-, during- and post-fire stages can be analysed with higher temporal resolution than from UAVs and satellites. Therefore, many countries developed ground-based wildfire video surveillance systems. In Croatia an OIV installed Fire Detect AI in 2018 which consists of 86 implemented cameras at 43 locations for monitoring the southernmost part of Croatia called Dalmatia (OIV, 2021). Although cameras in automatic mode can detect fire up to 10 km away or up to 25 km away in manual mode, because of different weather conditions, better confidence in such system can be achieved when combined with weather data. There are similar systems in other countries like IQ FireWatch in Germany (IQ FIREWATCH, 2021), ADELIE Fire Monitoring System in France (Paratronic, 2021), CICLOPE in Portugal (Instituto de Engenharia de Sistemas e Computadores Inovação, 2021), SR7 in Spain (Multinformática Principado, 2021), etc.

The usefulness of ground sensors for fire detection depends on their position, however, meteorological conditions can limit efficiency of fire detection. For example, atmospheric stability conditions have an impact on air properties, *i.e.* upward motion is suppressed (supported) in stable (unstable) conditions, which consequently affects smoke movement and its detection. Stipaničev (2019)

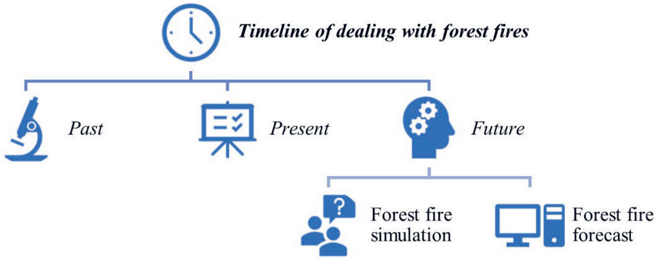

Figure 6. Timeline of dealing with forest fires divided in three categories, with a detailed division of category *future*.

showed an example of a false fire alarm caused by fog, but also how clouds, dust from the ground, rain drops, sun effects etc. can also lead to misdetection of fire. As forest fire monitoring and detection methods include humans and mechanical devices to monitor the environment, there is always needed to balance between human resources, danger, costs and decisions.

While this section advert multitude of ways of fire detection, even more resources for detection are expected to be developed in the future. The key of this section was to emphasize that relatively short time period, noted as *present*, can have a huge amount of information and different data sources. It could also be noticed that every step in *present* naturally leads to fire prediction on all time scales.

3.3. Sources of category future

Time scale of prediction is limited with available data sources and methodologies that will be used, but on the other hand, it also limits results and details that will be provided. Indeed, decision making procedure strongly depends on time scale of prediction. Because of different points of view, we divided this category in forest fire forecast and forest fire simulation (Fig. 6).

3.3.1. Forest fire forecast

As mentioned, fire prediction could be understood as an extension of fire detection. Based on UAV's images, Cruz et al. (2016) proposed Fire Detection Index (FDI) and more forest targeted Forest Fire Detection Index (FFDI). Calculations of such indices give preference to UAV's images rather than satellite images because their time and space sampling is closer to real-time use and can be used to estimate the direction of the fire's expansion and its velocity. According to Global Wildfire Information System (2021), the most widely used index for forest fire prediction is Canadian Forest Fire Weather Index (FWI) which consists of several sub-indices (van Wagner and Pickett, 1985). Indices are calculated for 12 UTC each day using four meteorological elements: air temperature, air humidity, wind speed and rainfall amount. After a test phase of 5 years, EFFIS adopted this index in 2007 as a method to assess fire danger level through Europe, Middle East and North Africa (European Forest Fire Infromation Statistics, 2021). Using numerical weather prediction models with different spatial resolutions, EFFIS provides forecasts from two deterministic models (ECMWF at 8 km and MeteoFrance at 10 km) and from one probabilistic model (ECMWF at 18 km). They also have different forecasted time periods: MeteoFrance at 10 km provides forecasts up to 3 days ahead, while ECMWF at 8 km provides 1 to 9 days ahead. Due to the variety of climatic conditions in Europe, EFFIS offers two indicators that provide information on local/temporal variability of the FWI compared to historical series of approximately 30 years. These indicators provide a standard deviation from the 30-year historical mean values and percentiles of occurrence of the values. Dowdy et al. (2009) compared Australian McArthur Forest Fire Danger Index (MARK-5) with Canadian FWI. Both indices are most sensitive to wind speed, then secondly to relative humidity and thirdly to air temperature. However, on a finer scale, FWI is more sensitive to wind speed and rainfall while MARK-5 is more sensitive to temperature and relative humidity. Certainly, there are also other indices that are used for detection of fire danger. U.S. Forest Service uses National Fire Danger Rating System (NFDRS) to estimate todays or tomorrow's fire danger for a given area (U. S. Forest Service, 2021). It is based on meteorological conditions, but also considers fuels, topography and risks. Soil moisture is also an important factor for fire development in forest and wildland areas (Keetch and Byram, 1968). Thus, dry fuels support deep-seated fires with a hardly predictable speed of propagation. Obviously, there are many influences on fire occurrence and behaviour and many inputs are needed, like meteorological conditions, vegetation, terrain etc. Based on existing indices, but also considering some specific needs, new indices can be developed. Bugarić et al. (2014) proposed a Site-specific Wildfire Risk Index (SWRI) for Adriatic regions using FWI as one of the input parameters. They performed statistical analysis considering meteorological, topological and anthropological parameters of past fires detected by satellites and proposed an improved method for calculating a site-specific fire risk. Such a method should be optimized for other parts of Adriatic regions besides Split-Dalmatia County, but also supplemented with more data sources, which are nowadays freely available, for better temporal and spatial forest fire risk assessment.

Predicting long term forest fire occurrence is difficult and is rather performed indirectly. For example, connecting wildfires with land-use types, vegetation's change, prediction of human settlement in new areas, possibilities for new tourist activities or sports, Bajocco et al. (2010) found a connection between land-use types and wildfires for Sardinia (Italy). They concluded that in the fire season, wildfires occur earlier in urban areas and in all agricultural land-use types while in forests, grasslands and shrublands wildfires occur later. Together with seasonality as an indirect consequence of climatic factors, authors also reported that human pressure directly influences fires incidence patterns.

3.3.2. Forest fire simulation

For already occurred fires, prediction of their behaviour is desirable and extremely important. A possible solution is to use a mathematical model for forest fire blow up that was presented by Viegas (2005). The author verified model on the fatal accident that occurred in Portugal in 2003. Although canyon fires, like this one, are not explained in the last detail, he tried to confirm its behaviour with laboratory experiments. There are also other fire behaviour simulators like Fire Area Simulator (FARSITE) (Finney, 1998), novel technologies for an acceleration of FARSITE simulation (Carrillo et al., 2018), AdriaFirePropagator with a use case for the southern part of Croatia (Bugarić et al., 2018), Fire Dynamics Simulator with an emphasis on numerical formulations specific to vegetation types with a use case in pine litter (Mueller et al., 2018), physics-based simulations of wind-driven surface fires (Sutherland et al., 2018) etc.

Fire simulation is also possible under numerical weather prediction model named Weather Research and Forecasting (WRF) model with a wildland fire-behaviour module, named WRF-Fire which is available from 2010. Coen et al. (2013) discussed many simplifications of the model such as the ability to simulate surface fire behaviour, however, it is not able to simulate crown fires, which are difficult to distinguish in real fires (*e.g.* mixed vegetation in nature of various heights). Self-igniting fires such as a fire caused by a lightning strike can also be taken into consideration. Mostajabi et al. (2019) have shown that a model which uses four commonly available surface weather elements, has a statistically considerable predictive skill for lead times up to 30 min.

Despite many fire prediction models and indices, the aim in giving warnings and fire risk assessment is the end-user. If forest fire warnings are provided through the internet and television, for example, those provided by the Norwegian Meteorological Institute, they need to be adapted for the end-user. The risk for people who walk and hike in nature, or for firefighters who must extinguish the fire, is not the same. Therefore, information about fire as well as spatial and temporal resolution of simulations should be provided according to their needs. One conclusion is common to all – to know how to behave and be aware of warnings and risks.

3.4. Examples of intertwining between categories

Although we separated dealing with forest fires in proposed categories, it is important to become aware where are the boundaries between categories and how thin they can be.

Connection between *past* and *future* appears in examples with analysing synoptic circulation patterns that are the most fire-prone (*e.g.*, Vučetić et al., 2007; Kozarić and Mokorić, 2012; Kassomenos and Paschalidou, 2017), finding a relationship between burnt area and both long-term climatic pre-conditions and short-term synoptic forcing (Trigo et al., 2016), what people have learned about fires and how they anticipate future wildfire risks (Lidskog et al., 2019) and how by learning from historical forest fire simulation, predict future fire spread and behaviour of current fire for a few hours ahead (*e.g.*, Finney, 1998; Viegas, 2005; Bugarić et al., 2018).

As an example of intertwining between *present* and *future* are UAVs and NDVI, as an indicator of vegetation state for estimation of future forest fire danger (de Simone et al., 2020).

There are also approaches which can be applied to all proposed categories for dealing with forest fires. For example, widely accepted Canadian FWI can be calculated for current conditions (by using measured data from meteorological stations), for future conditions (by using numerical weather model's output) or for reconstructed historical conditions (by using historical measurements or historical weather simulations) (European Commission, 2020). Another example is the possibility of using fire simulators for future fire behaviour prediction of actual forest fire, an imaginary future forest fire or for historical fires that we want to reconstruct from historical fire events.

4. Conclusion

Forest fires cause environmental and economic damages every year, especially in Mediterranean countries. However, other European countries have been also facing with increased number of forest fires. The risk of forest fires is projected to be enhanced in future (warmer) climate conditions and many countries will be threatened by wildfires. Therefore, preventing wildfires together with preparedness to extinguish a fire are extremely important issues. This can be achieved by analysing past and present fire cases and by developing fire models.

In this review article, an overview of existing methods, techniques and approaches of forest fire research is provided. As analogy to data analysis, monitoring of actual state and prognosis, we proposed three categories: *past*, *present* and *future*. Proposed categories distribute forest fire research area in additional subcategories. Advantages and disadvantages of each were explained emphasizing that the final choice of an approach depends on many factors: human resources, danger, costs and decisions which will be achieved. It is also shown that we cannot rely only on meteorological situation or rely only on technology as it is.

It is difficult to deal with all categories at the same time. Examples of smooth transition from one category to another prove that dealing with forest fires is very complex research area. However, the knowledge gained in a particular category can be applied to other categories as well. Intertwining between proposed categories was given with accompanying examples. In transition from one category to another, it turned out that the same method, technique or approach may be used in different categories.

Further development in forest fire research is expected, especially due to freely available data, growth of computing power, ability to store large amount of data and analyse data in a faster and easier way. In the future, it can be even possible to handle various sources of data that monitor weather, soil, vegetation and human activities in one place. Forecasting future fire danger and risk with high spatial and temporal resolution, in real time, is very important and necessary for effective forest fire suppression and extinguishing. Since different data sources are already available, comprising of satellite data, UAVs, fixed cameras and ground sensors, their amount and quality are expected to grow. New techniques of data analysis and technology will progress which consequently enables forest fire research to continue developing.

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SAŽETAK

Pregled smjerova istraživanja šumskih požara: Različiti pristupi za jedan cilj

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Šumski požari uzrokuju prirodne i ekonomske štete svake godine, a posebice u južnim dijelovima Europe. Pristup procjeni rizika od šumskih požara može varirati od praktičnog do znanstvenog budući da su razne struke uključene kao što su to vatrogasci, meteorolozi, vojnici i šumari. Internet Stvari omogućava povezivanje različitih izvora podataka na jednom mjestu, ali razumijevanje upotrebe podataka i procesa koji su uzrokovali štetu često nedostaje. Svrha ovog članka je pružiti sveobuhvatan pregled trenutnih mogućnosti u borbi s požarima te kategorizirati razne metode, tehnike i pristupe. Uzimajući u obzir vremensku crtu informacija o požarima s kojima raspolažemo, predlažemo tri kategorije: *prošlost* koja se uglavnom odnosi na analizu, *sadašnjost* koja obuhvaća praćenje trenutnog stanja i *budućnost* koja se odnosi na prognozu. Svaka od kategorija je detaljno opisana, potvrđena dosadašnjim radovima i primjerima te obogaćena izazovima i budućim smjernicama. Bavljenje šumskim požarima je vrlo kompleksno pa je stoga teško baviti se svim predloženim kategorijama u isto vrijeme. Međutim, prema sve dostupnijim izvorima informacija i povećanom interesu znanstvenika iz raznih istraživačkih područja, postoji mnogo načina isprepletanja područja bavljenja šumskim požarima. U budućnosti se očekuje da će biti moguće, u realnom vremenu, pristupati različitim izvorima podataka i prognozirati buduću požarnu opasnost i rizik s visokom prostornom i vremenskom rezolucijom.

Ključne riječi: šumski požar, EFFIS, FWI, modeliranje šumskog požara, prognoza šumskog požara

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