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Complex Analysis of Wildfires in Hungary in the Last Decade[1]

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Wildfires are one of the most common natural disasters in the world, which cause millions of hectares of damage each year. This fact poses a major challenge to the defence sector. Environmental safety problems caused by wildfires affect not only the ecosystem but also all aspects of society. Research on the effects of climate change predicts a more uneven rainfall distribution and rising daily average temperatures in summer and autumn in the Carpathian Basin. The effects of climate change will be indirectly detectable, such as the extension of fire risk periods, the increase in the number of wildfires and their spatial and temporal distribution, and the increase in fire intensity. Changes due to climate change will pose an even greater challenge in the future to the Hungarian authorities, which are responsible for preventing and extinguishing wildfires. One of the purposes of the paper is to define indicators that can be used to compare the number and extent of wildfires each year with the degree of the daily fire risk and the length of periods during which the wildfires occurred. For this, it is necessary to define the concept of the high fire risk days and the endangered areas and parts of the country in the Hungarian climatic conditions. Based on previous statistical studies, the authors will examine the spring and summer fire seasons separately because of the different fuel conditions and the causes of fire ignition. They examine statistical data on wildfires and apply GIS application. Another aim of the research is to find a correlation between the daily fire risk values, the number of wildfires and the burned area. A fire risk-based investigation of the wildfires that have occurred in the last decade can later help in official preparation, annual planning and preparation of forces involved in the prevention and firefighting.

Keywords: *wildfire, statistics, fire weather index (FWI), fire risk, raster, trends and changes of forest fire danger*

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Introduction

Ever since humanity has lived on Earth, science has been constantly dealing with the dangers and the risks that affect us. At different periods of history, different risk factors came into view. According to the Global Risks 2020 report of the World Economic Forum (WEF), four of the five most likely risk factors of today are related to climate change.[4] These include the failure to combat climate change, the loss of biodiversity, the frequent occurrence of extreme weather, and the risk of major natural disasters.[5] Long-term forecasts agree on certain things, such as drought and warming, however, not in terms of scale and seasonal as well as regional differences. In this case, we can already discover many differences in the scenarios.[6] Global climate change scenarios predict a rise in temperature of 1.1–6.4°C by the end of the 21st century. In addition, it is to be expected that the frequency of heat waves as well as heavy rainfall may increase further. Based on research and experience, some trends can already be identified about climate change: cold days will become less frequent, the number of cold mornings will become less and less, in contrast, heat waves will increase and the number of hot days and nights will increase.[7]

The study of global climate scenarios is also relevant in Europe. In Hungary, the regional climate scenario of the Carpathian Basin is the most cited research result. In the research of Bartholy et al., the period 2071–2100 was examined. With the help of the models they made, they were able to predict the temperature increase more accurately than the expected change in precipitation. Regarding the warming, the study of the summer months is more interesting, as warming is the largest at this time (3.7–5.1°C), as well as the most significant variance is also here. According to the study, the standard deviation will be the lowest in spring, estimated at only 2.4–3.2°C. During the summer season, the warming rate will increase in the southern parts of the country, and in winter and spring, moving eastwards.[5] In addition, the number of heat days, when the temperature reaches or exceeds 30°C ($T_{max} \geq 30°C$) will increase by 109–156%. The number of hot days – when the temperature reaches or exceeds 35°C – will increase ($T_{max} \geq 35°C$) from 4 days per year to 20–33 days. In contrast, the number of winters ($T_{max} < 0°C$) and frosty ($T_{min} < 0°C$) days will decrease and the number of harsh days ($T_{min} < –10°C$) will decrease significantly (from –87 to –95%) annually.

The climate of the Carpathian Basin will also be significantly affected by changes in precipitation distribution. According to the scenarios, the change in the annual amount of precipitation will not be significant, but its distribution will already change. We can expect a more significant decrease in precipitation in summer and autumn (10–33%). In winter and spring, a more significant increase in precipitation is expected. Furthermore,

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4 World Economic Forum: *The Global Risks Report 2020.*

5 Ivett Szászi: *Globális kockázatok 2019* [Global Risks in 2019].

6 Judit Bartholy et al.: A 21. század végén várható éghajlatváltozás Magyarországon [Regional Climate Change Expected in Hungary by the End of the 21st Century]. *Földrajzi Értesítő,* 56, no. 3 (2007). 147–167.

7 IPCC 2007: *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, Cambridge University Press.

the number of days with annual extreme rainfall (≥ 20 mm) may double in the future.[8] One of the consequences of global climate change is that extreme weather extremes are multiplying. As a result, the chances of heavy rainfall and thunderstorms are increasing in some parts of the Carpathian Basin. However, in other areas, the lack of precipitation periods will be extended in space and time.[9] During the drier months, the moisture content of the fuel decreases, thereby increasing its combustibility, and it gives a higher risk of fire ignition. One of the consequences of climate change is the increased risk of forest fires.

Analysing the climate scenarios about forest fires, it was found that even with an increase in the average temperature of 0.5 degrees in Hungary, the frequency of vegetation fires can increase by more than 50%.[10]

According to other scenarios, an increase in the average temperature of 4°C may increase the frequency of forest fires by up to 200 to 300%.[11] This will pose a continuing challenge to disaster management in the future.[12] Forests are one of the most important natural resources. For this reason, the fire protection activities of the disaster management are appreciated. In the event of damage or destruction of forest property by fire, there are high costs.[13] The effectiveness of forest fire prevention activities may affect the functioning of the environmental, economic and social sectors, and has an impact on the quality of life of the population living near the forest.

Fire prevention system in Hungary

Forest fire prevention activities are carried out in close cooperation with the disaster management agency and the forestry authority. Not only the European Union,[14] but also

8 Judit Bartholy – Rita Pongrácz: Regionális éghajlatváltozás elemzése a Kárpát-medence térségére [Analysis of Regional Climate Change in the Carpathian Basin]. In Zsolt Harnos – László Csete (eds.): *Klímaváltozás: környezet – kockázat – társadalom* [Climate Change: Environment – Risk – Society]. Budapest, Szaktudás Kiadó Ház, 2008.

9 Sándor Szalai – Péter Vigh: *Új térképek és adatok a klímaváltozás trendjéről* [New Maps and Data on the Trend of Climate Change]. Előadás, Klímaváltozás és az erdők [Lecture, Climate Change and Forests]. Budapest, Erdészeti Fórum, 2005.

10 IPCC Report: *IPCC jelentés: Éghajlatváltozási Kormányközi Testület Tematikus jelentése a szélsőséges éghajlati események kockázatáról és kezeléséről* [Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation]. Döntéshozói Összefoglaló. Budapest, Nemzeti Fejlesztési Minisztérium, 2011.

11 János Mika: A globális felmelegedés regionális sajátosságai a Kárpát-medencében [Regional Features of Global Warming in the Carpathian Basin]. *Időjárás*, 92, nos. 2–3 (1988). 178–189.

12 Attila Bussay et al.: *Az aszály magyarországi előfordulásainak vizsgálata és mérhetősége* [Investigation and Measurability of Drought in Hungary]. Budapest, Országos Meteorológiai Szolgálat, 1999; László Teknős: Current Issues in Disaster Management Aspects of Global Climate Change. In László Földi – Hajnalka Hegedűs (eds.): *Effects of Global Climate Change and Improvement of Adaptation Especially in the Public Service Area.* Budapest, Dialóg Campus, 2019. 145–162.

13 Ágoston Restás: Common Analysis of the Costs and Effectiveness of Extinguishing Materials and Aerial Firefighting. In Domingos X. Viegas – Luís M. Ribeiro (eds.): *Advances in Forest Fire Research.* Coimbra, Universidade de Coimbra, 2014. 1799–1813.

14 Regulation (EC) No 2152/2003 of the European Parliament and of the Council of 17 November 2003 concerning monitoring of forests and environmental interactions in the Community (Forest Focus).

the Hungarian legislation[15] requires the authorities to plan forest fire protection activities. The aim of it is the coordinated development and implementation of forest fire prevention activities. In addition, modern firefighting knowledge and the tasks of organisations involved in forest fire prevention have also been incorporated into the Hungarian legislation.

The basis of the forest fire prevention activity is the recording of forest fire events on forest land and other wooded land areas. By analysing forest fires in the register, we can gain knowledge about the characteristics of fires and the course of the fire season. Over the past two decades, the methodology and rules for data collection and analysis have been developed through the cooperation of the forestry authority and disaster management. IT systems for data collection and analysis have been set up by the responsible authorities. The register shall be kept by the provisions of the Ministerial Decree on the protection of forests against fire.[16] The regulation also regulates the activities necessary to prevent forest fires. It lays down the rules for ordering a fire ban also. The decree defines the criteria for the fire hazard classification of forest areas and the rules for the preparation of forest fire protection plans. The regulation provides a formal framework for cooperation between the forestry authority and disaster management. The regulation also sets out the prevention tasks for forest managers. These include the construction and maintenance of fire and fuel breaks, placing warning signs during a fire ban, constructing and maintaining fire pits, and the availability of various firefighting technical tools. The authority shall assist in the implementation of the forest management obligations. It prepares educational materials and organises training for foresters and farmers. Leaflets, issues and handbooks are freely available on the authority's website.[17]

The rules for fighting against forest fires (tactics, reconnaissance, intervention, safety regulations, mop-up) are contained in the sectoral legislation of disaster management. The rules for controlling fire protection are spelled out in the Fire Protection Act. The detailed rules of intervention are set out in the Law on Protection against Fire and its implementing regulations.[18]

The forest fire data are evaluated and sent to the European Forest Fire Information System (EFFIS) each year by the forestry authority. The EFFIS was established jointly by the European Commission (EC) services Joint Research Centre (JRC) and Directorate General for Environment in the year 2000 to support the national services in charge of the protection of forests against fires in the EU and neighbouring countries, and also to provide the EC services and the European Parliament with up-to-date and harmonised information on forest fires in Europe. EFFIS is the largest repository of information on individual fire events in Europe. The database is supported by the European Expert Group on Forest Fires. The author of this article is also a member of the expert group delegated by NÉBIH.[19] The database implements the exchange of information between member states.

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15 4/2008 (VIII.1.) Decree of the Ministry of Local Government on the protection of forests against fire.

16 Ibid.

17 FireLife Forest Fire Prevention Project.

18 Act XXXI of 1996 on the Protection Against Fire, Rescue Work and the Fire Service; Decree 39/2011 (XI.15.) of the Minister of the Interior on general rules of fire safety and technical rescue operations of fire brigades; Recommendation No 6/2016 (VI.14.) of the Fire Tactics Regulations and Technical Rescue Regulations.

19 For more information see https://effis.jrc.ec.europa.eu/partners

Member States and the EU Commission can assess the impact of measures taken to protect forests against fires. EFFIS provides data on the development of strategies for protecting forest fires, with a special emphasis on knowing the cause of the fire.[20]

On the European level, the fire situation is that the risk of forest fires has increased in the southern regions in the last two decades, but an increase in the number and extent of forest fires should also be expected in the Nordic countries. Currently, 85% of burned areas in Europe are located in Southern Europe (Portugal, Spain, France, Italy and Greece) due to the higher risk of weather conditions typical of the Mediterranean region. In these five Mediterranean countries, an average of almost half a million hectares of land has burned annually over the past 20 years. In addition to the increase in the annual number of high and extreme fire risk days, the impact of extreme fires will likely increase in large areas, with long-term effects. The forest fire season starts earlier and ends later, which puts an additional burden on disaster management agencies. Forestry and fire ecology research prove that, among the abiotic forest damages, forest fires can be effectively prevented in the short term with forestry methods and awareness-raising campaigns.[21]

In the next section, we present the fire situation in Hungary. To prepare the statistics, data recorded in the forest fire information system between 2011 and 2021 were used.

Presentation of the fire situation in Hungary

When recording fire data, fires are divided into four categories according to the type of site.[22] Courtyard of facilities means when a fire occurs on a property bordered by a fence in an indoor area, affecting vegetation. The most common case is when a fire breaks out in the yard of an apartment building or farmstead. The next class is the burning of household waste or garbage on the outskirts. The main target objects of EFFIS are forest fires, although also other wildfires are recorded. For the database forest fires are defined as uncontrolled wildfires spreading wholly or in part on forest and/or other wooded land. Thus, to be classified as a forest fire, the uncontrolled fire has to affect partially or totally, though not exclusively, forest and/or other wooded land and it does not necessarily have to start in a forest.

In the study, we examined those wildfires, where firefighting intervention was required. In case of events requiring an intervention, on-site data collection will take place. Figure 1 shows the number of fires in the examined period between 2011–2020 in the type of sites. 62% of all fires were wildfires in the examined period, firefighters intervened in 96% of these fires. In some years, compared to the ten-year average, there were quite a few fires (2013, 2016), while in other years there was a number of wildfires above the average (2012, 2022). The primary reason for this is the amount of precipitation and its distribution over

[20] Camia Andrea et al.: *The European Fire Database. Technical Specifications and Data Submission.* JRC Science and Policy Reports, 2014.

[21] Péter Debreceni et al.: Az erdőtűz kockázatának csökkentési lehetőségei Magyarországon [Methods of Forest Fire Risk Reduction in Hungary]. *Védelem Tudomány,* 2, no. 2 (2017). 1–11.

[22] 6/2014 (III.7.) BM OKF instruction on the data provision procedure for firefighting and technical rescue activities of disaster management bodies and fire departments.

time. In 99% of cases, wildfires in Hungary are caused by human negligence or intent. This rate is a few percent higher than in the countries of the Mediterranean region (95%), where the natural origin of fires is also not uncommon.

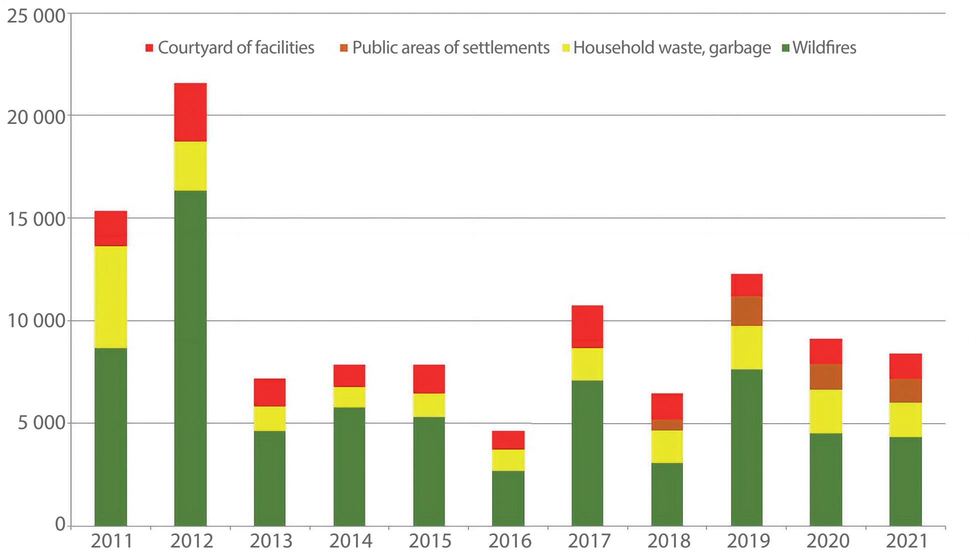

Figure 1: Total number of fire events in the type of sites between 2011–2021

Source: Compiled by the authors based on the database of the National Directorate General for Disaster Management, Ministry of the Interior, the National Food Chain Safety Office and the Forest Fire Information System.

Table 1: Total number of wildfires between 2011–2021

Year	Wildfires (including forest fires)		Forest fires	
	Number of fires	Burned areas (ha)	Number of fires	Burned areas (ha)
2011	8,436	24,662	2,021	8,056
2012	15,794	90,668	2,657	14,115
2013	4,424	8,020	761	1,955
2014	5,535	25,140	1,042	4,454
2015	5,057	14,938	1,069	4,730
2016	2,531	3,414	452	974
2017	6,782	13,761	1,454	4,934
2018	2,981	3,016	530	906
2019	7,296	13,922	2,088	6,541
2020	4,339	6,230	1,239	2,895
2021	4,350	6,038	1,154	2,413

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

Table 1 shows the total number of wildfires that occurred between 2011–2021, highlighting the number of fires and the burned areas. Wildfires typically burn outside residential areas on natural grasslands, forest land and other wooded land. Forest fires are defined as uncontrolled wildfires spreading wholly or in part on forest and/or other wooded lands.

The average number of wildfires was 6,139 in the examined period. In case of forest fires, the average number of fires is 1,315 and the average burned area is 4,725 hectares. Studying the high number of fires, it is important to note that these fires were caused by violations of fire regulations. According to the current regulations, the incineration of vegetation in the open air is fundamentally prohibited.[23] At least 10 days before the combustion of dead fuel, a notification must be made to the disaster management. Combustions in connection with forest management must be reported to the disaster management at least 48 hours before the start of it. One indicator of the severity of a wildfire is the size of the burned areas. Examining the size of the burned areas during a fire, we divided the fires into nine groups. A fire of less than one hectare is considered a small fire. Fires between 1 and 50 hectares can be classified as medium and wildfires of more than 50 hectares are considered large fires. In case of medium and large fires, several fire services may be alarmed, taking into account the risk factors. For all wildfires, the area affected by forest fires in the examined period averaged 3.2 hectares. Analysing the data in Table 2, it can be determined that the proportion of small fires has been increasing constantly. It has exceeded 60% in every year since 2012 and 70% since 2018.

Table 2: The proportion of wildfires in classes of burned area

Classification of burned area	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
0–0.1 ha	33.8	36.8	41.7	36.2	37.8	40.5	35.1	37.7	40.1	44.9	61.5
0.1–0.5 ha	9.2	10.4	10.1	10.7	12.1	9.3	13.8	20.2	15.5	15.7	14.6
0.5–1 ha	15.2	14.3	15.8	14.1	12.9	15.7	14.2	14.5	15.2	14.3	11.1
1–5 ha	28.7	24.4	24.2	25.0	24.8	27.2	23.9	20.2	18.5	16.1	9.3
5–10 ha	7.2	6.6	5.0	6.1	6.1	4.0	6.3	5.3	5.3	4.7	1.9
10–50 ha	4.7	6.1	2.8	6.8	5.1	3.1	6.1	2.1	4.7	4.1	1.4
50–100 ha	0.8	0.8	0.4	0.6	0.8	0.2	0.6	0.0	0.5	0.2	0.1
100–500 ha	0.2	0.7	0.1	0.5	0.4	0.0	0.1	0.0	0.3	0.1	0.1
More than 500 ha	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

Figure 2 shows that the number of forest fires below 0.5 ha has increased in the last decade. In particular, the increase in the number of so-called point fires below 1,000 m^2 is significant. The number of forest fires between 1–5 ha was reduced. The number of fires larger than 10 hectares has not changed in the last decade.

23 54/2014 Decree of the Ministry of the Interior on the National Fire Regulation.

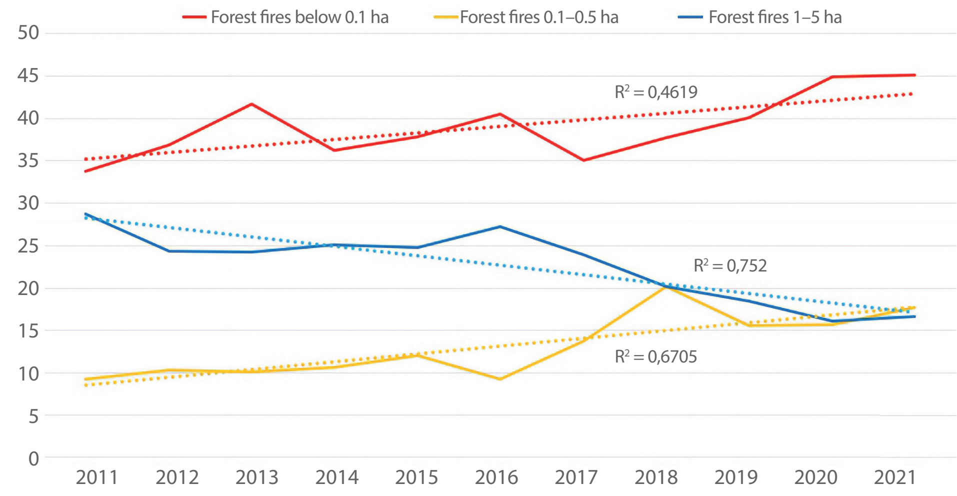

Figure 2: The proportion of forest fire events within classes of burned areas between 2011–2021

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

Examining the fires in non-wooded areas shows an even stronger trend in the case of point fires. To examine the reasons behind the unfavourable trend, it will also be necessary to know the factors influencing the fire risk (meteorological conditions, surface cover and topographic conditions).

Based on the date of wildfires, two high fire risk periods can be distinguished during the fire season (Figure 4). Spring forest fires (February–May) accounted for 56.3% of the total number of forest fire cases. In the last decade, only in the spring of 2013 has there been significant rainfall, with hardly a few fires. In the other years, there were high fire risk periods in March and April. During this period, the rate of wildfires was above 50% in six springs compared to the annual number of fire events. At the beginning of this decade, the number of forest fires began to increase at the end of February, and high numbers of fire cases were registered by the end of April. The length of the high fire risk period in spring has depended on the distribution of spring precipitation. This trend has begun to change by the end of this decade. Due to the extreme droughts of the last three years, the number of forest fires started to rise from the second week of February and we recorded extremely high fire numbers until the end of April. In May and the first half of June, depending on the rainfall distribution, the fire risk decreases and we do not see any outliers in the number of recorded wildfires.

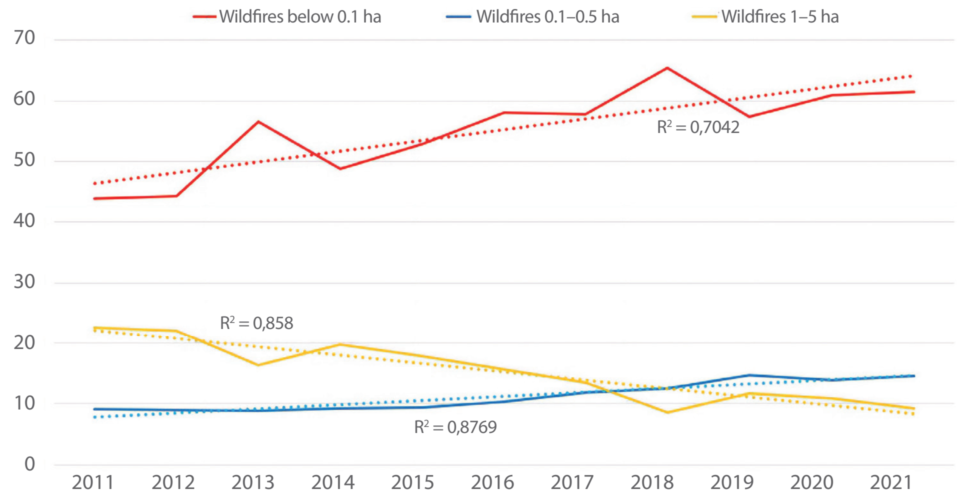

Figure 3: The proportion of wildfire events within classes of burned areas between 2011–2021

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

Based on the number of wildfires, the second high-risk period of the year is in July and August. In the second half of the last decade, a lack of precipitation also developed in September and October. Some large fires also occurred in the autumn period, which is an unusual phenomenon in Hungary. In recent years, due to the summer drought, several large-scale crown fires have developed in the lowland pine forests and also in the forest and shrubs of the northern part of the country. The increasing number of fires shows that due to climate change, fires brake out as early as at the beginning of the year, unlike in previous decades. Over the next decade, there could be more firefighter interventions in the spring period.

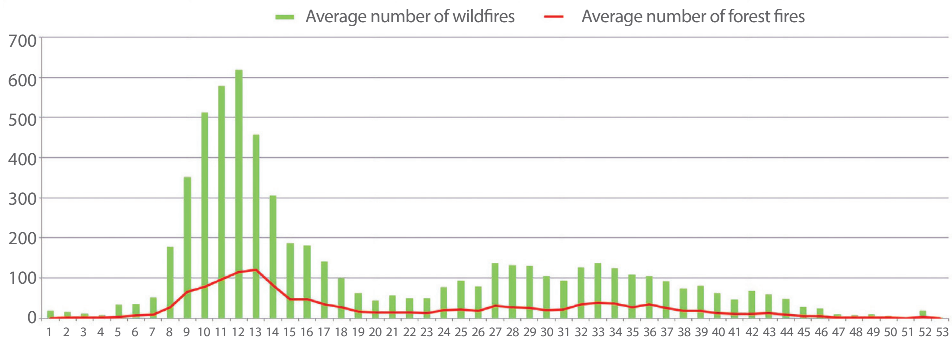

Figure 4: Average number of wildfires and forest fires per week between 2011–2021

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

As shown in Figure 5, it can be stated that based on the number of fires and the burned areas, the most endangered parts of Hungary are Bács-Kiskun, Borsod-Abaúj-Zemplén, Heves, Nógrád, Pest and Szabolcs-Szatmár counties.

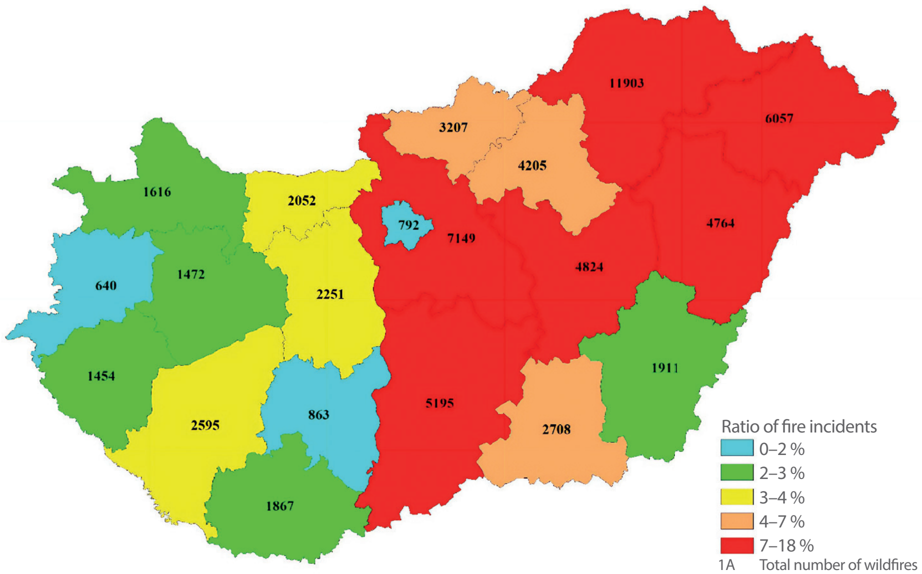

Figure 5: Total number and ratio of wildfires in counties between 2011–2021

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

In the last decade, 45.1% of spring fires occur in the Northern Hungary region (Borsod-Abaúj-Zemplén, Heves, Nógrád) and Pest county. It refers to the high vulnerability of

Borsod-Abaúj-Zemplén county; 20.8% of the spring wildfires and 25.5% of the burned areas were in this region.

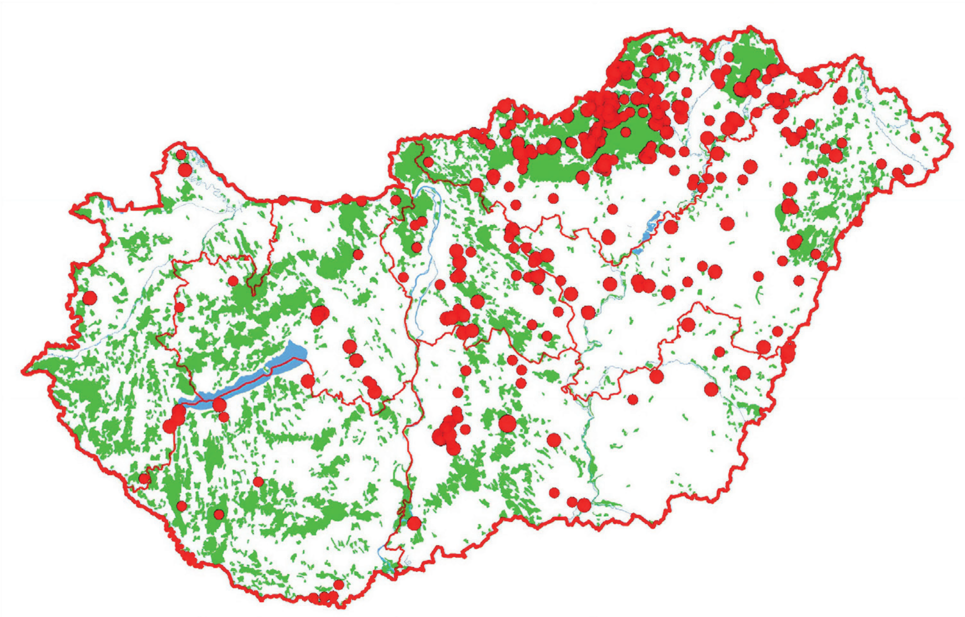

Figure 6: Wildfires larger than 50 hectares in the spring period (2011–2021)

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

56.7% of the wildfires in summer occur in the Great Plain region, where crown fires can also break out. During the summer, 103 large-scale wildfires exceeding 50 hectares were registered. 60.8% of these also occur in the pine areas of the Great Plain region. In Hungary due to climatic conditions and the composition of the fuel, only 1% of all wildfires break out by natural causes. Most causes of the fires are human negligence or intent. According to the national fire database, these can be cigarettes discarded from cars or trains, neglected campfires, careless burns, or poorly organised barbecues.

Legislative background for the definition of high fire risk periods in Hungary

Fire bans that can be ordered in case of high fire risk periods are already covered by Act LIV of 1996 on Forests and the Protection of Forests.[24] During this time, the Minister of Agriculture ordered a general fire ban in case of high fire risk periods. The ban was issued in the Hungarian Official Gazette. Forest fire prevention rules have also been incorporated

[24] Act LIV of 1996 on Forests and the Protection of Forests (repealed).

into Act XXXVII of 2009 on forests, on the protection and management of forests[25] (Forest Act). Between 2009 and 2017, the law ordered the promulgation and revocation of the total fire ban in a ministerial decree. A significant change from the previous regulation was that from that date not only the responsible Minister for forestry but also the forest authority could order a fire ban in its jurisdiction area – in consultation with the County Disaster Management Directorate – at the county or municipality level. During this period, a general fire ban was announced at the county level. Based on the amendment of the Act in 2017, the order of announcement of the fire ban has changed. From this date, the high fire risk period is announced for the entire country or county or local level. The Minister responsible for forestry ensures the determination of the high fire risk period and informs the public with the involvement of the National Directorate General for Disaster Management and the Ministry of the Interior (NDGDM). The determination and revocation of the high fire risk period depend on meteorological conditions, the drought of living and dead fuel on the forest floor, and the frequency of fires. According to the Forest Act, in case of a high fire risk period, it is forbidden to light fire in the forestland and its outskirts area within 200 metres. A fire ban is also valid if the competent authority has not imposed a fire ban, but the high fire risk area has been identified. In addition to the Forest Act, other legislation in connection with the ignition in wildlands also links the prohibition measures to the high fire risk periods.

An overview of the application of wildfire indicators on the EU level

Fire risk depends on the combined effect of several factors such as climatic conditions, vertical and horizontal structure of the vegetation, moisture content of the dead biomass, forest management methods, forest fire prevention activities and socio-economic conditions. Large-scale wildfires occurred in the world due to extreme weather conditions. However, most of the fires can lead back to human activity.

On hot, dry days, such weather conditions can develop fire outbreaks. This can increase the number of areas, where fires can break out and extend the fire season. The number of fires and burnt area indicators can characterise high fire risk regions over a longer period. So in countries where long-term datasets are available, these data are used as indicators to characterise the main processes.

Based on the forecast of international and domestic climate research, the number of heat and summer days is expected to increase. At the same time, the number of rainy days decreases, and the risk of drought increases. Rainy periods shift to autumn and winter, which increases the chances of spring and summer fires. It is a feature of almost every European country that much of the fire can be traced back to human intervention. In addition, meteorological conditions and combustible fuels also play a crucial role in the development of fire hazards. In Europe, the correlations between the fire risk periods of the last three decades and the fires have been examined with the Canadian Forest Fire

[25] Act XXXVII of 2009 on forests, on the protection and management of forests.

Weather Index (FWI) used by the EFFIS. Research by the European Environment Agency notes that the wildfire risk of Hungary was similar to northern Spain and Greece, but by the end of the century, it would increase to the same level as the Mediterranean region.

The increase in fire risk will result in more and more extremes in the distribution of precipitation. A lot of rainfall in a short period can cause serious damage to areas affected by wildfires, which endangers forest regeneration. Analysing the data of the EFFIS, it was determined three high fire risk periods that can occur in the European Union. In winter, wildfires burn in mountainous regions, in spring in Northern and Central Europe, and in areas associated with summer droughts. Processes over the last 30 years have been examined using the Canadian Forest Fire Weather Index, which is based on a daily fire risk calculation. The special indicator derived from the model is the so-called Seasonal Severity Rating (SSR). This is a dimensionless value, so it is possible to compare fire risk over time and space between years and regions. SSR showed a significant increase in many regions of Europe between 1981 and 2010.[26]

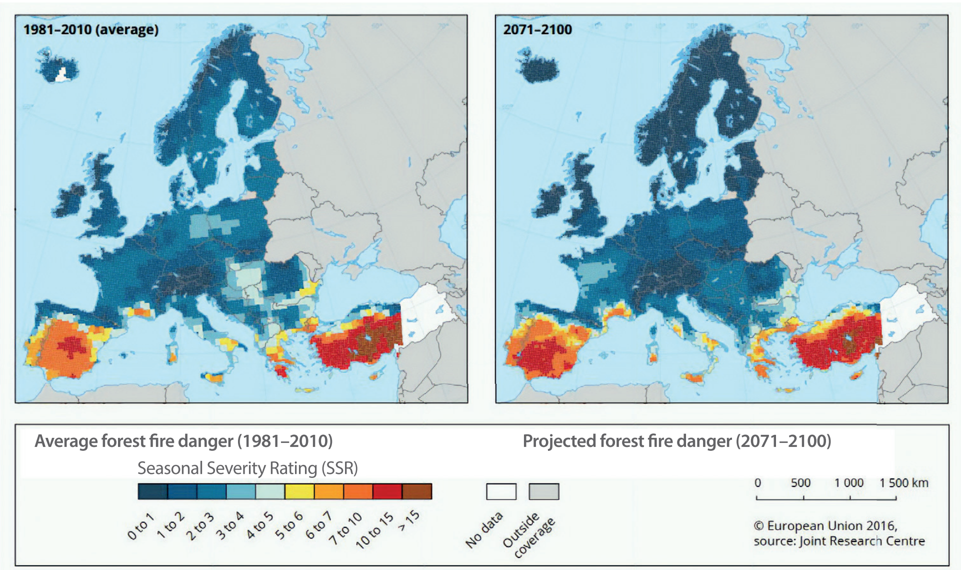

Figure 7: Development of fire risk in the European Union between 1981–2000 and the change predicted by the models for the period between 2071–2100

Source: European Environmental Agency.

Based on forecasts, the length of fire risk periods is expected to increase. As a result of it, wildfires may start in February and also even in October. As Figure 2 and Figure 3 have shown, an increase in the number of small fires has been demonstrated over the past decade. Fire intensity and the rate of spread can increase on high fire risk days, increasing the size

[26] EEA Report No 15/2017: *Climate change adaptation and disaster risk reduction in Europe. Enhancing coherence of the knowledge base, policies and practices.*

of the burned area and making it more difficult to control the fire during firefighting. Studies on the effects of climate change predict significant warming, heat waves and longer dry periods, mainly in the Mediterranean region and in Central Europe, including Hungary. The length and impact of the fire seasons can increase, and risk areas and the risk of large-scale fires and desertification in these areas may also increase in the future.

The scenario shown in Figure 8 predicts that in the next 30 years the size of the burned area in one fire season, the risk of large-scale fires and the emission of greenhouse gases will increase in Hungary.[27] In the Central and Northern regions of Europe, the risk of fire and the area affected by the fire will also increase due to rising temperatures. An increase in the fire potential is also forecast in Hungary compared to the period between 1961–1990. Given the expected increase in fire risk, it will be important in the future to investigate anthropogenic impacts on the spatial distribution of fire and land use habits. Consequently, a fire risk assessment will be a daily task inevitably in the future. In the next part, some indicators will be examined that can show the differences between consecutive years on the country level.

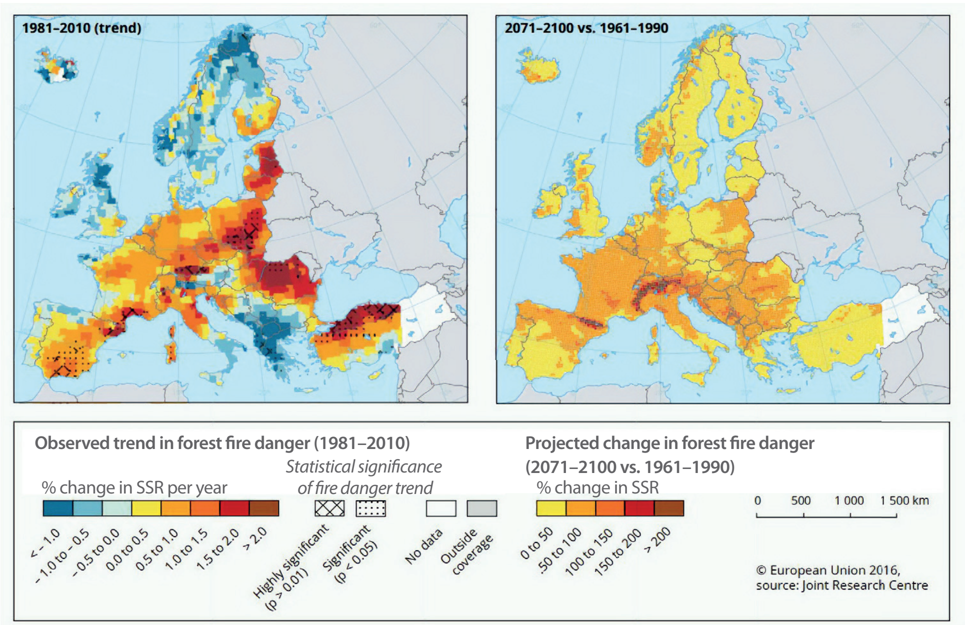

Figure 8: Change in the trend of fire hazard between 1981–2000 and change compared to the period between 2071–2100

Source: European Environmental Agency.

[27] EEA Report No 1/2017: *Climate change, impacts and vulnerability in Europe 2016. An indicator-based report.*

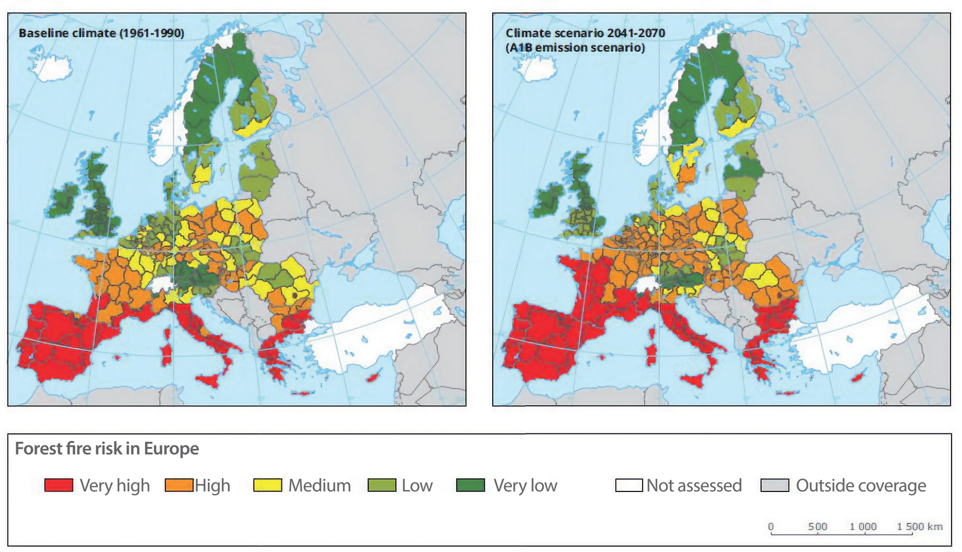

Figure 9: Change in fire risk trend between 1981–2000 and change compared to the period 2041–2070

Source: European Environmental Agency.

Some domestic research predicts that in the future the distribution of precipitation in the Carpathian Basin will become more uneven and the average daily temperatures in summer and autumn will also increase. The effects of climate change will also be seen in the extension of high fire risk periods, the increase in the number and distribution of wildfires, and the increase in fire intensity. However, forest fire prevention can only be effective if potential risks are identified and potential impacts can be evaluated.

Wildfire indicators and the definition of high fire risk periods on the country level

The wildfire risk of a country or a region is characterised by the number and burnt areas in national reports. Many conclusions can be drawn from these data, especially if they include additional information on the fuel conditions of the burnt areas. However, in our opinion, they are poorly suited to measuring the effectiveness of fire prevention activities and comparing annual data sets. It does not matter if there were 100 wildfires in 1 million hectares of endangered forest that resulted in 1,000 hectares of burned areas or if it evolved from 100,000 hectares of endangered forest. It should also be examined whether there were 50 high fire risk days or 150 in a year, as the same burnt area is a great achievement if the length of the endangered period increases. Few wildfires do not necessarily mean that there is no wildfire risk, but they can also mean that the forest fire prevention system works well. In this case, we can say that fire prevention is more effective from both an economic and ecological point of view. Due to several factors influencing wildfires, we need to produce an intensity ratio, where the numerator contains the data of the fires that occurred in the given period and the denominator contains the number characterising the potential fire risk of the period. The change in the intensity ratio shows more effectively the effect of the measures in the case of weather-dependent forest fires. As the size of the endangered forest area did not change during the examined period in Hungary, the number and extent of annual fires should be compared with the degree of fire risk or the length of the periods. Of course, an intensity ratio can be developed that takes into account territorial changes or even the extent of individual measures.

To be able to compare the number and burnt area in forest fires each year, it is necessary to define the concept of a wildfire risk day and region. The spring and summer fire seasons will be considered separately for different fuel conditions and fire causes.

Two questions need to be always answered:

1. When do we consider a particular day to be a high fire risk day?
2. What is the size of the area to which the concept of a fire day is applied?

For the first question, we can start with the number of fires that have occurred or meteorological and fire risk data, which show the possibility of a fire being potentially caused. For the second question, the fulfilment of the wildfire risk day criterion should be applied to the area related to the data. This method can sometimes lead to simplification.

Looking for possible solutions, we have found the following four criteria feasible for Hungarian wildfires.

- at least 2 wildfires per 1 hectare
- 5-day moving average and trend of the number of fires
- the number of summer and heat days compared to the number of wildfires
- criteria system based on fire weather index

At least 2 wildfires per 1 hectare

When evaluating the data of the fires, we considered a wildfire risk day when at least 2 wildfires occurred in one day with a total burned area of at least one hectare. Fires in spring usually start in the grass fuel and in many cases, they spread from there to the forest. So it is worth considering the two types of fire (wildfire and forest fire) together in this criterion. Due to the higher number of cases of spring wildfires and their territorial focus in the Northern Hungary region, this criterion can be applied nationwide for the spring fire season. The limitation of its use happens when the number of fires is reduced or if fire prevention is significantly improved. In this case, if no fire occurs on a potentially high fire risk day, the criterion does not indicate this. In the last decade, there have been an average of 77 days throughout the year when no wildfire occurred.

Table 3: Days when no wildfire occurred between 2011–2021

Year	Number of days	Spring	Summer	March–April
2011	48	4	6	1
2012	61	12	4	0
2013	87	35	8	16
2014	95	19	11	0
2015	76	15	5	0
2016	89	19	7	4
2017	71	14	8	2
2018	91	26	6	9
2019	70	14	5	0
2020	86	2	9	2
2021	80	20	1	0

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

The two highly endangered months (March and April) had a total of 34 days in the last decade when no wildfire burned. There were a total of 109 days when 100 or more wildfires occurred in one day. 47% of these fires were in 2011 and 2012. The most fires occurred on the 17th of March 2012, when a total of 462 wildfires were recorded.

Figure 10 shows the number of days when at least two wildfires occurred on the same day during the spring fire season and the average burned area exceeded one hectare. In the examined period, the spring fire season was affected by the distribution of precipitation. The number of days meeting the criterion increased in the drought springs. Rainy years have resulted in a decline, but the last two years of the decade have shown a slight increase based on the moving average.

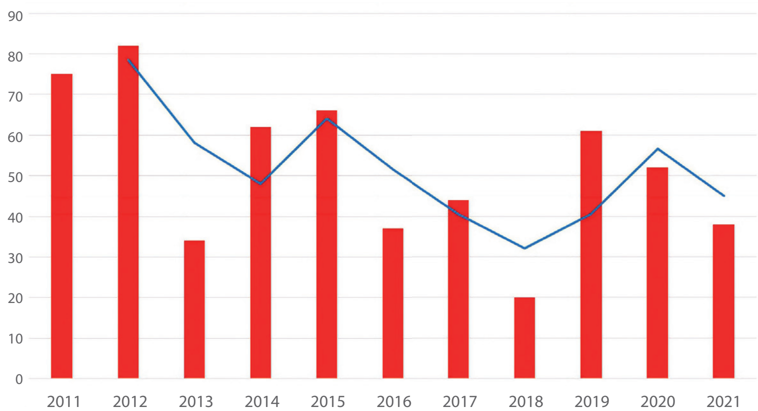

Figure 10: Number of days when at least 2 wildfires occurred during the spring fire season and the average burned area exceeded 1 ha (2011–2021)

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

Figure 11 shows the number of days when at least two wildfires occurred on the same day during the summer fire season and the average burned area exceeded 1 hectare. It shows a declining trend in the period between 2011–2021 in terms of the moving average.

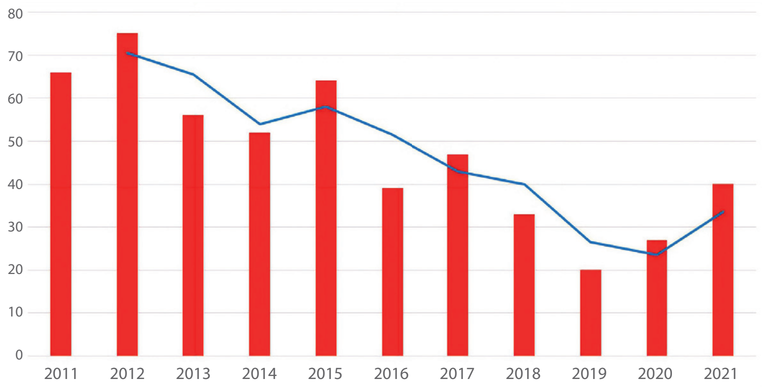

Figure 11: Number of days when at least 2 wildfires occurred during the summer fire season and the average burned area exceeds 1 ha (2011–2021)

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

Figure 12 shows that large fires of more than 50 hectares occurred during well-defined periods of the year. The high risk of the spring period is also confirmed by the data displayed on the graph.

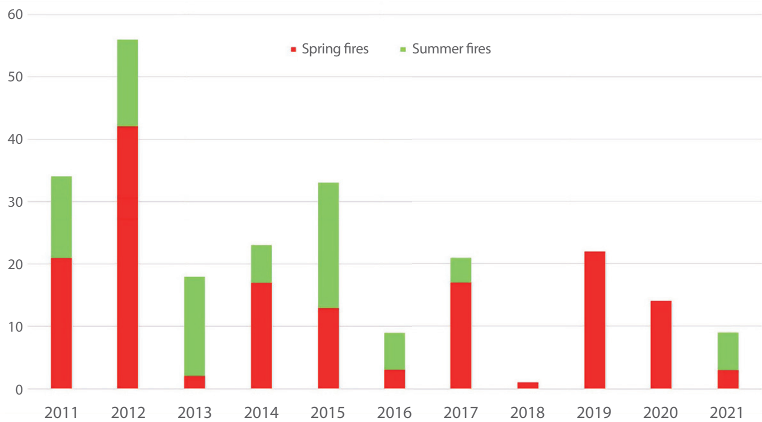

Figure 12: Number of days with more than 50 hectares burned areas (2011–2021)

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

5-day moving average and trend of the number of fires

The trend of daily fire numbers can also be determined by the moving average method. Each year represents a separate fire season, so every year can be examined separately. So the effect of fluctuations within a year can be filtered out. This method helps to predict the processes expected in the coming days, i.e. the increase or decrease in the number of fires. The moving average method is a little bit more inaccurate, but it can be used and accepted in all cases. In the case of wildfires, we examine the 5-day moving averages, as the fine fuel responds to the amount of precipitation from the previous 5 days (100 hours).[28] The moisture content of the fuel parts is determined by the environmental conditions and their size, shape and relative surface. The moisture content index shows how quickly the fuel part can reach the equilibrium state with the relative humidity. According to it, we distinguish biomass parts that reach equilibrium in 1–10–100–1000 hours. In the future, meteorological data and the values of the fire weather index derived from them will be needed to study the processes behind the decrease and increase in the number of fires. Figure 9 shows the number of daily fires in the period from the 15th of February to the 30th of April 2020 and the 5-day moving average calculated from them. The fluctuations are adjusted by the moving average, but the trend expected from the values of the last 5 days is well shown during the vulnerable period of the spring fire season.

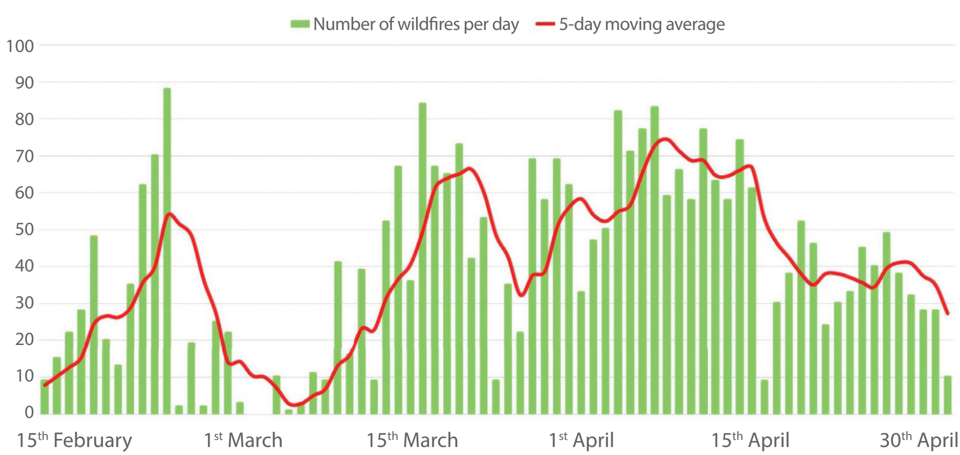

Figure 13: The number of daily wildfires in the period from the 15th of February to the 30th of April 2020 and the 5-day moving average calculated from them

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

[28] Mike Wotton: *A Grass Moisture Model for the Canadian Forest Fire Danger Rating System.* 8th Fire and Forest Meteorology Symposium, 2009.

Number of summer days, heat days and number of forest fires

During the summer fire season, light dead fuel with a large specific surface area can be burned within a few hours even after a small rainfall, if the weather is warm. It can be said that wildfires can typically develop in summer and on heat days. As the data refer to Hungary, we can find areas where the conditions for generating a fire do not exist. In general, however, the number of summer and heat days is a good indicator of the length and level of risk of the summer fire season.[29]

During the summer fire season, 38.1% of fires and 27.6% of the burned area are generated. In Figure 14, we compared the number of wildfires in the period between 2011–2021 to the number of summer and heat days. We considered those wildfires that resulted in at least 0.5 hectares of burnt area. Smaller fires usually occur due to the careless use of fire and not because of meteorological conditions. Over the last decade, the number of wildfires has shown a declining trend compared to the summer and heat days. To refine the system of fire ban criteria during the summer fire season, it is recommended to take this trend also into account in the future.

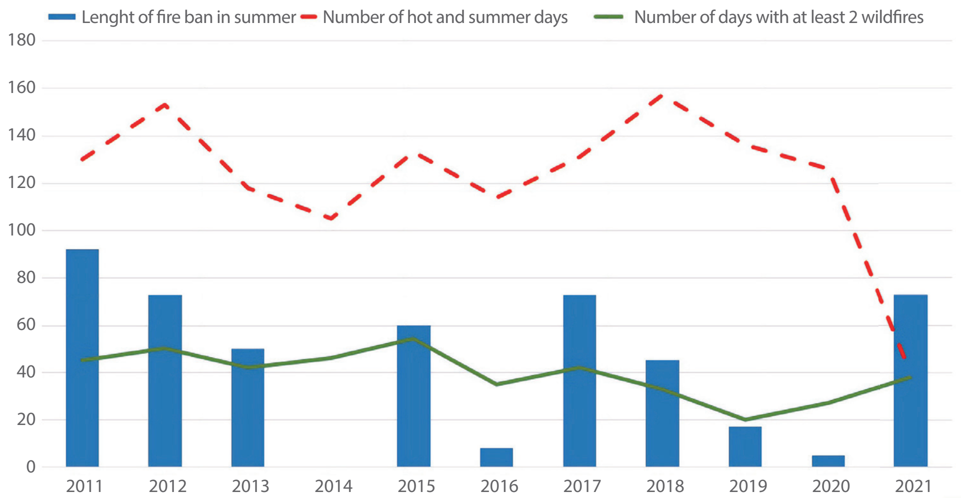

Figure 14: Comparison of summer and heat days with the number of wildfires reaching at least 0.5 hectares

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

[29] Péter Debreceni – Péter Pántya: A fokozottan tűzveszélyes időszakok meghatározásának lehetőségei [Possibilities for Definition of High Fire Danger Periods]. *Műszaki Katonai Közlöny,* 29, no. 1 (2019). 243–260.

Criteria system based on fire weather index

The Canadian Fire Weather Index is also used by the European Union's Joint Research Centre to assess the risk of wildfires in the coming period. The Canadian system models the changes in fuel moisture content based on the meteorological parameters in an area, where the weather data is available. If we would like to use the index at the operational level, its values must be validated at the member states' level.[30]

Before presenting the effects that can be detected based on the criteria system based on the FWI, we present the structure of the index. The index contains six subcomponents, the first three shows the moisture content of the fuel in the soil based on meteorological parameters. The two other subcomponents of the model show the expected fire behaviour and provide us with some information about the propagation of the fire. The sixth element is the value of the composite index, which is derived from the sub-indices. The sub-indices are calculated from the combination of different meteorological factors.[31]

Humidity indices are calculated first. A value indicating the moisture content of fine fuel with a diameter of less than 1 cm expresses the flammability. The forest litter moisture value characterises the moisture content of the loose, less compact soil layer for the average depth. The drought value refers to the moisture content of larger dead biomass elements. It can be used to predict drought periods and ignition. Because wildfires are most easily generated and propagated in the fine fuel, therefore, the values of the fine fuel component are important in determining the fire risk period in the spring. This sub-index responds to the amount of precipitation over the previous five days, so in the rapidly changing spring period, as this value increases, the probability of fires also increases exponentially.

In the second step, two sub-indices of the extent of the fire are calculated. The value indicating the expected rate of fire spread is the value calculated from the wind speed and the moisture content of the fine fuel. The fire development value is a combination of the forest litter and the drought value, which shows the probability that the fire can spread most easily to the biomass types with higher burning intensity.

In the third step, the complex value for forest fire hazard is calculated, which is a combination of the previous two values. FWI values are classified into six classes, which are displayed on a map. The same classification is applied to all countries in Europe, so they are comparable with each other. However, a country-specific scale may need to be developed in the future due to the effectiveness of official measures.

The index can be used to show the effects of the weather on the expected development of fires. The index can be used to assess the effects of weather on the moisture content of biomass in the forest, in case of large fires, it helps to estimate the expected fire behaviour. Changes in the sub-indices of biomass provide an opportunity to continue monitoring the fire potential.[32] The index also refers to the fire intensity per unit of the fire front;

30 Joaquín Bedia et al.: Seasonal Predictions of Fire Weather Index: Paving the Way for their Operational Applicability in Mediterranean Europe. *Climate Services,* 9 (2018). 101–110.

31 Christian van Wagner: *Structure of the Canadian Forest Fire Weather Index.* Ottava, Department of the Environment, Canadian Forestry, 1974.

32 B. D. Lawson – O. B. Armitage: *Weather Guide for the Canadian Forest Fire Danger Rating System.* Edmonton, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 2008.

therefore, in case of large fires, it can also be used to determine the conditions required for the firefighting. The index can also be used to delimit the periods and the locations of the country, where the conditions of controlled ignitions have been established. As a result of the index, the beginning of the fire season can be determined, but also a forecast of the expected fire season can be made. The map and the updates on the daily fire danger are available on the EFFIS website.[33] During vulnerable periods, the index is recalculated daily, thus providing a three- and six-day fire danger forecast. The meteorological data required for FWI are provided by the German and French meteorological services (Meteo-France and DWD). To calculate the FWI, a biomass map is generated based on the Corine Land Cover (CLC) and Map of Natural Vegetation of Europe (MNVE) databases. FWI values are classified into fire danger classes, which are displayed on a map.

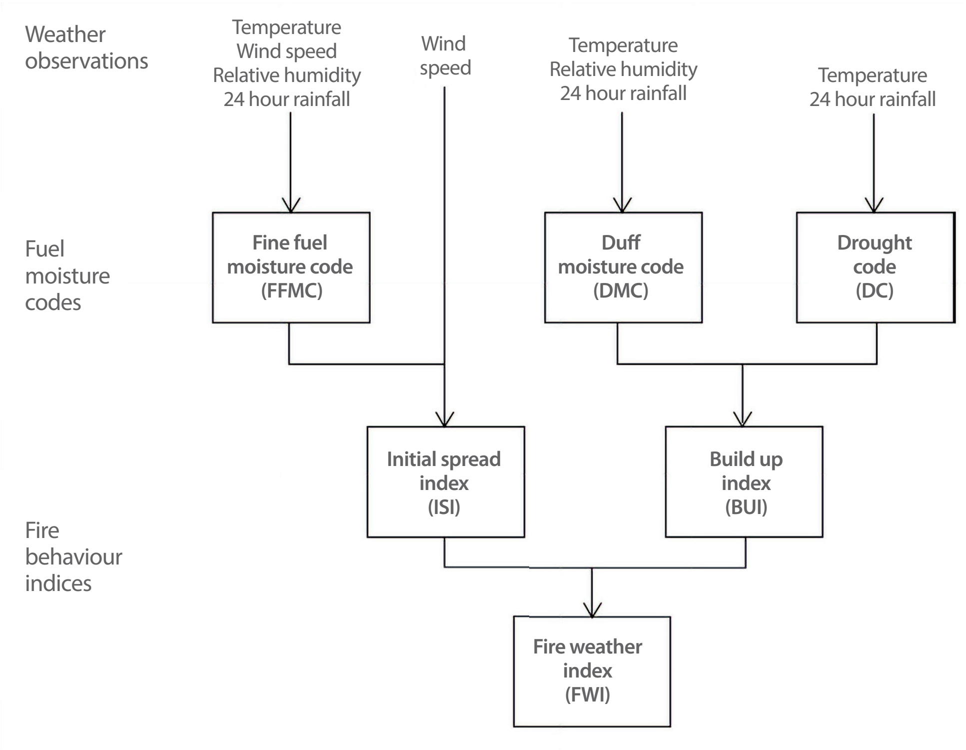

Figure 15: Structure of the Canadian Fire Weather Index

Source: Canadian Forest Fire Weather Index (FWI) System

[33] European Forest Fire Information System (http://effis.jrc.ec.europa.eu/static/effis_current_situation/public/index.html).

Relationship between fire risk days and fires based on the weather index

The Joint Research Centre provides FWI values on a 28 km resolution raster map daily. The relationship between FWI and wildfires was examined over two years for the entire territory of the country. According to the JRC recommendation, a day in the spring fire season was considered risky if the FFMC value was greater than 75; and in the summer fire season when the FWI value was greater than 19.

By using GIS, we examined two aspects in 2012 and 2018.

1. Daily, how many pixels meet the criteria for the wildfire risk day separately in the spring and summer fire seasons.
2 What are the grid points where the most wildfires occur in spring and summer?

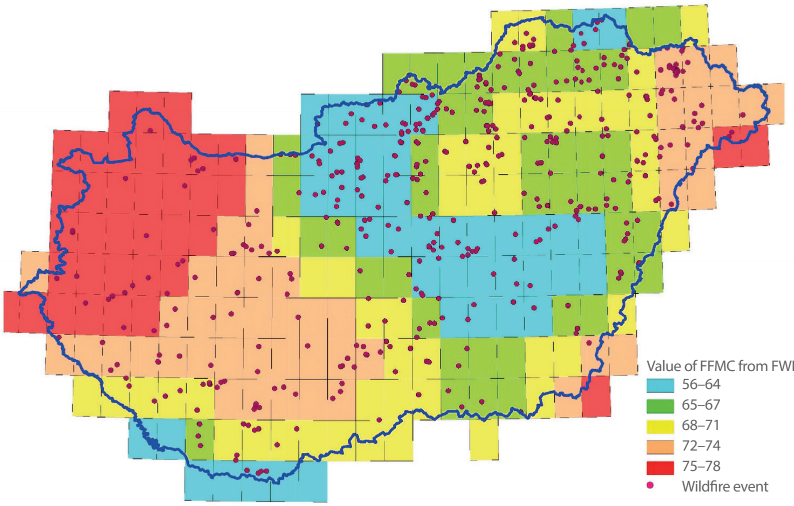

Figure 16: Grid of Fire Weather Index with values of FFMC and wildfire events on the 17th of March 2012

Source: European Forest Fire Information.

Figure 16 shows that during the spring fire season, most fires occur in that part of the country where, based on the fire weather index Fine Fuel Moisture Code sub-index, the wildfire risk is not yet high. This contradiction shows that human factors (cause of fire) must also be taken into account in the fire risk assessment. In the geospatial analysis, we examine the values of the Fire Weather Index grid shown in Figure 16. The data of the grid were downloaded from the freely available database of the Copernicus Emergency Management Service. The European Space Agency created a harmonised database in the framework of the Copernicus program, which contains the values of the index. After registration, the data can be freely used for research purposes. The database works by drawing a 0.25-degree grid over the entire globe. Index values were given for each grid point and each day. The index contains 8 sub-indexes. This means that for each day there is a grid point identifier and 8 index values for a date.[34]

Figure 17 shows how many pixels were classified as high fire risk daily between February and May in 2012 and how many of these grid points resulted in wildfires. The graph shows that in the early spring period when it was a dry period, the moisture content of the dead biomass reacted quickly to the rainless period. At the end of spring, due to rainier days, the number of the grid points decreased.

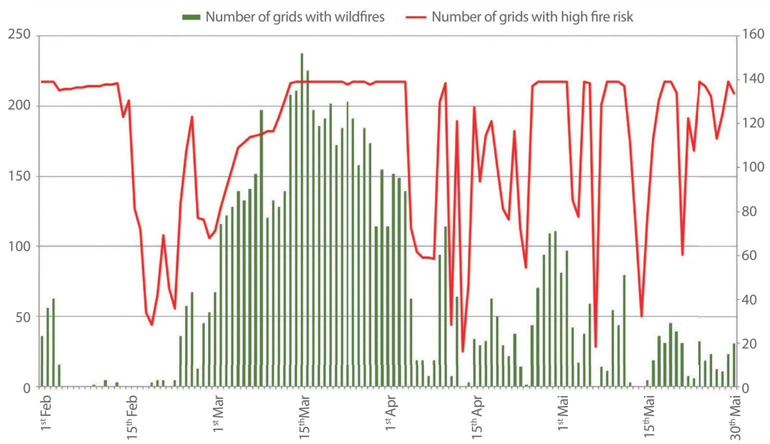

Figure 17: The number of grid points that are considered wildfire risk days and the number of grid points affected by wildfire in spring 2012

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

In the summer of 2012, due to a more even distribution of precipitation, there were several shorter periods when a fire risk developed in most parts of the country, as shown in Figure 18. As the fire danger area increased, the number of grid points affected by the fire also increased slightly.

[34] Fire Weather Index ERA5 dataset (https://confluence.ecmwf.int/display/CKB/ERA5).

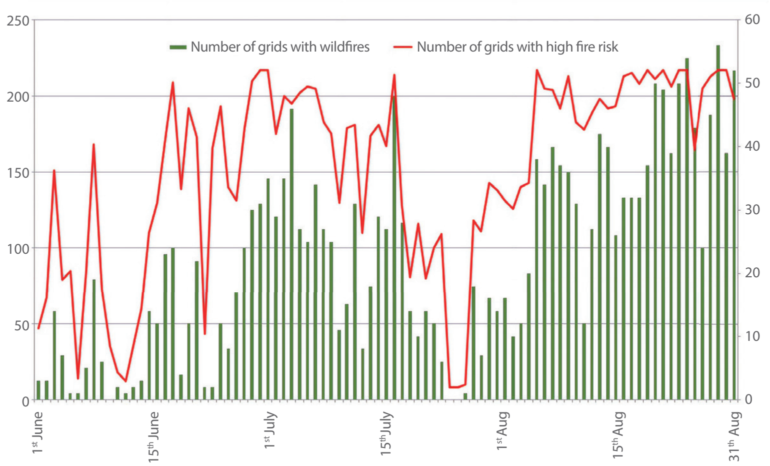

Figure 18: The number of grid points that are considered wildfire risk days and the number of grid points affected by wildfire in summer 2012

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

In the spring of 2018, due to the rainy weather, no long-term fire hazard period developed in Hungary. In the second half of spring (April), there was a four-week period, where high-danger grid points were registered in nearly two-thirds of the country. Compared to the situation in 2012, the number of grid points where ignition took place despite the risk of fire has significantly decreased (Figure 19).

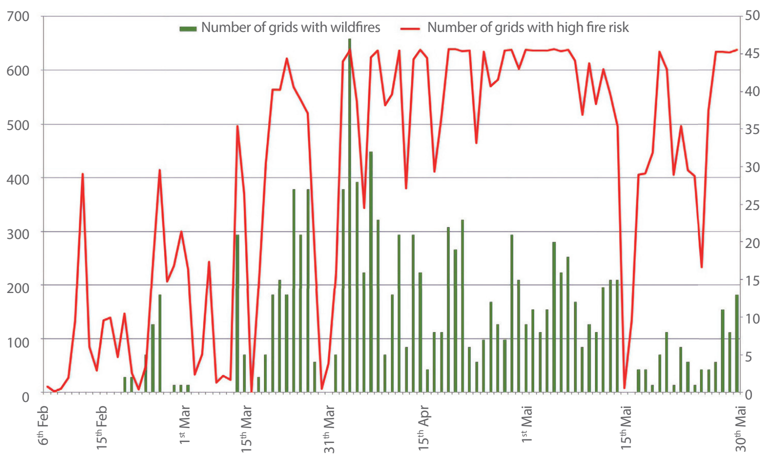

Figure 19: The number of grid points that are considered wildfire risk days and the number of grid points affected by wildfire in spring 2018

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

During the summer fire season, there were days in August when the fire risk period was present in half of the country (Figure 20).

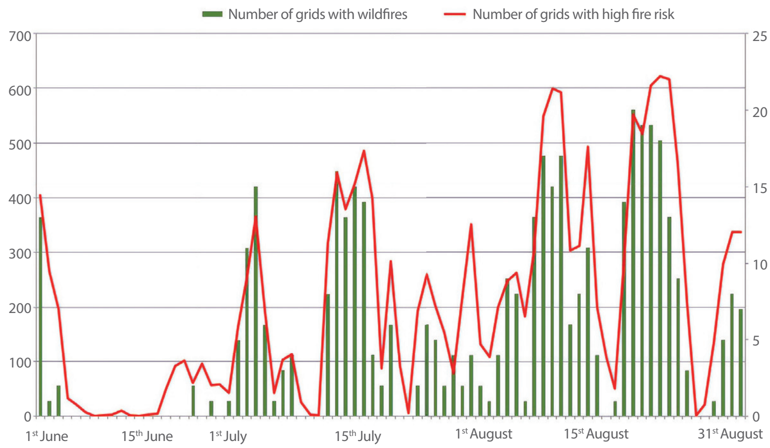

Figure 20: The number of grid points that are considered wildfire risk days and the number of grid points affected by wildfire in summer 2018

Source: Compiled by the authors based on the data of the National Food Chain Safety Office and the Forest Fire Information System.

Summary

The fire risk depends on the combined effect of several factors: climatic conditions, vertical and horizontal structure of the vegetation, moisture content of the dead biomass, forest management methods, forest fire prevention activities and socio-economic conditions. In case of droughts, because of the weather conditions lots of wildfires occur. Indicators within a year help us to assess the fire risk. Forecasting the risky periods during the fire season is very important for the preparation and implementation of official measures. Indicators based on the number of fires can be used as indicators to evaluate and compare each year. One of the purposes of the paper was to define indicators that can be used to compare the number and extent of wildfires each year with the degree of the daily fire risk and the length of periods during which the vegetation fires occurred. For this, we defined the concept of the high fire risk days and the endangered areas and parts of the country in the Hungarian climatic conditions. We also examined the spring and summer fire seasons separately, because of the different fuel conditions and the causes of fire ignition. In addition, we examined statistical data on wildfires and applied GIS systems. We have found a correlation between the daily fire risk values, the number of wildfires and the burned area.

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