How does climate change increase the risk of forest fires in Austria?
An initial survey and assessment study

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KKL-ÖAW Study Report – February 2021



Photo credits: D. Henner 2020 (left), recreational forest scene Lahnsattel; OBI C. Lauer fireworld.at 10.5.2020 (top right); © 2020 die.wildbach (bottom right), forest fire Leppen-Bad Eisenkappel May 2020.

Report Content

Study Report summarizing the results of the KKL-ÖAW-funded small review study "Kleinstudie über das Risiko von Waldbränden in Österreich unter dem Einfluss des Klimawandels" (Nov.-Dez.2020)

Authored & Issued by

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Graz, February 2021

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Executive Summary

Climate change—an accelerator of compound risks for forests and forestry

Anthropogenic global warming leads to a particularly strong and complex imprint in regional climate change and its biophysical and societal consequences in the Alpine region and its southern & eastern forelands towards the Mediterranean area (Zscheischler et al., 2018). The expected intensification of extreme hot and dry spells in severity, frequency, and spatio-temporal extent under climate change in the warm seasons in this region, complemented by land use and management practices that tend to increase exposure and vulnerability, will likely have strongly adverse effects on forests (e.g., NASA, 2020). Forests under stress will then have a negative impact on economy, society and ecosystems.

Forest fire risk—a key forest risk expected to increase worldwide and in Austria

One such potentially severe climate change risk to forests is wildfires. The substantial increase of forest fires in many countries, also at middle and higher latitudes, shows already the fingerprint of climate change (Climate Council, 2020; European Commission JRC, 2017). Among highly unusual forest fires in Austria in April 2020 (Müller, 2020a), forest fires started to burn way ahead of the usual fire season in arctic regions in 2020 (Fire & the Boreal–Global Forest Atlas, 2020; NASA, 2020). Strong increases in temperature above landmasses and increasingly stationary weather patterns, imprints of climate change, result in extremely hot and dry periods in summer. When these conditions are met by already dry soils and drier-than-usual forests and meadows, high-vulnerability conditions for forest fires are met (Fire & the Boreal–Global Forest Atlas, 2020; Herring et al., 2020; Zscheischler et al., 2018). Therefore, climate change increases fire risks also in Austria and hence, in view of this threat, Steininger et al. (2020) identified and recommended the topic as a climate risks study priority under-researched so far.

Study goals—assess forest fire risk increase in Austria under climate change

This study helps to address the questions around growing risk of forest fires in Austria under increasing climate change conditions, a focus that has not been well assessed so far despite extensive research on fire risks in general for Europe (European Commission JRC, 2017; EFFIS Portal, 2020; EFFIS Report, 2020). Causes for forest fires in Austria are reviewed, and an assessment is undertaken for understanding risks of increase under climate change and impacts for economy, society and ecosystems. That is, the causes for recent past forest fires are brought into context with expected climate change conditions so that the level of risk could be estimated. Furthermore, the study addresses the negative impacts from increased forest fires for key impact domains (economy, society, ecosystems) individually, and as well discusses in an introductory manner the underlying interconnections between the impacts caused.

Methods—literature review, initial database assessments, fire risks summary table

A careful literature review has been undertaken to survey the causes, patterns, and impacts from forest fires, with a focus on relevance for Austria. Historical (recent past) fire data time series are available in Europe and regularly updated within the European Forest Fire Information System EFFIS (EFFIS Portal, 2020). EFFIS addresses forest fires in Europe in a comprehensive way, providing EU-level assessments from pre-fire to post-fire phases, thus supporting fire prevention, preparedness, fire-fighting and post-fire evaluations. To complement the information, data on past forest fires are routinely used to rate the fire potential due to weather conditions. For example, the Canadian Forest Fire Weather Index (FWI) System (Natural Resources Canada, 2020) is used by EFFIS to rate the daily fire danger conditions in Europe. EFFIS data, and other suitable data, have been inspected for Austria, recent and future climate change effects have been assessed, and related key risk areas identified by the study. Specifically for Austria, the utility of the fire danger assessment system IFDS (Müller et al., 2020b) was assessed and the tool found of high value and promise (see next page).

Summary of results and recommendations—findings of the report

Section 1 of the report assesses the status quo and the causes of forest fires. Forest fires in Austria are increasing, depending on heat and drought throughout the year. Given vulnerable forests, most forest fires are triggered (ignited) by humans or lightning strikes, with both causes likely increasing.

Section 2 reports that the forest fire risk in Austria is clearly expected to increase over the next decades under climate change. Figure 1 below illustrates a recent risk assessment for forest fires that combined fire data with geospatial data on forests (Müller, 2020c). Reporting more detail, Section 2 provides a tabular assessment of risk increases for climate change-driven and other risk-influence factors (see Table 1 on page 16). The forest fire risk in some parts of the Alps and the Alpine forelands may even become very high (in a five-classes ranking from "very low" to "very high"), with only small parts remaining at a very low risk (see also Müller et al., 2020a; 2020b). This enhanced risk is caused by a combination of climatic and biophysical factors. While some of the factors are expected to have no relevant change impact on future forest fire risk, climate change-driven factors will increase the related overall risks significantly.

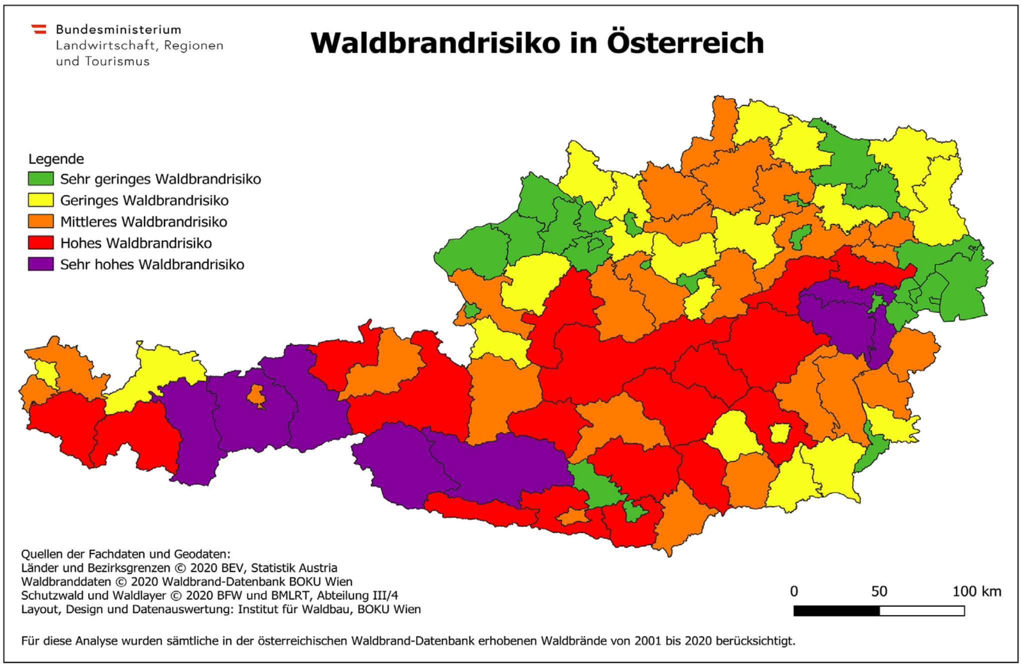

Figure 1: *Regional risk assessment map of estimated forest fire risk in Austria, based on 2001-2020 fire data combined with forest geodata (language German). Source: Inst. of Silviculture, BOKU Vienna (Müller, 2020c)*

A new Integrated forest Fire Danger assessment System (IFDS) specifically for Austria was introduced by Müller et al. (2020b) that includes i) daily fire weather index data, ii) a countrywide hazard map for fire ignition through human activities, iii) a lightning fire hazard map, iv) a high-resolution fuel type map, and v) a topography-based estimation of the fire hazard.

This study recommends taking the IFDS tool as a starting basis for refined studies and further risk assessment developments. Currently, the prototype tool is evaluated by scientific users and is set to be improved over the coming year. A tool like this which can help understand all major underlying factors, also in changing combinations, will be invaluable for the development of adjustments and measures for mitigating and adapting to forest fire risks under climate change.

Section 3, the closing section of this report, also provides more specific recommendations for further studies and implementation actions (see page 20).

Content

Introduction

Anthropogenic global warming leads to a particularly strong and complex imprint in regional climate change and its biophysical and societal consequences in the Alpine region and its southern & eastern forelands towards the Mediterranean area (Zscheischler et al., 2018). The expected intensification of extreme hot and dry spells in severity, frequency, and spatio-temporal extent under climate change in the warm seasons in this region, complemented by land use and management practices that tend to increase exposure and vulnerability, will likely have strongly adverse effects on forests (NASA, 2020). Forests under stress will then have a negative impact on economy, society and ecosystems.

One such potentially severe climate change risk to forests is wildfires. The strong increase of forest fires in many countries, also at middle and higher latitudes, shows already the fingerprint of climate change (Climate Council, 2020; European Commission JRC, 2017). Among highly unusual forest fires in Austria in April 2020 (Müller, 2020a), forest fires in arctic regions started to burn way ahead of the usual fire season in 2020 (Fire & the Boreal–Global Forest Atlas, 2020; NASA, 2020). Strong increases in temperature above landmasses and increasingly stationary weather patterns, imprints of climate change, result in extremely hot and dry periods in summer (NASA, 2020). When these conditions are met by already dry soils and drier than usual forests and meadows, high-vulnerability conditions for forest fires are met (Fire & the Boreal–Global Forest Atlas, 2020; Herring et al., 2020; Zscheischler et al., 2018). Climate change also increases fire risks also in Austria and hence, in view of this threat, Steininger et al. (2020) identified and recommended the topic as a climate risks research priority.

In recent years, intensities of wildfires have increased around the world due to the anthropogenic climate change. Recent forest fire events proved quite well that forest fires are also an urgent issue in the Alpine region which can lead to the destruction of protection forests, increasing vulnerability to natural hazards and high costs up to millions of Euros per fire (Müller et al., 2020a; Steininger et al., 2020). Fire frequency and severity will likely increase due to climate change, more recreational use of forests and changing forest management (Müller et al., 2020a). Especially protection forests dominated by coniferous tree species on Southern slopes were found to be at risk and the impacts of fires in these vulnerable forests can lead to new avalanche-prone slopes, increased rockfall, and mudslides or soil erosion (Müller et al., 2020a). Furthermore, the costs of firefighting, restoration of forests, and of protective measures may seriously rise (Müller et al., 2020a; Steininger et al., 2020).

Besides human-caused fires, lightning from thunderstorms is a major reason for forest fire ignition worldwide. However, information on fire events, lightning characteristics and impact points is often missing or controversial, due to the difficulty of lightning stroke localization and the relation to single forest fire events (Müller et al., 2020a). Austria as an Alpine country experiences a high number of thunderstorms and lightnings. Data from the Austrian Lightning Detection and Information System made it possible to link single lightnings and their characteristics to location and attributes of individual forest fires. Additional data on time of ignition, burned area, exposition and burned vegetation were investigated. A probability was estimated for lightning being the cause and it was found that about 15% of all recorded forest fires in Austria were lightning caused (EFFIS Report, 2020; Müller et al., 2020b).

Nearly all these fires were found during the summer months, i.e., almost 40% of all fires occurring from June to August were naturally caused. They primarily occurred in the South and East of Austria, at higher altitudes with southern or western exposition, mainly in stands of Norway spruce. Pine species were four times more often affected than the actual tree species distribution in Austria would assume. The median burned area was lower than for anthropogenic forest fires.

Section 1: Assessment of the Status Quo

The International Association of Wildland Fire recently stated that "Climate change has already had significant consequences in the global wildfire reality, affecting citizens as well as the global wildland fire community." They also emphasized that "There is already evidence of climate-driven fire regime change in the Northern Hemisphere with fire risk increasing in non-traditional fire-prone countries". One of these regions are the European Alps. Wildfires are an emerging issue that can lead to high damages in protection forests, further increasing the risk of natural hazards and resulting in threats for people and high costs up to millions of Euros for fire suppression and restoration measures (Müller et al., 2020a). The recent extremely dry and hot summers in different parts of the Alpine space, e.g., 2013, 2015, 2017 and 2018, and a changing fire regime towards more intense and frequent wildfires supported the need to be better prepared (Moris et al., 2020; Müller et al., 2020a). In this context, experts in integrated fire management at the 4th European Climate Change Adaptation Conference (ECCA) in Lisbon, Portugal, in May 2019 emphasized the importance to "include the social dimension of fire in land management approaches by focusing on fire as not just an ecological problem, but an economic and social one" (Müller et al., 2020a).

Definition and causes of forest fires

In the Alpine context, forest fires are defined as uncontrolled fires in forested area, independent of cause, size, and fire type, including fires on clear-cuts, in young forest, coppice and vegetation at the Alpine forest border (Müller et al., 2020a; 2020b). Ignition source and moisture content of the fuel or burnable material are the most important factors determining fire ignition. Recent research found that about 90% of fires in the Alpine region are ignited directly or indirectly by humans (EFFIS Report, 2020; Müller et al., 2020a; 2020b). Main causes found are cigarettes, fires getting out of control, flying sparks from trains or during work, arson, hot ashes, and power lines. The remaining 10% of forest fires in the Alps are caused by lightning strikes (Müller, 2020b; Nachappa et al., 2020). The behaviour of wildland fires, including propagation and intensity, is highly dependent on fuel moisture content, vegetation structure and continuity, topography, and wind (Müller et al., 2020a).

Floods, wildfires, heatwaves and droughts often result from a combination of interacting physical processes across multiple spatial and temporal scales. The combination of processes (climate drivers and hazards) leading to a significant impact is referred to as a 'compound event' (Zscheischler et al., 2018). Traditional risk assessment methods typically only consider one driver and/or hazard at a time, potentially leading to underestimation of risk, as the processes that cause extreme events often interact and are spatially and/or temporally dependent (Müller et al., 2020a, 2020b; Nachappa et al., 2020). A better understanding of compound events may improve projections of potential high-impact events (Zscheischler et al., 2018).

One such event was the Leppen, Bad Eisenkappel, Carinthia, forest fire in May 2020. Persistent strong winds and extreme drought allowed the fire in 600 to 1100 meters height to burn an area of approximately 23 hectares which makes it the area wise largest forest fire in Austria since 2015 (bmlrt.gv.at, 2020; Müller, 2020b). The same forest area had already been impacted by storm "Yves" in 2018 and had been reforested. This regrowth is now destroyed and the slope very much susceptible to erosion and landslides. Mechanical measures will be necessary to stabilise the slope for coming heavy rain and snow events (bmlrt.gv.at, 2020).

Fire drivers and impacts of fires

Forest fire activity in the Alpine region will likely increase in the coming years and decades, due to climate change bringing along an increasing intensity of heat waves and drought periods. This effect will be further strengthened by the fire hazard resulting from changes in human settlement and more recreational activities in the Alps (EFFIS Report, 2020; Müller et al., 2020a; Zscheischler et al., 2018). The mountain forests in the Alps are important providers of numerous ecosystem services to the population (safety, recreation, food, and so on) and fulfil an important protection function against natural hazards (Müller et al., 2020a, 2020b).

Forest fires can initiate numerous causes for new natural hazards for inhabitants of the area, among them new avalanche-prone slopes, higher risk of rockfall, mudslides, widespread soil erosion and local changes in the hydraulic regimes or reduced water quality in lakes and rivers (Gheshlaghi et al., 2020; Müller et al., 2020a; Nachappa et al., 2020). Due to topography and exposure to higher levels of drought, forests on steep, southern slopes are especially susceptible to forest fires. This is dangerous when protective forests fall into these categories (bmlrt.gv.at, 2020; Müller et al., 2020a, 2020b; Zscheischler et al., 2018). Protective forests are of immense importance also from an economic point of view. In the Austrian Alps, protective forests of approximately 820,000 ha protect humans, buildings, and transport & energy infrastructures from avalanches, landslides, and rockfall (Steininger et al., 2015). Climate change-increased forest fires have the potential to put this protective system further at risk (Steininger et al., 2015).

Caused by rugged topography and low accessibility, firefighting is generally a difficult task in mountainous regions like the Alps (bmlrt.gv.at, 2020; Müller et al., 2020a). Given the expected, before mentioned, change in fire regime, costs of firefighting, civil protection measures, post-fire reforestation and restoration and necessary protective measures will likely strongly rise (bmlrt.gv.at, 2020; Müller et al., 2020b).

The negative impacts of forest fires in the Alps can be summarized as (the first five bullet points based on Müller et al., 2020a):

- Reduction of the protection function of mountain forests and hence increased vulnerability to natural hazards
- Loss of natural resources and decreased productivity through increased soil erosion
- High costs from firefighting and post-fire management
- Increased danger for humans and infrastructure at the Wildland-Urban-Interface (WUI)
- Increased air pollution and biogenic carbon release
- Health related impacts for affected citizens and firefighters
- Potential impact on temperature, aerosols, and precipitation by larger-scale fires

The total costs attributed to firefighting and post-fire management, but excluding necessary prevention measures, relating to forest fires in the Alpine region are estimated around 75 Mio. Euro per year (EFFIS Report, 2020; Müller et al., 2020a). Indirect costs, including potential health effects (both immediate and long-term health impacts) and potential impacts on climate-related factors such as increased biogenic carbon emissions would be much higher, but are currently not reasonably quantified (Steininger et al., 2015, 2020). Temperature impacts were recently investigated in an initial way based on satellite data as the topic of an innovative case study by Stocker and Steiner (2021).

Austrian forest fire research initiative

In 2008, the Austrian Forest Fire Research Initiative (AFFRI) was launched at the Institute of Silviculture, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria. Within the framework of the project and various follow-up projects, current and historical forest fires in Austria have been processed and imported into an online database, which now comprises more than 6000 data records. Via a public Web GIS interface, interested persons can access the information collected over the past 25 years (1993–present), compile graphics and statistics and report forest fires independently (http://fire.boku.ac.at). The database provides information on all major fire events in Austria that have taken place in the last 25 years (Eastaugh & Vacik, 2012). Collected data include date, time and duration, location, coordinates (WGS 84 system), burned area, cause of the fire, affected vegetation and tree species, fire type, fire behaviour, number of action forces, helicopters and fire brigades involved (Eastaugh & Vacik, 2012).

Canadian forest fire danger rating system

The Canadian Forest Fire Danger Rating System (CFFDRS) is a national system for rating the risk of forest fires in Canada. Forest fire danger is a general term used to express a variety of factors in the fire environment, such as ease of ignition and difficulty of control (Natural Resources Canada, 2020). Fire danger rating systems produce qualitative and/or numeric indices of fire potential, which are used as guides in a wide variety of fire management activities. The CFFDRS has been under development since 1968. Currently, two subsystems–the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behaviour Prediction (FBP) System–are being used extensively in Canada and internationally.

The diagram below illustrates the components of the CFFDRS (Fig. 2). Risk, weather, fuels, and topography provide the necessary inputs to predict fire weather, fire occurrence, and fire behaviour. Fuel moisture models are currently being developed for a range of Canadian forest types. Together, these systems predict the potential fire danger within the forest.

The European forest fire system (see next subsection below) also uses the CFFDRS system.

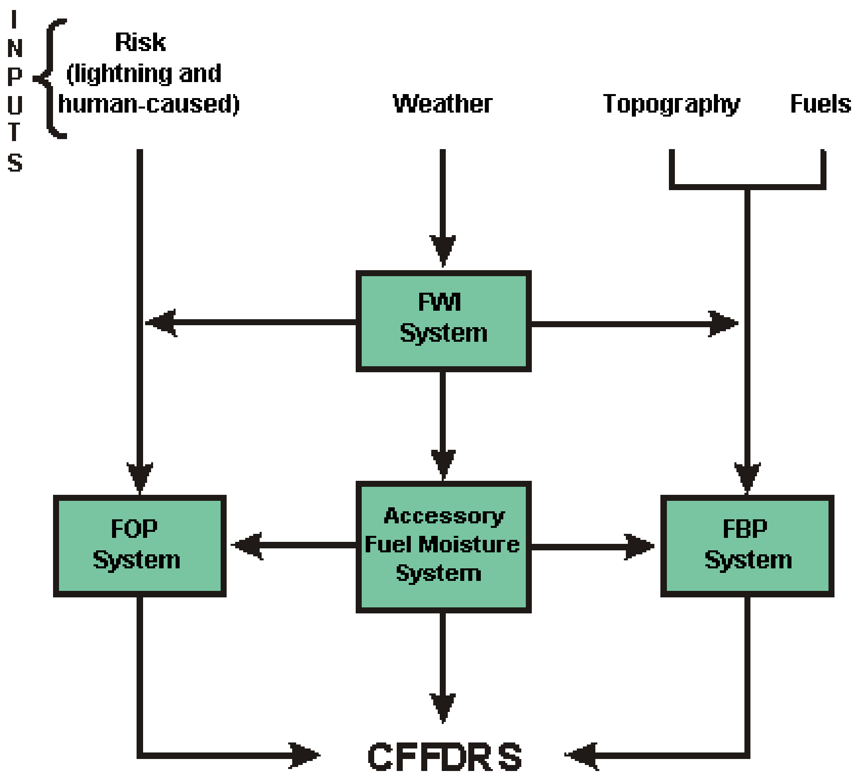

Figure 2: *The diagram illustrates the components of the CFFDRS. Risk, weather, fuels, and topography provide the necessary inputs to predict fire weather, fire occurrence, and fire behaviour. Fuel moisture models are currently being developed for a range of Canadian forest types. Together, these systems predict the potential fire danger within the forest. (Natural Resources Canada, 2020)*

European forest fire information system

The European Forest Fire Information System (EFFIS) (EFFIS Portal, 2020) supports the services in charge of the protection of forests against fires in the EU countries and provides the European Commission services and the European Parliament with updated and reliable information on wildland fires in Europe. The aim of EFFIS is to provide harmonised information on forest fires and their effects in the pan-European region. The map below shows an example for the Forest Fire Danger Index on 14th July 2020 including all forest fires in the 2020 fire season (Fig. 3). The additional map for the fire situation on 11th September 2020 shows the active fires but also gives an overview of the fire danger index for the coming 7 days (Fig. 4).

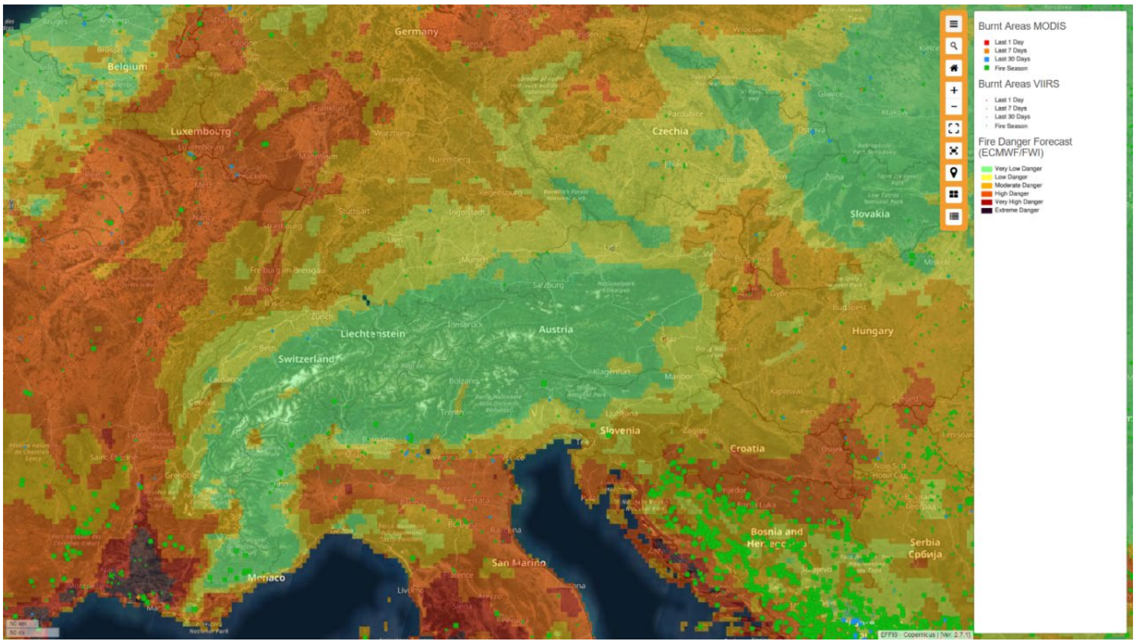

Figure 3: *Forest Fire Danger Index mapped on 14th July 2020 including all Forest Fires in the 2020 fire season as seen in EFFIS. (EFFIS Portal, 2020)*

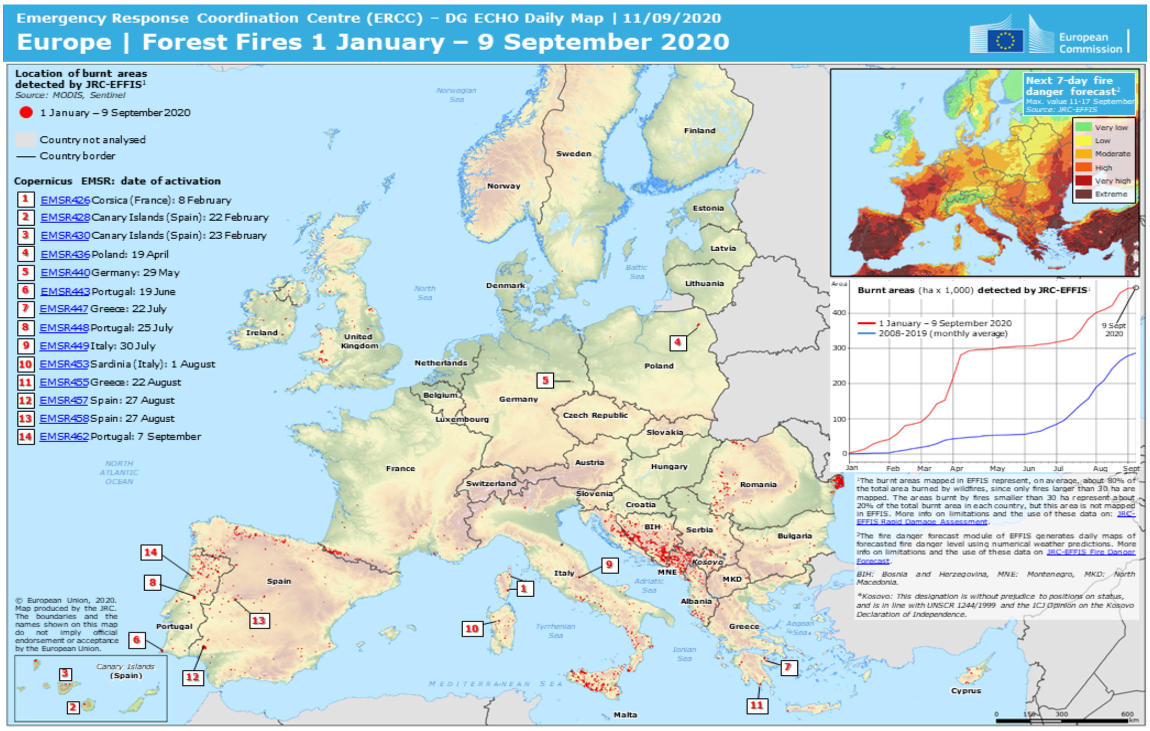

Figure 4: *EFFIS forest fire season 2020 – daily map for 11th September 2020. (EFFIS Portal, 2020)*

The annual EFFIS report for forest fires in Europe, Middle East and Northern Africa provides information about the forest fire situation including causes for fires, areas and fuel burnt (European Union, 2020). Each country provides a team that supports the report with current data. In Austria, forest fires have been noted in all months in 2019, ranging from 1 in December to 68 in July. July also had the most lightning induced fires (40) of all months (Fig. 5). Looking at the data for Austria from 1993 to 2019, burnt areas range from almost zero to 190 ha per year (Fig. 6). Numbers of fires for the same period range from 10 to 300. The average fire size ranges from 0.1 to 1.7 ha per year.

The years with the highest number of fires do not necessarily correspond with the largest burnt areas or the fire sizes. One notable exception are the years of 2002 and 2003 which were extremely hot and dry all over Austria. In these years, the numbers of fires were among the highest on record and the areas burnt were the highest on record for Austria. In 2019, as usual, most of the forest fires in Austria were ignited by anthropogenic causes (campfires, cigarettes, exhausts, and so on), complemented by a notable number of forest fires in the summer months started by natural sources (lightning) (Fig. 5).

Current efforts to manage forest fires in the Alpine region are unable to prevent the occurrence of extreme forest fire events (Müller et al., 2020a, 2020b; Nachappa et al., 2020). The implementation of a foresighted and integrated forest fire management is highly needed and should include measures on fire prevention, fire suppression and post-fire management (Müller et al., 2020a, 2020b; Nachappa et al., 2020).

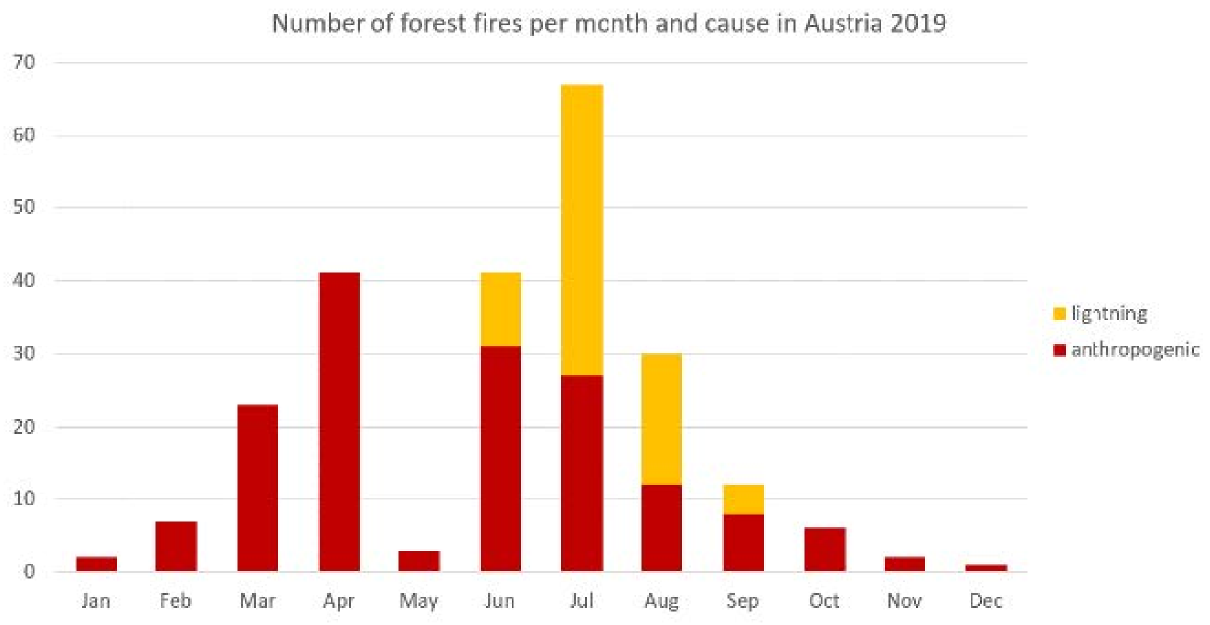

Figure 5: *Monthly number of fires caused by anthropogenic or natural sources in Austria in 2019. (EFFIS Report, 2020)*

(a)

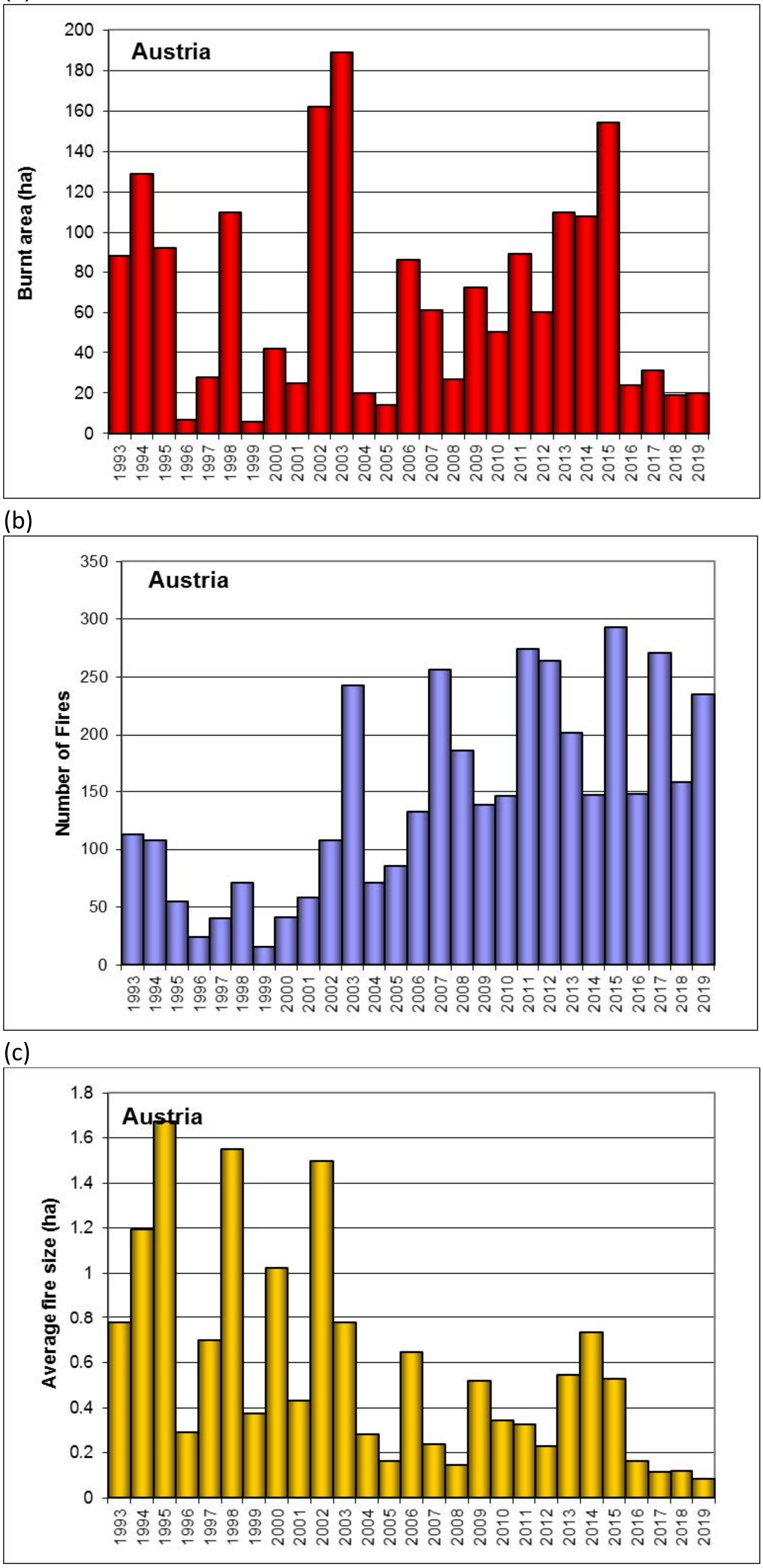

Figure 6: *Burnt areas (a), number of fires (b), and average fire size (c) in Austria from 1993 to 2019. (EFFIS Report, 2020)*

Section 2: Assessment of Future Climate Risks

In order to assess the forest fire danger in the present climate and projected changes under two climate change scenarios, the climate change assessment of the Fire Weather Index (FWI) aggregated component was computed daily from 1980 to 2100 for five models (see also Table 4 of (European Commission JRC, 2017). The daily FWI is computed for each scenario realisation based on a corresponding model. The entire time series has been estimated and the 90 % quantile of each time period has been computed. The median of the five-model ensemble is shown for each period (Fig. 7).

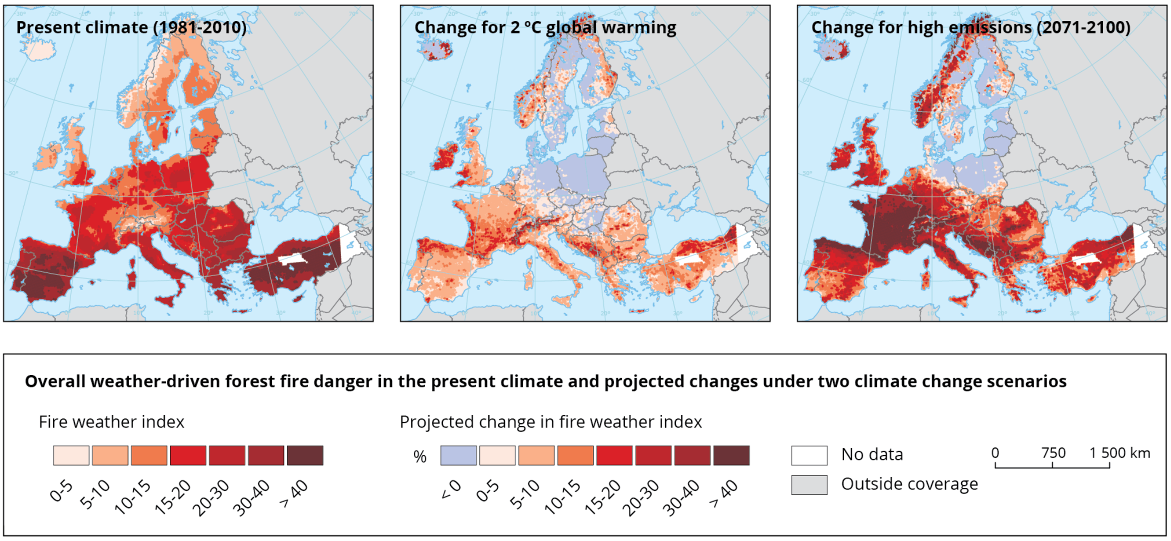

Figure 7: *Climate change assessment of the Fire Weather Index (FWI) aggregated component, computed daily from 1980 to 2100 for five models, with the daily FWI computed for each scenario realisation based on a corresponding model. The entire time series has been estimated and the 90 % quantile of each time period has been computed. The median of the five-model ensemble is shown for each period. (Adapted from Figure 8 of de Rigo, et al. 2017, Forest fire danger extremes in Europe under climate change: Variability and uncertainty. EU Publications Office, https://doi.org/10.2760/13180)*

A great share of the Alpine forests consists of Norway spruce (‘Picea abies’) or Scots pine (‘Pinus sylvestris’) (Jandl, 2020; Nothdurft & Engel, 2020; Seidl et al., 2011). Especially Spruce dominated forests at lower altitudes, e.g., in Lower Austria or Southeastern Styria, are already suffering from climate change and will become even more affected if temperature and dryness rise as expected (Jandl, 2020; Nothdurft & Engel, 2020; Seidl et al., 2011). In addition, under future altered climatic conditions, historically less fire-prone forests could be affected by large wildfires as well. This effect was already noticed for the Central-European beech mountain forests in particularly dry years over the last decades in some parts of the Alps (Maringer et al., 2016b, 2016a; Müller et al., 2020a; Müller et al., 2015; Valese et al., 2014). At higher elevations, open grasslands, which are traditionally used for grazing cattle in Austria, and shrub stands of mountain pine (Pinus mugo), often situated adjacent to forests, provide easy burnable fuel for fires (Jandl, 2020; Müller et al., 2020a; Seidl et al., 2011).

Invasive neophytes increased over the last decades and can have a detrimental effect on forest recolonization after fire, by that further increasing pressure for indigenous tree species (Maringer et al., 2012; Müller et al., 2020a). Trees under pressure are susceptible to risk from windstorms and bark beetle outbreaks which leads to even more fuel accumulation, further increasing the wildfire hazard (Jandl, 2020; Nothdurft & Engel, 2020; Seidl et al., 2011; Henner, 2007a, 2007b).

In the future, when the already current intensive use of forests as recreational areas may potentially increase, the likelihood of fire ignition through negligence and carelessness could increase as well

(Müller et al., 2020a; Müller et al., 2020b; Zscheischler et al., 2018). Rural settlements near forests can lead to increased fuel quantity and continuity, and by that potentially to a more aggressive fire behaviour and higher fire intensity (Müller et al., 2020a).

Finding a good balance for future forest fire management between actions on fire prevention, fire suppression and post-fire management is a difficult, yet important task (Jandl, 2020; Müller et al., 2015, 2020a, 2020b; Nachappa et al., 2020; Seidl et al., 2011). According to Müller et al. (2020a), today the greatest focus and most money is spent on fire suppression. They also found that especially in the Alpine region, too little attention is paid to forest fire prevention and not enough measures are present. Due to the assumed intensified fire regime over the next decades, improved pre-fire management will be crucial (Müller et al., 2020a, 2020b).

Integrated fire management in the Alps is affected by two main challenges. On one side, the changing environment (especially climate change) increases the need for integrated fire management and on the other side the changing socio-economic conditions (such as human settlement or intensified recreational activities) show the need for professionally and inclusively managing fire risk (Henner, 2007a, 2007b; Müller et al., 2020a, 2020b). According to the EUSALP report, tourism and recreational activities are the most important social factors for forest fires in Austria (Müller et al., 2020a).

Climate change as the major long-term driver

It is well known that the Alps are among the most affected regions by climate change (Dupire et al., 2017; Gobiet et al., 2014; Gobiet & Kotlarski, 2020; Müller et al., 2020a). Over the last decades, several drought and temperature records occurred in the Alpine region, among them the driest July ever recorded in 2013 in Austria or the extremely hot summer in 2015 (Gobiet & Kotlarski, 2020; Müller et al., 2015; Müller et al., 2020a). This drought led to anomalies in the current forest fire regime (Müller et al., 2020a). Current climate scenarios assume a temperature increase of +2 to +5 °C in the coming decades, if no suitable climate mitigation measures are taken (Dupire et al., 2017; Gobiet et al., 2014; Gobiet & Kotlarski, 2020; (Müller et al., 2020a). Recent research found that precipitation is likely to increase in winter, but with less snow by that increasing the potential for spring drought, while longer heat waves and droughts are most likely in summer (Gobiet et al., 2014; Gobiet & Kotlarski, 2020; IPCC, 2014; Trnka et al., 2016). This will potentially result in more days with high fire danger in the Alpine region (Müller et al., 2020a).

Drought can induce higher tree mortality rates, especially for trees not adapted to changing climate, by that further increasing fire hazard (Allen et al., 2010; Anderegg et al., 2015; Choat et al., 2012, 2018). It is also expected that extreme precipitation events will probably increase (Dupire et al., 2017; Gobiet & Kotlarski, 2020). This will likely result in fluctuations between very dry and very humid conditions in the future. Tactics of fire brigades and action forces will be challenged, and plans will likely have to be adapted (Dupire et al., 2017; Gobiet & Kotlarski, 2020; Müller et al., 2020a). Reduced snowfall in winter will likely result in lower spring snowpacks, both in surface and in duration, which may increase the areas exposed to potential winter and spring fires (Müller, 2020a). This change is already notable and may become a greater problem in the future (Müller, 2020b).

The FIRIA project (Fire Risk and vulnerability of Austrian forests under the impact of climate change) assessed the future occurrence of forest fires in Tyrol, Austria (Müller et al., 2020a). The Canadian Build-Up Index (BUI), a sub-component of the Fire Weather Index (FWI) that correlates well with the distribution of summer forest fires in Austria, was used to analyse the number of days in the highest BUI classes (Arpaci et al., 2013; Müller et al., 2020a). Model calculations by regional models (ALADIN, RegCM3 and REMO) estimated that the number of days with high forest fire danger might increase regionally by more than 40 days until 2100 (Arpaci et al., 2013; Müller et al., 2020a). The project also found that in the future, even areas that have previously not shown any relevant risk will be increasingly endangered (Sass & Sarcletti, 2017). Unfortunately, this applies in particular to protection forests which may cause further danger to humans (Müller et al., 2020a; Sass & Sarcletti, 2017). The results of this Tyrolean study may be transferable to other Alpine regions as well (Müller et al., 2020a).

According to recent research, the before mentioned change of the fire regime in the Alpine region will probably occur within the next decades (Gobiet & Kotlarski, 2020; Müller et al., 2020a, 2020b; Sass & Sarcletti, 2017). As shown by Müller et al. (2020a; b), a rapid and disruptive change is more likely than a steady one, which means that some low fire seasons may be followed by a very intense one. It is likely that weather conditions like in 2003, 2012 and 2019 will happen much more often by the years 2030/2040 (European Environment Agency, 2019). While it is quite clear and already visible that the Southern Alps will encounter more and more dryer and by that fire prone conditions, the tendency for the Northern Alps is still somewhat uncertain (Müller et al., 2020a). Many indirect effects and tipping points, e.g., loss of arctic ice shield together with changed atmospheric circulation pattern in the northern hemisphere, may influence the situation worldwide, but also in the Alps (Dupire et al., 2017; Gobiet & Kotlarski, 2020; Müller et al., 2020a).

Research found that the number of lightning strikes in Central Europe shows a decreasing trend for several years, but the number of lightning induced forest fires shows a rising trend in most of the Alpine countries (Conedera et al., 2009; European Union, 2020; Müller et al., 2020a, Moris et al., 2020). A recent study by Müller et al. (2013) showed that high lightning activity does not correlate with more lightning induced forest fires, but local drought can lead to more ignitions despite a lower amount of lightning strikes.

Data analysis from recent years showed that current fire seasons are shifting and expanding, with potentially new fire seasons developing (Müller et al., 2015, 2020a, 2020b). Particularly late autumn and winter fires, caused by drier conditions and less snowpack, may become more relevant in the future, as the years 2011 (Schunk et al., 2013), 2015 and 2018 have already shown (Müller et al., 2020a). In contrast to that, also emphasising the changing nature of climatic conditions, in2020, all Austrian forest fires occurred before June which was caused by the wetter summer and autumn weather (Müller, 2020a; 2020b).

Socioeconomic drivers of the fire regime

Apart from climate change, the most important driver of future fire regimes is the human influence (Müller et al., 2020a). Due to the before mentioned stronger recreational use of the forested areas and higher numbers of visitors, the amount of potential fuel ignition sources is increasing as well (Müller et al., 2020a, 2020b). Tourist regimes and activities are changing because of changes in the vegetation season (Müller et al., 2020a). In addition, rural abandonment and declining management measures in private forests and the associated increase in deadwood can increase the intensity of uncontrolled fires and the risk of crown fires (Agee et al., 2000; Müller et al., 2015; Müller et al., 2020a).

Assessment of factors affecting future forest fire risks in Austria

An assessment of factors affecting future forest fire risks in Austria was conducted. Table 1 below shows the factors affecting forest fire risk, grouped into climatic, biophysical and geographical factors plus the causative factors of fire ignition. The risks, as indicated by arrows, are mostly increasing with some factors, while staying unaffected or just slightly increasing with a limited number of factors. The unaffected factors are associated with the geographical factors slope, exposure and distance to settlement (Müller et al., 2015, 2020b).

Another factor which will likely not change will be the fuel type (Müller et al., 2020b). In Austrian forests, there is generally too much fuel because so-called “prescribed burning” is not common, as is the case in countries with large forest fire risk (Jandl, 2020). The climate related factors likely have an increasing fire risk (Dupire et al., 2017; Gobiet & Kotlarski, 2020; Jandl, 2020). Wind will have an indirect impact on forest fires in the sense of increasing the strength of fires which are already burning (Müller et al., 2020b). There is also indication that the causes for ignition will increase (Müller et al., 2020a, 2020b). Lightning strike induced fires are increasing already, and this will like worsen with increasing heat, drought, wind and thunderstorms under climate change (Conedera et al., 2009; Moris et al., 2020; Müller et al., 2020a). Human pressure on nature is generally increasing, with a steadily increasing number of people spending time in the forests (Müller et al., 2020b).

Table 1: *An assessment of factors affecting future forest fire risks in Austria. The risks, as indicated by arrows, are mostly increasing, with a limited group of risks estimated to stay unaffected.*

Factors affecting forest fire risks in Austria		**Future risks tendency**	**Assessment key references**
Climatic factors	Temperature	↑	Müller et al., 2015, 2020b; Dupire et al., 2017; Gobiet & Kotlarski, 2020; Jandl, 2020
	Precipitation	↑	Müller et al., 2015, 2020b; Dupire et al., 2017; Gobiet & Kotlarski, 2020; Jandl, 2020
	Relative humidity	↑	Müller et al., 2015, 2020b; Dupire et al., 2017; Gobiet & Kotlarski, 2020; Jandl, 2020
	Wind	↗	Müller et al., 2015, 2020b; Dupire et al., 2017; Gobiet & Kotlarski, 2020; Jandl, 2020
Biophysical factors	Fuel moisture	↑	Müller et al., 2015, 2020b; Arpaci et al., 2013; Sass & Sarcletti, 2017
	Fuel type	↔	Müller et al., 2015, 2020b; Arpaci et al., 2013; Sass & Sarcletti, 2017
Geographical factors	Slope	↔	Müller et al., 2015, 2020b; Sass & Sarcletti, 2017
	Exposure	↔	Müller et al., 2015, 2020b; Sass & Sarcletti, 2017
	Distance to settlements	↔	Müller et al., 2015, 2020b; Agee et al., 2000; Moris et al., 2020
Causative factors of ignition	Human interference	↑	Müller et al., 2015, 2020b; Agee et al., 2000; Moris et al., 2020
	Lightning from thunderstorms	↑	Müller et al., 2015, 2020b; Conedera et al., 2009; Moris et al., 2020

Section 3: Conclusions and Recommendations

This report found some important points to conclude with, and to base recommendations upon, which will be synthesized below.

Conclusions and perspectives

Inspecting the risks for forest fires from data over the last 20 years at the district level in Austria, through bringing the wildland fires into context with the forests present for risk estimation (Müller, 2020c), it becomes obvious that there are some hotspot regions of fire activity (Fig. 8). This risk will likely increase over the next decades as evidenced by recent research (Müller et al., 2020a) and explained above in Section 2.

The forest fire risk in some parts of the Alps and the Alpine forelands may even become very high (in a five-classes ranking from "very low" to "very high"), with only small parts remaining at a very low risk (see also Müller et al., 2020a; 2020b). This enhanced risk is caused by a combination of climatic and biophysical factors shown before in this report (Table 1 on the previous page above). While some of the factors are expected to have no relevant change impact on future forest fire risk, climate change-driven factors will increase the related overall risks significantly.

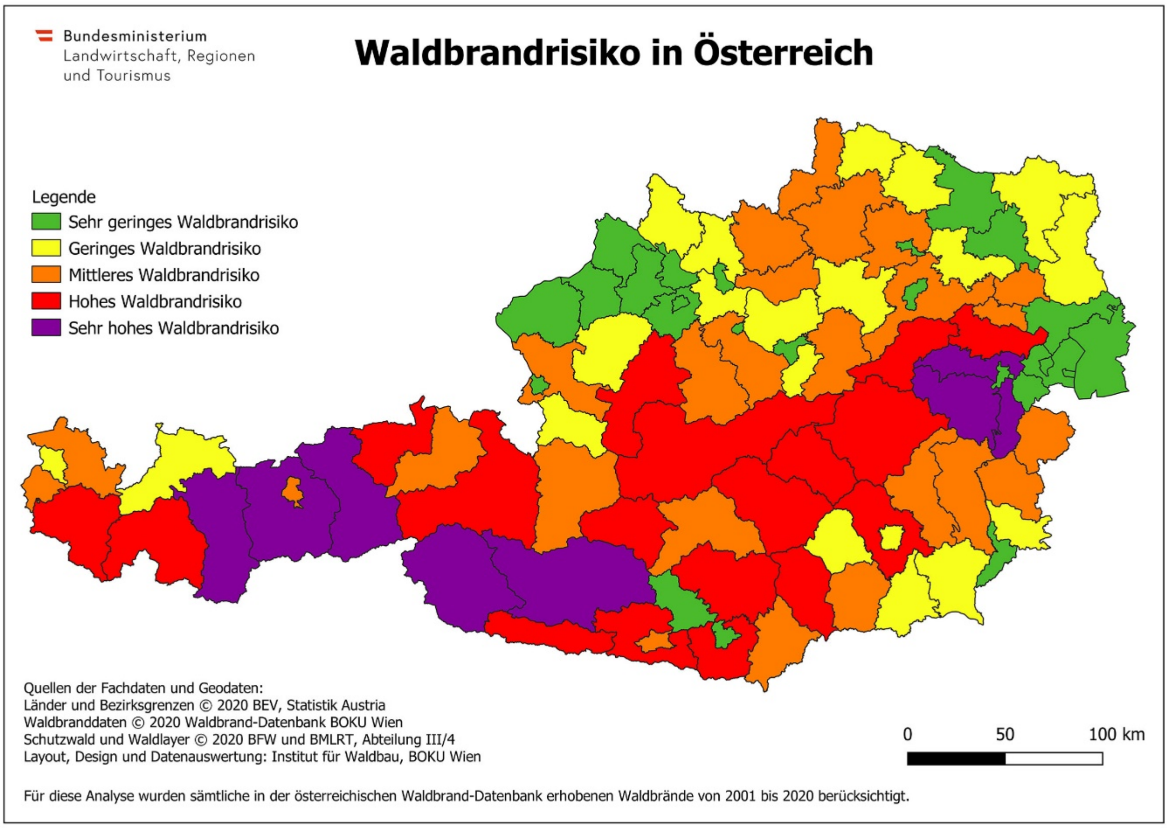

Figure 8: *Regional risk assessment map of estimated forest fire risk in Austria, based on 2001-2020 fire data combined with forest geodata (language German). Source: Inst. of Silviculture, BOKU Vienna (Müller, 2020c)*

While there is no direct way to change the risk caused by climatic factors like heat and drought, there are some ways to move with adaptation and mitigation measures towards this direction.

Using tree species, which can adapt better to climate change could somewhat reduce the risk for large forest fires (Jandl, 2020; Seidl et al., 2011). This effect could either be direct (with trees being healthier and by that holding more water, also in the soil) or also indirect (Allen et al., 2010; Choat et al., 2018). On the latter, forests which are heavily affected by bark beetle infestations, caused by species which are not adaptable to climate change, are much more prone to burning than healthy stands (Choat et al., 2012, 2018).

In lieu of the possibility to change the risk directly, one must drive forward measures to reduce global climate change and limit global warming by climate change mitigation measures, which foremost requires a rapid and sustained reduction of anthropogenic greenhouse gas emissions (IPCC, 2014; Brunner et al., 2017; Dupire et al., 2017; Gobiet & Kotlarski, 2020; Steininger et al., 2020).

Human interference, primarily due to negligence and carelessness, was found as a significant cause for ignition. This is mostly caused by outdoor activities in forests, which are already under stress (Müller et al., 2020a).

Recently also important research was undertaken in Austria to develop a framework tool to analyse the inherent causes, risks, and areas affected by forest fires. This tool aims to enable detailed fire risk analyses, which will be an important task over the coming decades under climate change.

IDFS as a key tool and starting basis for further study in Austria

As summarized in this report, the European Alps experienced in recent years higher temperatures, more heatwaves, and more severe wildfires (Müller et al., 2020a; 2020b). Improving fire danger assessment, especially for sensitive ecosystems often found in the Alps, is a core element of future-oriented fire management strategies in the face of climate change. While meteorological systems are common to predict fire danger in many countries, other factors such as vegetation, topography, lightning occurrence, and human impact are generally not considered (Müller et al., 2020b).

A new Integrated forest Fire Danger assessment System (IFDS) for the Alpine country Austria was hence introduced by Müller et al. (2020b). As described therein, this IFDS includes i) daily fire weather index data, ii) a countrywide hazard map for fire ignition through human activities, iii) a lightning fire hazard map, iv) a high-resolution fuel type map, and v) a topography-based estimation of the fire hazard (see Figures 9 to 11). At risk class "high", as seen in Southeastern Styria on April 18, 2020 (Fig. 11), any open fire will cause a forest fire that is prone to fast development, growth, and widespread burning areas.

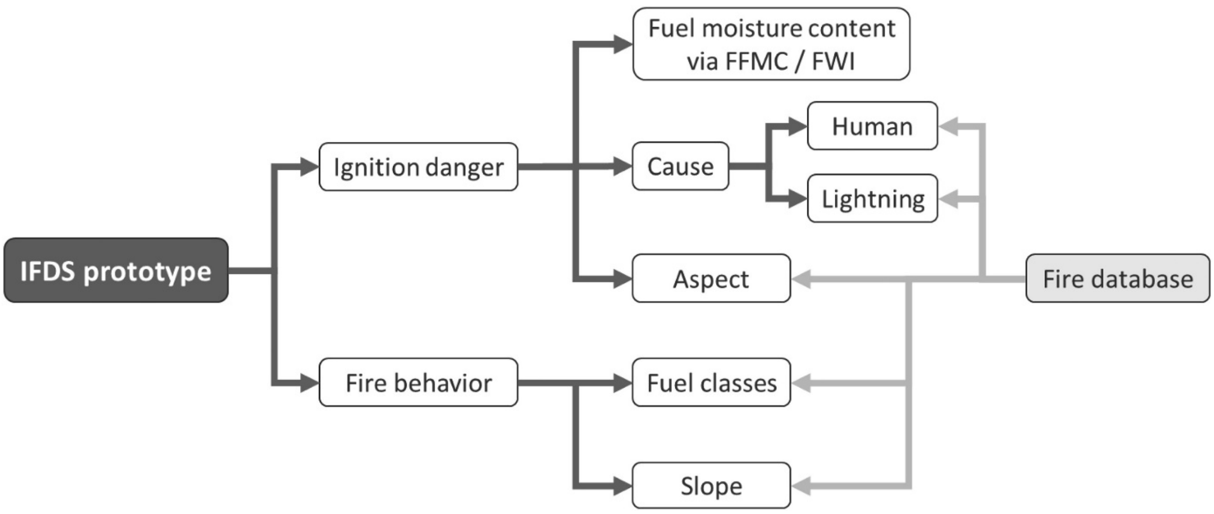

Figure 9: *Schematic illustration of the IFDS prototype and the data layers included. (Müller et al., 2020b)*

The IFDS is currently available as a prototype tool on a (password-protected) server under https://www.waldbrand.at. Exemplary screenshots of the Web-GIS application are shown in Figures 10 and 11. The coloured maps show the Fine Fuel Moisture Code (FFMC) danger classes that can range from “very low” to “very high” danger; in the second example case (Fig. 11) it is the Southeastern Styria region that reaches high danger.

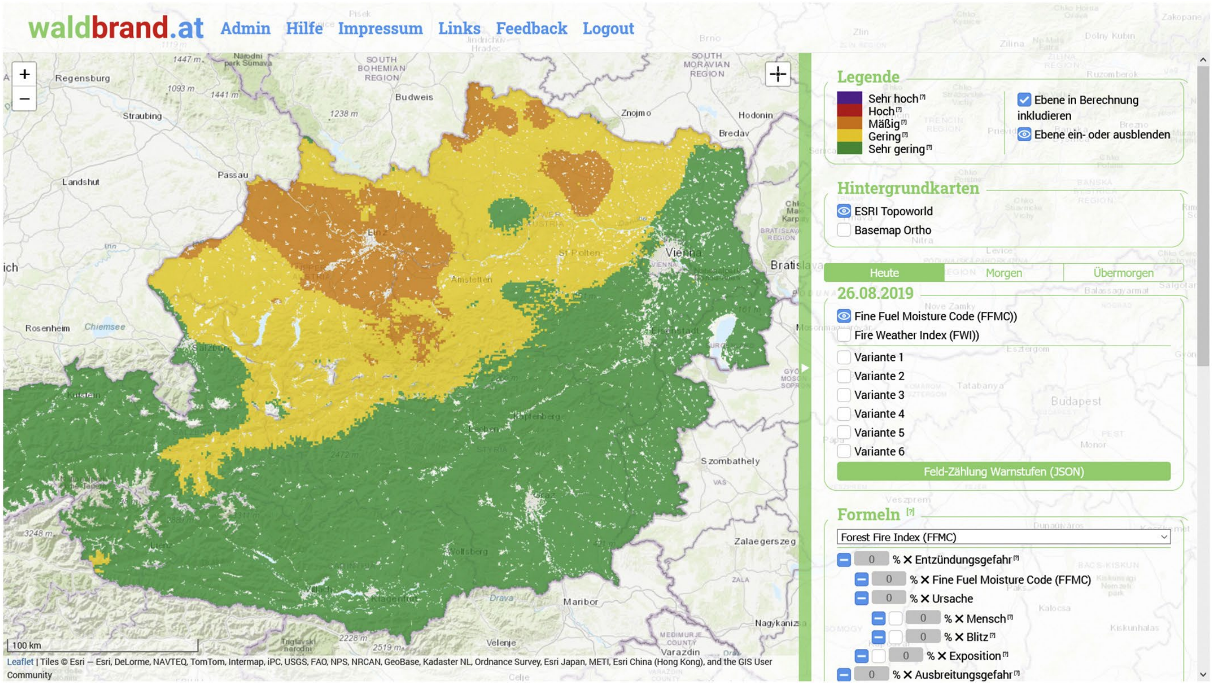

__Figure 10:__ Screenshot of the IFDS Web-GIS application (language German). The coloured map shows the Fine Fuel Moisture Code (FFMC) danger classes for August 26, 2019 in the north of Austria. Green coloured fields mean a “very low” fire danger, yellow a “low” one, and orange a “moderate” one. (Müller et al., 2020b)

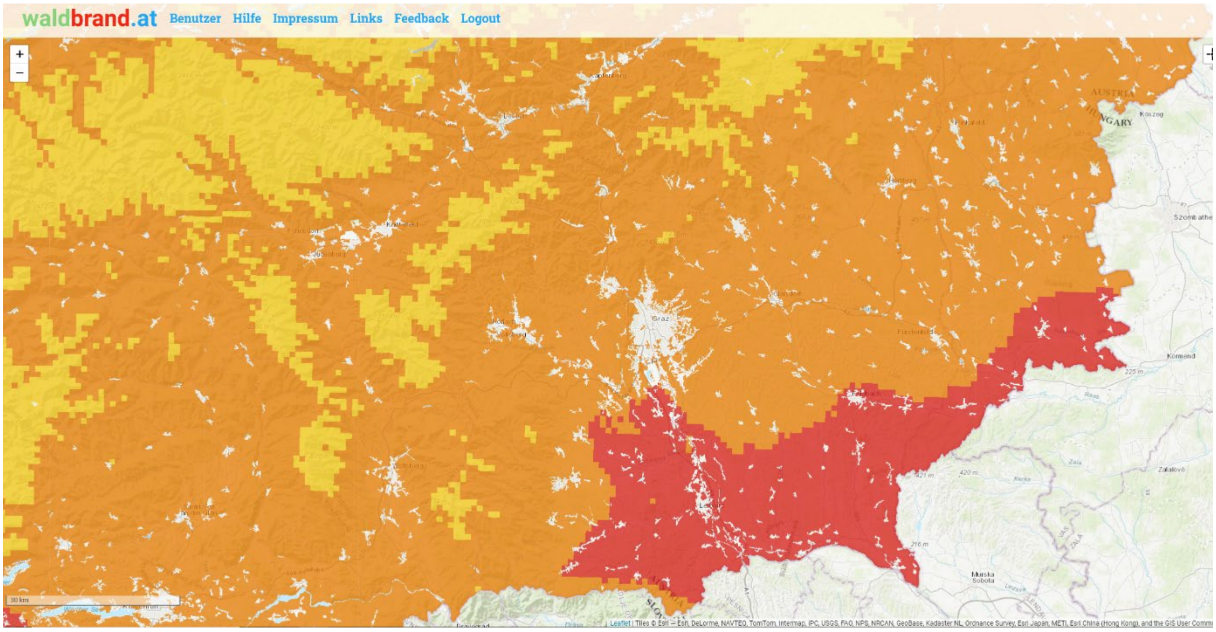

__Figure 11:__ Screenshot of the IFDS Web-GIS application (language German). The coloured map shows the Fine Fuel Moisture Code (FFMC) danger classes for April 18. 2020, with high danger in Southeastern Styria. Yellow denotes a “low” fire danger, orange a “moderate” one, and red a “high” one. (Müller et al., 2020b)

Recommendations for further studies

This study recommends taking the IFDS tool forward as a main basis for future intensified research on the topic in Austria. Currently, as per February 2021, the prototype tool is evaluated by scientific users and is set to be improved over the coming year. A tool like this that can help understand all major underlying factors, also in changing combinations, will be invaluable for the development of adjustments and measures for mitigating and adapting to forest fire risks under climate change.

More specifically, but still just as a broad guidance as available from this initial study, we recommend the following lines of further studies and implementation actions:

- Analyse more closely the occurrence, and the underlying causative factors, of dangerous ignition situations
- Analyse and better quantify the risks for humans and ecosystems, such as health risks and risks of habitat losses, and the potential for adaptations to more resilient forestry
- Improve and widen the use of more climate change-robust forest species and forest management practices
- Increase climate change mitigation efforts to reduce global warming as the fundamental driver of the widespread increase also of forest fire risks

Furthermore, in a direction oriented more towards progress in basic research on potential indirect impacts, it would be of interest to study the impact of forest fires on the aerosol amount and composition, as for example well measurable in Austria by the long-term background aerosol observing facilities at the Sonnblick Observatory (https://www.sonnblick.net). Likewise, it would be interesting to study potential impacts on precipitation formation, through the perturbations induced in the aerosol that also acts as a supply for cloud condensation nuclei, as well as the impacts on temperature from the substantial heat energy released to the atmosphere.

Finally, improved quantification of the related biogenic carbon emissions, primarily of the increased carbon dioxide emissions to the atmosphere from the burnt forest biomass, will be essential for reliable future emission estimates for the land use and forestry sector, as a potentially growing complement to the energy-use and industry emissions from burning fossil fuels.

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