Cartography M.Sc.

Master thesis

Mapping and Analysing Human Exposure to Wildfires in a Central European Context

Evripidis Avouris

Technical University of Munich

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

TECHNISCHE UNIVERSITÄT DRESDEN

ITC
UNIVERSITY OF TWENTE.

2023

TECHNISCHE UNIVERSITÄT DRESDEN

Statement of Authorship

Herewith I declare that I am the sole author of the thesis entitled

„Mapping and Analysing Human Exposure to Wildfires in a Central European Context“

which has been submitted to the thesis assessment board today.

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Dresden, 06/10/2023 Avouris, Evripidis

Abstract

Climate change has been causing a noticeable rise in disastrous wildfires across Southern Europe. However, even Central Europe is not immune to such destructive events as a recent wildfire burned significant parts of two National Parks in Germany and Czech Republic. This acted as a warning for the scientific community and local stakeholders, that demonstrated the need to adapt to this new reality. In this context, this thesis attempts to create a wildfire preparedness map, for an area that includes the two affected National Parks as well as two adjacent Conservation Areas. This map aims to visualize the degree of exposure of human settlements to wildfires in this area. This map takes the form of a web-based interactive map. To that end, nine wildfire scenarios were devised, based on varying wildfire durations and weather conditions. The map was tested with the general audience for its usability and with stakeholders for its usefulness. Validation tests were also conducted using historical wildfire data for the study area.

Acknowledgements

I would like to thank the following people, for lending me their support:

My first supervisor JProf. Dr. Matthias Forkel, who has provided me with his invaluable expertise in the field of environmental remote sensing throughout this thesis, and who helped me find respondents for my questionnaires and translate my questions. My second supervisor Christopher Marrs, who helped me develop my ideas into clear and concise written arguments, and who helped me not lose focus of my goals. Kristina Beetz who blazed the trail of this thesis, by providing the fuel models map she developed in her own MSc thesis, and who helped me understand fuel models and their importance in wildfire science. Charles Mchugh of the Missoula Fire Sciences Laboratory provided important support in helping me understand FlamMap in depth by answering my many emails. Andrea Binn of TU Wien, who proofread my questionnaires and persuaded me to significantly shorten them. The members of the Junior Professorship in Environmental Remote Sensing of TU Dresden, who attended my colloquium presentations, and gave me insightful opinions on how to proceed with my work. Erico Kutchartt of the University of Padova who expressed interest in my work and assisted me in locating canopy data. Falk Böttcher for providing me with valuable literature which helped me better understand the WBI index. The Landratsamt of Sächsische Schweiz-Osterzgebirge who provided me with data on the locations of fire stations in my study area. Markéta Poděbradská who helped me better understand the process of fire modelling in a Central European context from an expert's perspective. Sacha, who helped me make my graphs look amazing, and who provided valuable motivational support which helped me move forward, whenever I was stuck with my modelling. My friends from the 11th Cartography intake with whom I shared many a laugh even when we were all struggling, and who have been with me on this cartographic journey across Central Europe. My family, who supported me even if they were far, and who brought me the warmth of our home over video calls. Monika, who helped me capture some of the magic of her maps by helping me ameliorate mine, and who was always there for me, in the difficult and in the happy parts of this adventure. Finally, Charlie: even if some years have passed since you helped me last, I realised in the writing process of this thesis that the argumentation skills you had taught me are not yet lost.

Table of Contents

Statement of Authorship iii
Abstract v
Acknowledgements vii
Table of Contents 1
List of Figures 4
List of Acronyms 6
1 Introduction 7
1.1 Motivation 7
1.2 Study Area 8
1.3 Related Work 10
1.3.1 Hazards, Disasters and Wildfires 11
1.3.2 Exposure, Vulnerability and Coping Capacity 12
1.3.3 Disaster-related Maps 14
1.3.4 Wildland Urban Interfaces 16
1.3.5 Fire Modelling 18
1.3.6 Fuel Types & Fuel Models 20
1.4 The Aim of this Study 24
2 Method of Work 25
2.1 Creating the Fire Modelling Landscape 25
2.1.1 Elevation, Slope and Aspect 25
2.1.2 Fuel Models Map 25
2.1.3 Canopy Cover 26
2.1.4 Canopy Height, Crown Base Height and Crown Bulk Density 26
2.2 Burn Probability and Flame Length 27
2.3 Creating Wildfire Scenarios 28
2.3.1 Fire Duration 29
2.3.2 Ignition Locations 30
2.3.3 Fire Weather 31
2.4 Fire Weather (Fuel Moisture) 31
2.4.1 Fuel moisture Content 31

2.4.2 Dead VS Live Fuels 32
2.4.3 Fuel Moisture in FlamMap 32
2.5 Fire Weather (Wind) 33
2.5.1 Wind and Wildfires 33
2.5.2 Wind in FlamMap 34
2.5.3 Calculating Wind for Different Scenarios 34
2.5.3.1 Acquiring Wind Data 34
2.5.3.2 Selection of Classification Method 34
2.5.3.3 Wind Data Processing 35
2.6 From Modelling Runs to Bivariate Rasters 38
2.6.1 Workflow Introduction 38
2.6.2 Weighted Mean Rasters 40
2.6.3 Bivariate Raster Algorithm 43
2.6.3.1 Selection of Colours 47
2.7 Adding Exposure and Vulnerability to the Raster 48
2.7.1 Settlements 48
2.7.2 Support Capability Indicators 49
2.7.2.1 Fire Stations 49
2.7.2.2 Transportation Infrastructure 49
2.8 Creating a Web-Based Interactive Map 50
2.8.1 Map Type and Tool Selection 50
2.8.2 Interactive Map Features 51
2.9 Map Evaluation Questionnaires 52
3 Results and Evaluation 55
3.1 Static Map 55
3.2 Interactive Map 58
3.3 Modelling Evaluation 60
3.3.1 Evaluation of Modelling Scenarios 60
3.3.2 FlamMap Evaluation 64
3.4 Questionnaire Results Evaluation 67
3.4.1 Usability Questionnaire 67
3.4.2 Usefulness Questionnaire 71
4 Discussion and Future Work 75

4.1 Fuel Models ... 75
4.2 Canopy Data and Crown Fires ... 76
4.3 Wildfire Scenarios and Wildfire Modelling in FlamMap ... 76
4.4 Usability, Usefulness, and Involving Local Stakeholders ... 78
5 Conclusions ... 81
References ... 83
Appendix A: Illustrations ... 95
Appendix B: Usability Questionnaire ... 104
Appendix C: Usefulness Questionnaire (English Version) ... 110

List of Figures

Figure 1: Study Area. The study area consists of 2 National Parks and 2 Conservation Areas in Czech Republic and Germany, and it experienced a large wildfire that burned areas of both National Parks in 2022. 9

Figure 2: Land Use map for thesis study area. Land Use data derived from (Copernicus Global Land Service, n.d.). Grouping of forest land cover layers based on documentation by (Buchhorn et al., 2020). 17

Figure 3: List of fuel types presently included in the Canadian Forest Fire Behaviour Prediction (FBP) System (Wotton et al., 2009, p. 2) 21

Figure 4: Fuel model map Elbe Sandstone Mountains pre-fire 2022 (Beetz, 2023, p. 42) 23

Figure 5: Flame Length, retrieved from *4.1 Flame Length | National Wildfire Coordinating Group* (n.d.) 28

Figure 6: Map showing the ignition locations used in all FlamMap modelling runs. The location of the Lichtenhain-Mittlendorf meteorological station, from which all weather data was derived is also displayed. Finally, the municipalities that are in and around the study area (for each of which a daily Forest Fire Risk Index is calculated), as well as the one chosen to classify winds are visualised. 29

Figure 7: Prominence of each wind direction for each of the three datasets with hourly winds. The three most prominent wind directions for each WBI value are highlighted. 36

Figure 8: The mean speed of every wind direction for each of the three hourly winds' WBI datasets is shown here. The mean speeds of the three most prominent wind directions for each WBI value are highlighted. 36

Figure 9: Wind roses for winds that occurred on days with WBI = 3, 4 and 5 in Bad Schandau from 15.02.2009 until 12.08.2022 37

Figure 10: Workflow for the derivation of a bivariate raster for a wildfire scenario. Here, the example of a wildfire taking place under conditions WBI = 5 and which lasted 3 days is presented. 39

Figure 11: Flame Length classes and suppression difficulty. Adapted from Sá et al. (2022, p. 3933) 41

Figure 12: Derivation of weighted mean BP raster from the three BP rasters of prominent winds. This example showcases the scenario of a wildfire lasting 3 days under WBI = 5 conditions. 42

Figure 13: Figure 14: Derivation of weighted mean FL raster from the three FL rasters of prominent winds. This example showcases the scenario of a wildfire lasting 3 days under WBI = 5 conditions. 43

Figure 15: Combination of FL and BP classes and the respective bivariate raster value that is assigned. 44

Figure 16: Bivariate raster legend. The bivariate raster's possible cell values are assigned to the respective colours used to represent them. 45

Figure 17: Derivation of bivariate raster from BP and FL rasters. This example showcases the scenario of a wildfire lasting 3 days under WBI = 5 conditions. 46

Figure 18: Preliminary version of bivariate raster's legend. 48

Figure 19: Interactive web map layers and layer descriptions. 51

Figure 20: User Experience honeycomb developed by Morville (2004) 52

Figure 21: Static exposure map for wildfire scenario WBI = 5, duration = 3 days. Actual map size is A0. 56

Figure 22: Detail from static map (WBI = 5, duration = 3 days), showing villages of Hřensko, Mezná, Janov and their surroundings. 57

Figure 23: Zoomed-in legend of static map. 58

Figure 24: Interactive web map features. 59

Figure 25: Interactive web-map example usage. 60

Figure 26: 'Historical wildfire data description for burned area perimeters larger than 100 ha, from 2001 to 2019: (a) probability of ignition, (b) frequency of burning, (c) fire sizes, and (d) percentage of the number of fire perimeters and burned area perimeters by classes of area'. Derived from Sá et al (2022, p. 3920). 61

Figure 27: Map matrix comparing the extent of the 2022 study area wildfire, with the extent of nine FlamMap-modelled wildfires, each considering a wildfire scenario devised in this thesis. 63

Figure 28: Time series showing wind velocity (speed and direction), as well as daily WBI values throughout the duration of the 2022 study area wildfire. 64

Figure 29: Comparison of three daily FlamMap runs with satellite-detected fires. 66

Figure 30: User profiles of usability questionnaire respondents. 68

Figure 31: Responses showing difficulty of completion of interactive map activity. 69

Figure 32: Answers to the questions regarding understanding of the map's colours. 70

Figure 33: Responses to the question concerning ease of understanding of the legend............70

Figure 34: Usefulness questionnaire respondents' ranking of interactive map layers. 72

List of Acronyms

BP	Burn Probability
CDC	Climate Data Centre
FL	Flame Length
MODIS	Moderate Resolution Imaging Spectroradiometer
MTT	Minimum Travel Time
OSM	OpenStreetMap
THW	Bundesanstalt Technisches Hilfswerk (Federal Agency for Technical Relief)
VIIRS	Visible Infrared Imaging Radiometer Suite
VOST	Virtual Operations Support Team
WBI	Waldbrandgefahrenindex (Forest Fire Risk Index)
WUI	Wildland Urban Interface

1 Introduction

The thesis begins by looking at the motivation behind this study. It will then examine work related to this subject, to position this thesis amongst the scientific fields from which it draws inspiration. Finally, the aim of the thesis will be presented, in the form of two research questions.

1.1 Motivation

Wildfires are uncontrolled fires occurring in a forest, grassland, brushland, or land sown to crops (*Wildfire | Definition & Facts | Britannica*, 2023). People coming from southern European countries, such as the author, may witness many wildfires during their lifetimes. These tragic events occur every summer and leave behind a trail of cinders, destruction and sadly mourning the loss of lives. In August 2023, the largest wildfire in the EU since 2000, when the European Forest Fire Information System (EFFIS) began recording data occurred in northern Greece (European Civil Protection and Humanitarian Aid Operations, 2023). Moreover, as recently as in 2017, Greece suffered 101 fatalities in its deadliest wildfire in history (Vacca et al., 2020). However, Greece is not the exception in terms of recent deadly wildfires: Spain, Italy and Portugal also face this ever increasing threat; Portugal for example, also recently experienced its deadliest wildfire in recorded history, the 2017 Pedrógão Grande fires, which claimed the lives of 65 people (Vacca et al., 2020).

Environmental Remote Sensing has made several contributions to the study of wildfire risk assessment and management (Chuvieco et al., 2014), (Chuvieco et al., 2020). Research in this field has shown that the rise in number of destructive wildfires extends far beyond the Mediterranean basin; it is a global and escalating phenomenon related to climate change (Bowman et al., 2017). Due to climate change, forest wildfires that affect areas where human civilization intermingles with natural vegetation –such as the aforementioned ones in Greece and Portugal–, the so-called wildland–urban interface (WUI), are on the rise, even in temperate European countries, which have historically been spared from destructive WUI wildfires (Heisig et al., 2022).

However, in contrast to Mediterranean countries, European countries with a temperate climate –such as those in Central Europe– both the vegetation firefighting capacities as well as society's awareness of fire-induced disasters are in an early stage of development, making wildfires in such places potentially much more difficult to handle (Heisig et al., 2022). This situation creates the need of informing the public of Central Europe of the potential danger they and their properties could be in, due to wildfires. Moreover, the stakeholders responsible for dealing with wildfires in Central Europe, such as firefighters, land mangers such as national park administrations and relevant government agencies, should be aware of the potential danger that areas under their jurisdiction are increasingly in. In the words of Xanthopoulos (2009): "The people in fire prone countries need to be educated about forest fires, about the need and measures to prevent them, the risks they pose and the ways to protect themselves and their property” (p. 74).

Part of this education, entails making stakeholders responsible for the livelihood of people residing in WUIs aware of the danger they could face in case of a wildfire: This MSc thesis aims to bring awareness to people living in such a spatial context by visualising the potential exposure of settlements to wildfires. The resulting visualisation integrates the locations of fire stations and road networks, two types of infrastructure that are of vital importance to the suppression of fires; this integration aims to make the user of the visualisations capable of gaining a general understanding of a settlement’s proximity and access to such crucial infrastructure. This visualisation, which takes the form of an interactive online map, is also expected to help decision makers in implementing appropriate countermeasures that can help to avoid any loss of life and property in case of wildfire.

1.2 Study Area

The study area in this thesis extends across a transboundary area of approximately 700 km² on both sides of the River Elbe in Germany and the Czech Republic. Specifically, the study area consists of two national parks, Saxon Switzerland (Sächsische Schweiz) and Bohemian Switzerland (České Švýcarsko) and two conservation areas, the Conservation Area of Saxon Switzerland (Sächsische Schweiz) and the Conservation Area of the Elbe Sandstone Mountains (Chráněná krajinná oblast Labské pískovce) (*Bohemian National Park Region – Nationalpark Sächsische Schweiz*, n.d.).

As seen in the map below (Figure 1) the Conservation Area of Saxon Switzerland consists of several ‘holes’. The holes are not part of the Conservation Area; however, they are considered part of this thesis’ study area. These holes contain settlements, as will be shown in Figure 2. The study area is dotted by a plethora of towns and villages (in Figure 1, only local towns are indicated), which are often located within a matrix of potential fuels such as forest. This results in several WUIs and thus for WUI wildfires which could prove to be a risk for such settlements, as will be discussed in Section 1.3.4 of this chapter. It was for this reason, that the aforementioned holes were included; all villages and towns will need to be considered for a more comprehensive understanding of settlements in the study area that could be endangered.

The selection of this site was principally motivated by the occurrence of a serious wildfire in this area in the summer of 2022 which lasted from 24.07.2022 until it was extinguished on 12.08.2022, and which burnt 113 ha in the Saxon Switzerland National Park, Germany and 1,060 ha in the Bohemian Switzerland National Park, Czech Republic (Beetz, 2023) (Figure 1). Such a fire reiterates the fact that wildfires do not respect political borders and, in this case, nor those of national parks and protected areas.

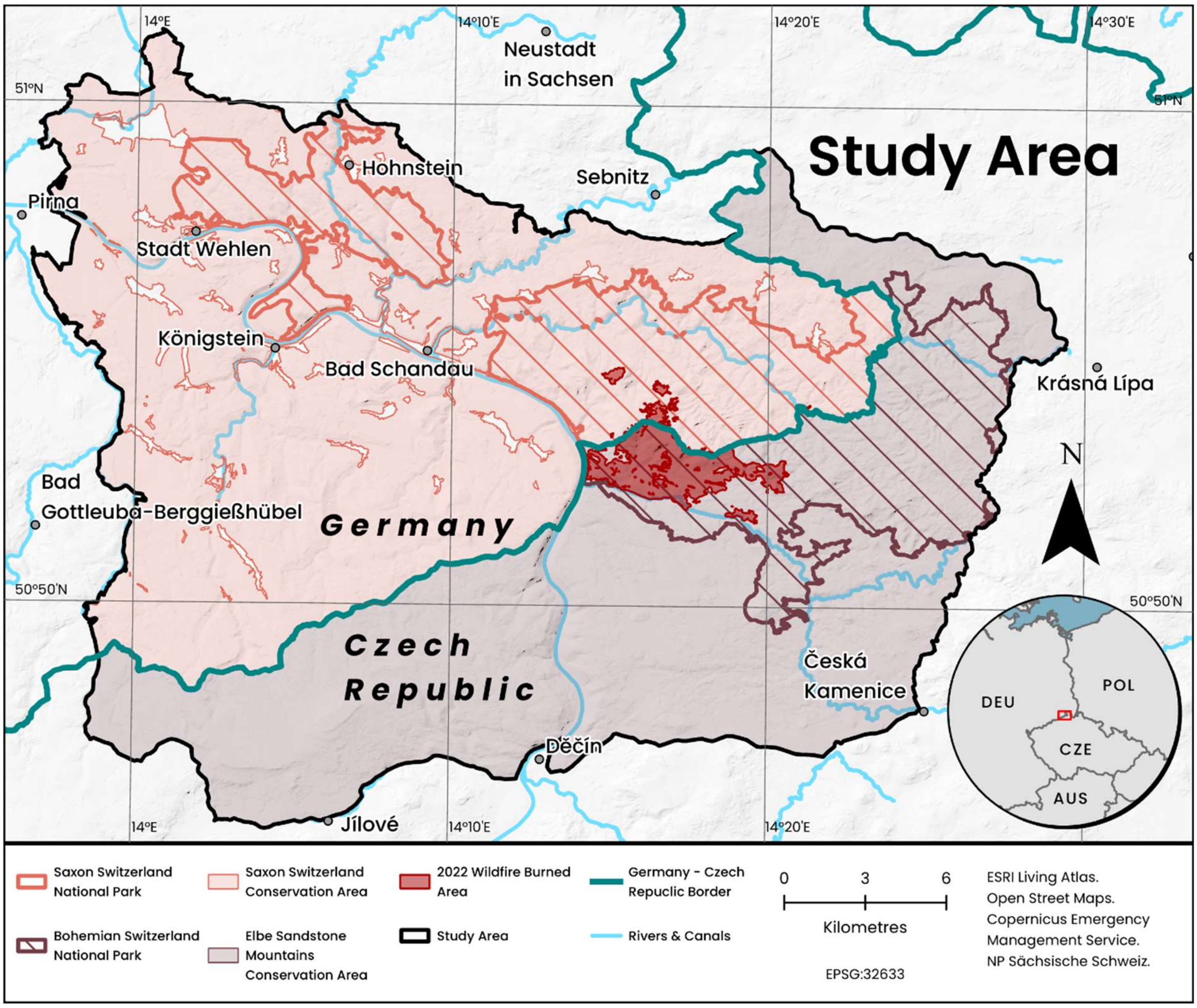


Figure 1: Study Area. The study area consists of 2 National Parks and 2 Conservation Areas in Czech Republic and Germany, and it experienced a large wildfire that burned areas of both National Parks in 2022.[1]

During the 2022 fire it became apparent that stakeholders were caught largely unprepared (Lukeš, 2022). Speaking on the need, for example, to better organise future coping capacities in national parks, the Director General of the Fire and Rescue Service of the Czech Republic pointed out the need to build fire breaks, to ensure adequate water supply points, and to better manage unmanaged forests in order to guarantee the timely arrival of fire technology and equipment (Idnes, 2022 as cited in Berčák et al., 2023). Similarly, the Director of the Civil protection and Crisis Management division of the Fire Rescue Service of the Czech Republic highlighted the need for a fundamental change in fire safety mechanisms in national parks and forests in general (e.g., early detection, access). However, the source of the lack of coping mechanisms –i.e., measures to minimise the risk of wildfire-associated disasters- lies deeper. Berčák et al. (2023) point out a general lack of fire prevention legislation that affected the areas

[1]Terrain Hill-shade derived from ESRI's Living Atlas (ESRI, 2020). Country borders derived from Natural Earth (Natural Earth, 2023). Locations of towns derived from Open Street Maps through Geofabrik (Geofabrik, n.d.). 2022 fire limits derived from the website of the Copernicus Emergency Management Service (Copernicus Emergency Management Service, n.d.). National Parks' and Conservation Areas' borders derived from (*Bohemian National Park Region – Nationalpark Sächsische Schweiz*, n.d.)

that burned in the 2022 wildfires. Looking towards the future, they recognise the need for new legislation and better application of existing laws, in order to cope with the emerging potential disasters resulting from Central European wildfires (Berčák et al., 2023).

Another reason that influenced the study area's selection, is the prevalence of bark beetle infestation. Bark beetle (in the study area these predominantly belong to the species *Ips typographus*) cause serious disturbances in forests they infest (Müller et al., 2008). Though wildfires in Central Europe are not as dangerous as those in Southern Europe, Central European fires can prove as perilous as the most serious fires of Southern Europe if they occur in disturbed forests, such as those infested by bark beetle (Berčák et al., 2023). Bark beetle infestation have been called by the German Agency for Renewable Resources as by far the most economically significant insect pests, especially in spruce forests (Kautz et al., 2023). Notably, the study area is dominated by monocultures of spruce (*Picea sp*) (Národní Park České Švýcarsko & CHKO Labské pískovce as cited in Beetz, 2023; Nationalparkverwaltung Sächsische Schweiz & Mayr, 2022 as cited in Beetz, 2023). *Ips typographus*, have a high reproduction potential and result in a high risk of new outbreaks (Grodzki & Fronek, 2019) rendering defence against this species challenging. The prevalence of *Ips typographus* infestations has escalated in recent decades, thereby playing a substantial role in the observed twofold increase in canopy mortality within Central Europe (Seidl et al., 2014 as cited in Hlásny et al., 2021; Senf et al., 2018 as cited in Hlásny et al., 2021). The Czech Republic more specifically, has emerged as a focal point for bark beetle infestations. According to Hlásny et al. (2021) a countrywide drought-fuelled bark beetle dynamic in 2017-2019 has affected vast regions simultaneously, which was an occurrence of unprecedented magnitude. This outbreak has primarily been fuelled by drought, a phenomenon previously unobserved in Central European forests (Hlásny et al., 2021). On the other hand, in the Saxon Switzerland National Park, between 2018-2020, due to extreme drought conditions, high temperatures and the resulting bark beetle infestation, 2000 ha of spruce forest died in a short period of time, which resulted in large amounts of deadwood in that area (Nationalparkverwaltung Sächsische Schweiz & Mayr, 2022). An increased amount of deadwood, can in turn , render the infested areas much more likely to burn in case of a wildfire; during the 2022 wildfire, most of the fire burned the forest stands that had been affected by bark beetles outbreaks (Berčák et al., 2023). The extent of the bark beetle infestation in the study area, before the 2022 wildfire, can be seen in Figure 4, in Section 1.3.6.

The author is aware of only one other research that has focused on this thesis' study area; though related, its main focus was on fuel types, fire dynamics and fire severity on this region (Beetz, 2023). This thesis is nevertheless closely related to Beetz's (2023) as the classification of this study area's fuel types conducted in that study, was an integral part of modelling the settlements' exposure to wildfires, as we will see in the second chapter.

1.3 Related Work

The following Section introduces the research fields from which this study draws upon.

1.3.1 Hazards, Disasters and Wildfires

To better understand and categorise wildfires, one must first take a closer look at the definitions of ‘hazard’ and ‘disaster’; we will see how wildfires are a type of hazard and that they may or may not cause disasters.

Cannon (1994) defines hazards as risks inherent in nature, which present humans with challenges, in terms of humans’ production (such as frosts affecting agricultural yield) and aspects of their safety and likelihood (e.g., droughts, floods, earthquakes). More specifically, the United States’ Federal Emergency Management Agency (FEMA) defines natural hazards as ‘environmental phenomena that have the potential to impact societies and the human environment’ (*Natural Hazards | National Risk Index*, n.d., para. 1).

On the other hand, a disaster has been defined as ‘a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts’ (*Disaster | UNDRR*, 2007, para. 1). The United Nations Office for Disaster Risk Reduction (*Sendai Framework Terminology on Disaster Risk Reduction | UNDRR*, 2023) further clarifies that disasters often push the limits of a community or society's self-reliance, usually necessitating support from external entities. These external sources could encompass neighbouring regions or even national and international bodies (*Sendai Framework Terminology on Disaster Risk Reduction | UNDRR*, 2023). State-level programmes and policies for disaster prevention, relief and reconstruction have been well studied by social scientists, especially in Western and developed countries (Attinà, 2012). Moreover, on an international level, several agreements in the last decade -such as the 2015 Sendai Framework for Disaster Risk Reduction-, have paved the way for stronger disaster risk governance and increased interstate cooperation on disaster management (Enia, 2020; Raikes et al., 2022). Finally, in terms of their duration, disasters can evolve over an extended timeframe, as in the case with climatic disruption or the effects of a sustained pandemic, or they may be sudden, for instance, in the form of the effects of hazards such as an oil spill, an earthquake -or more relevant to this study, an uncontrolled fire- (*Disaster | Definition & Types | Britannica*, 2023).

Directly related to natural hazard is the term ‘natural disaster’ which has been defined, as ‘the negative impact following an actual occurrence of natural hazard in the event that it significantly harms a community’ (*Natural Hazards | National Risk Index*, n.d., para. 5). For instance, and according to these definitions, hail, heat waves and wildfires are all understood to be natural hazards (amongst the 18 defined by FEMA), and their effects (e.g., destroyed crops, depleted water sources, burned forests) can be understood as natural disasters.

The term ‘natural disaster’ as defined above, is a commonly used term in hazards and disasters studies; Mohamed Shaluf (2007), Glade & Alexander (2013), Watt & Weinstein (2013) and

Kunreuther & Michel-Kerjan (2013), amongst many others, all use this term to refer to the effects of natural hazards when they negatively affect communities. However ‘natural disaster’ is a contested term; As Cannon (1994) points out, some hazards can be considered natural, but in general, disasters should not be considered as inevitable outcomes of a hazard’s impact; it is often human actions that permit a hazard to become a disaster. Moreover, as noted by Gizzi (2022), terming disasters as ‘natural’ is a tactic often employed by the media, politicians, scientists and international organisations to make the public feel less responsible, in other words, it is a term that leads people to believe that natural disasters are unavoidable. As early as in 1976, O’Keefe et al. (1976) had argued that not all hazards induced by natural phenomena can lead to a disaster. In fact, it can be the vulnerability of a population that can cause a hazard to turn into a disaster. Shamsipour & Shekhi (2010) argue for example, that a natural disaster needs a vulnerable area (i.e., an inhabited location) for a natural disaster to occur; for example, a strong earthquake in an uninhabited area, doesn’t necessarily lead to a natural disaster. According to O’Keefe et al., (1976) then, a population can and should implement precautionary planning, in order to understand their own vulnerability, and to incorporate strategies to mitigate future disasters. It should be noted however, that there are those who argue that humans negatively being affected is not the only criterion that should define a natural hazard’s outcome as a disaster; The United Nations’ International Strategy for Disaster Reduction, also includes unmanageable environmental losses in its definition of natural disasters (ISDR, 2004 in Tacnet & Curt, 2013).

The natural hazard and its associated natural disasters directly related to this thesis are “wildfires”; Wildfires are defined as “unplanned wildland fires” (Scott, 2019, p. 8), whose ignitions are due either to natural causes (mostly lightning), or to anthropogenic causes. Wildland fires are understood as fires burning in vegetation (Scott, 2019). We can therefore conclude that wildfires are unplanned fires that burn in vegetation. Though their origins can be both anthropogenic or non-anthropogenic, wildfires are commonly categorised as natural hazards, by e.g., Watt & Weinstein (2013), Burkett (2013) and Migoń (2013). Common natural disasters resulting from wildfires are evacuations, damages, destruction of homes and infrastructure, disruption of essential services and most important of all, the loss of life (Czaja, 2015). In the following Section, we will be discussing wildfire exposure, and vulnerability which are important concepts in understanding which assets could potentially face a disaster in case of a wildfire.

1.3.2 Exposure, Vulnerability and Coping Capacity

The concepts of vulnerability, exposure and coping capacity, closely associated with natural hazards and natural disasters, were briefly mentioned in the previous Section, however, a more in-depth understanding of them is in order.

Exposure, can be described as the condition of human assets, such as people, infrastructure, housing, and production capabilities, being situated in areas that are susceptible to hazards

(Safaie et al., 2017). Vulnerability refers to the circumstances influenced by physical, social, economic, and environmental elements or events that heighten the likelihood of an individual, a community, assets, or systems being affected by the consequences of hazards (i.e., disasters) (Safaie et al., 2017). Coping capacity signifies the capability of individuals, organisations, and systems to effectively handle adverse conditions, risks, or disasters by utilising their existing skills and resources; effective coping capacity diminishes the risk of disasters a hazard may bring (Safaie et al., 2017). From these three interrelated terms one can deduce that in order for an area to develop appropriate coping capacity strategies against potential disasters, its exposure and vulnerability to hazards should be studied and quantified.

In terms of wildfires, wildfire vulnerability, expresses the attributes and conditions of a community, system, or asset that render it prone to the harmful effects of a wildfire (Abrahams et al., 2017). This term has been interpreted and quantified differently by different authors; Oliveira et al.,(2020) for example, identified 14 different wildfire vulnerability variables in their study area in rural Portugal, which were then classified into those having positive influence (decreasing vulnerability) and those having a negative one (increasing vulnerability). These variables ranged from socioeconomic ones (e.g., a high percentage of young or highly educated population, which were considered as variables with a positive influence) to rural planning ones, (e.g., high percentages of isolated buildings or buildings built before 1980 were both considered as variables with a negative influence).

There exists a plethora of different wildfire coping mechanisms, i.e., measures to minimise the risk of wildfire-associated disasters. The development of firebreaks (Cui et al., 2019), fuel reduction treatments (Waltz et al., 2014), wildland fire use (allowing a fire to burn under prescribed conditions) (Keane et al., 2005), spatial management of a fire station network (Degel et al., 2014; Yao et al., 2019) and pre-emptive fire appliance allocation (Yeboah & Park, 2018) are just a few of many different examples of wildfire coping mechanisms. Examples of variables utilised to quantify coping capacity include for example distance of a settlement from the nearest fire station and the time its residents need to reach a shelter (Oliveira et al., 2020).

Wildfire exposure finally, as defined by Johnston et al., (2020, as cited in Oliveira et al., 2021), is the evaluation of the assets that could be endangered in case of a wildfire, and to what extent. A more detailed definition by Abrahams et al., (2017) states that 'Wildfire exposure is simply the spatial juxtaposition of wildfire likelihood and intensity metrics with the location of Highly Valued Resources and Assets (HVRAs) found in a specific area' (p. 5).

Assets can be human-related infrastructure (e.g., buildings), forests, agricultural lands or natural protected areas, with different research focusing on different assets' exposure (Oliveira et al., 2021). To derive wildfire exposure, one must analyse fire occurrence, likelihood, or hazard in relation to assets. This can be achieved either by using historical fire data (e.g., the extent of historical wildfires) (Chas-Amil et al., 2020 as cited in Oliveira et al., 2021), or by integrating stochastic and probabilistic wildfire simulations with the spatial distribution of assets (Jahdi et al., 2020; Alcasena et al., 2019; Salis et al., 2021 as cited in Oliveira et al., 2021). In this thesis, discussed in Chapter 2, the second method has been employed to deduce wildfire exposure, and human settlements are the assets in focus.

The mapping of natural disasters, and the three main categories of disaster-related maps are explored in the following Section.

1.3.3 Disaster-related Maps

Three fundamental uses of maps are the amalgamation of diverse forms of data into a unified, expressive medium, the transmission of spatial and topological connections among entities, and the manipulation of spatial attributes to underscore specific aspects of information (McKenney & Schneider, 2016). These three uses of maps, namely, the integration of information, the communication of spatial relationships and the emphasis of specific information, makes maps excellent tools in the pursuit of good situational awareness.

Situational awareness is indispensable in helping decision makers plan better disaster responses and develop appropriate coping mechanisms. Natural disaster-related mapping can be broadly divided into three categories; mapping to prepare for/respond to disasters, mapping disasters as they unfold (crisis mapping), and mapping the aftereffects of disasters.

The first category of natural disaster-related maps can be termed natural disaster preparedness maps. These are created to recognise potential disasters, to inform citizens who could be affected by such disasters, and to better prepare stakeholders, to advert them. A preparedness map, may focus on a potential disaster's adverse economic effects from a socio-economic approach; Yamano et al. (2007) e.g., made a map of Hyogo prefecture, Japan, showcasing estimated disaster-related economic loss. Parameters used to factor each locations' economic fragility includes potential disaster-driven changes in the supply sources, disruptions of transport networks and damages on residential buildings. Another example is the work of Alcasena et al. (2017); they used fire modelling and cadastral maps to estimate residential expected economic losses (eEL) for communities of Northern Spain.

Some natural disaster preparedness maps, are also exposure maps, as they fit the definition of locating assets that are susceptible to hazards (Safaie et al., 2017). Exposure maps can show a variety of assets that could be endangered by different hazards, e.g., cities by tsunamis (Sagara & Saito, 2013), or in relation to this thesis forests by wildfires (Kalabokidis et al., 2014). As a reminder, wildfire exposure, needs to showcase the spatial juxtaposition of both wildfire likelihood and intensity metrics, with the location of assets (Abrahams et al., 2017). Authors have interpreted this concept differently: Some, have created two separate maps to represent the two metrics (Ager et al., 2011; Kalabokidis et al., 2014; Mallinis, 2014) . Others, have opted for a bivariate exposure map, where wildfire likelihood and intensity are simultaneously represented on every part of the map (Heisig et al., 2022; Mallinis et al., 2016; Sá et al., 2022).

Wildfire exposure maps, are sometimes enhanced with vulnerability variables, in order to represent the attributes of an asset, that render it prone to the harmful effects of a wildfire (Abrahams et al., 2017). These variables, divide vulnerability into two dimensions, criticality and support capability (Bergonse et al., 2022). Criticality communicates individual susceptibility and capacity for recuperation. Examples include sociodemographic factors, such as the age of population and the average purchasing power per capita of citizens who live in exposed areas (Alcasena et al., 2017). Research that focuses on the WUI, considers criticality as differing interface models between settlements and forested areas (e.g., an isolated house surrounded by a forest is very vulnerable) (Caballero et al., 2007). Support capability on the other hand, describes the infrastructure and equipment (whether public or private) located within a particular territory which serve to bolster the preparedness for, response to, and recovery to disasters, in other words they decrease the impact caused by disastrous events (Pereira et al., 2005 as cited in Bergonse et al., 2022). Variables describing support capability may include road network density (Bergonse et al., 2022) and settlements' distance to the nearest fire station (Oliveira et al., 2020). Other examples of variables include exposure mapping by Mallinis et al., 2016 where the variables used were monasteries located on Mount Athos, a UNESCO World Heritage site, where a bivariate approach (Burn Probability and Flame Length) with 4 classes was used.

It has been argued that wildfire exposure studies such as this, could possess significant utility as integral elements for the development of comprehensive wildfire protection and policy (Abrahams et al., 2017). The main difference between this case study and this thesis, is that this thesis, will integrate two support capability factors, while the above map does not use any vulnerability factors.

Crisis maps include maps created with data gathered through a variety of sources, such as social media, remote sensing and drones, to give first respondents a clear and adaptive situational understanding (Gao et al. 2011, as cited in Tsou et al., 2017). A type of crisis mapping framework, is the development of constantly updating static maps. For example, San Diego County produced a crisis map of local wildfires every 6-12 hours as a component of their collective operational understanding for internal decision-making, and for the benefit of first respondents in the field (Petersen, 2014). These maps included elements such as fire locations, evacuation centres and areas deemed safe for return. A relatively recent innovation which has nevertheless become crucial to fast and effective crisis maps is Volunteered Geographic Information (VGI) (Tzavella et al., 2022). Typical VGI data sources include OpenStreetMap, Crowdsourcing and Twitter. VGI-derived crisis mapping can be found in a range of case studies. As an example, the cluster mapping of Twitter-derived keywords was utilised to deduce where shelters and supplies are most needed in the aftermath of the 2015 Nepal earthquake (Tsou et al., 2017). An open source crisis mapping platform is Ushahidi (*Ushashidi*, 2023). Ushahidi has been implemented in various locations including Kenya, Mexico, Afghanistan, and Haiti. (Gao et al., 2011). The platform utilises Web 2.0 technologies to amalgamate data from diverse sources such as phones, web applications, email, and social media sites like Twitter and Facebook. As the disasters from the 2010 Haiti earthquake were unfolding, the large amount of nearly real-time reports allowed relief organisations to identify and respond to urgent cases in time (Gao et al., 2011).

The two key aims of the final category of natural disaster-related maps are estimation of damage and assisting in the recovery phases of disaster management. In an urban setting for example, the process of quantifying and mapping the buildings that have experienced damage after a natural disaster, can prove instrumental in facilitating precise post-disaster evaluation, enabling the estimation of property losses and providing guidance for subsequent repairs in the aftermath of such events (Shao et al., 2020). Various techniques have been employed to that end; Cao and Choe used object detection to create a method for post-hurricane building damage assessment (2019 as cited in Shao et al., 2020). In the aftermath of the Wenchuan Earthquake of 2008 Guo et al. (2010) used optical and synthetic aperture radar images to map damaged houses, collapsed bridges, schools, houses and blocked rivers and roads. Post disaster maps are not solely limited to urban assets; (Falaras et al., 2022) developed a web app that showcased the aftereffects of a wildfire showing the erosion, burned area, and burned severity of a wildfire that burned parts of the Attica region in Greece in 2021.

A specific type of area where human settlements can be particularly exposed to wildfire disasters, therefore deeming disaster-related maps useful, are Wildland Urban Interfaces; the study area analysed in this thesis is a prime example of such.

1.3.4 Wildland Urban Interfaces

Wildland Urban Interfaces are areas characterised by a mixture of wildland fuels (such as vegetation and trees) and human-made structures such as buildings and infrastructure (Molina-Terrén et al., 2019). This results in WUIs acting as areas where wildfires can have a significant impact on both natural and human environments, and they pose unique challenges to traditional firefighting approaches due to their complexity and the interface between different land uses (Caballero & Beltrán, 2003). Moreover, WUIs are expanding and in addition, the negative effects of climate change are worsening, therefore rendering WUI wildfires even more potentially disastrous (Oliveira et al., 2020).

Relevant to this thesis is WUI research that studies: (a) The deadly effects of WUI wildfires, such as the one by Molina-Terrén et al. (2019), (b) the modelling of WUI wildfires' spread, such as the one by Alcasena et al. (2017), (c) the prevention planning and emergency management solutions to fights against WUI fires, such as the one by Kalabokidis et al., (2012), and (d) the classification of different types of WUIs to better asses potential wildfire risk, such as the one by Caballero et al., (2007). The study area that will be examined in this research contains two national parks and two conservation areas and is dominated by closed forests (dark green area, Figure 2). These four areas are home to many human settlements of varying sizes (farms, hamlets, villages and towns), which are often surrounded by forested areas (light and dark green, Figure 2), as well as agricultural lands (pink area, Figure 2) as such the study area represents a prime example of a Wildland Urban Interface. This can be seen in Figure 2 below where human settlements (red areas) are often surrounded entirely by vegetated areas. Large settlements (towns) are shown with their names on the map below.

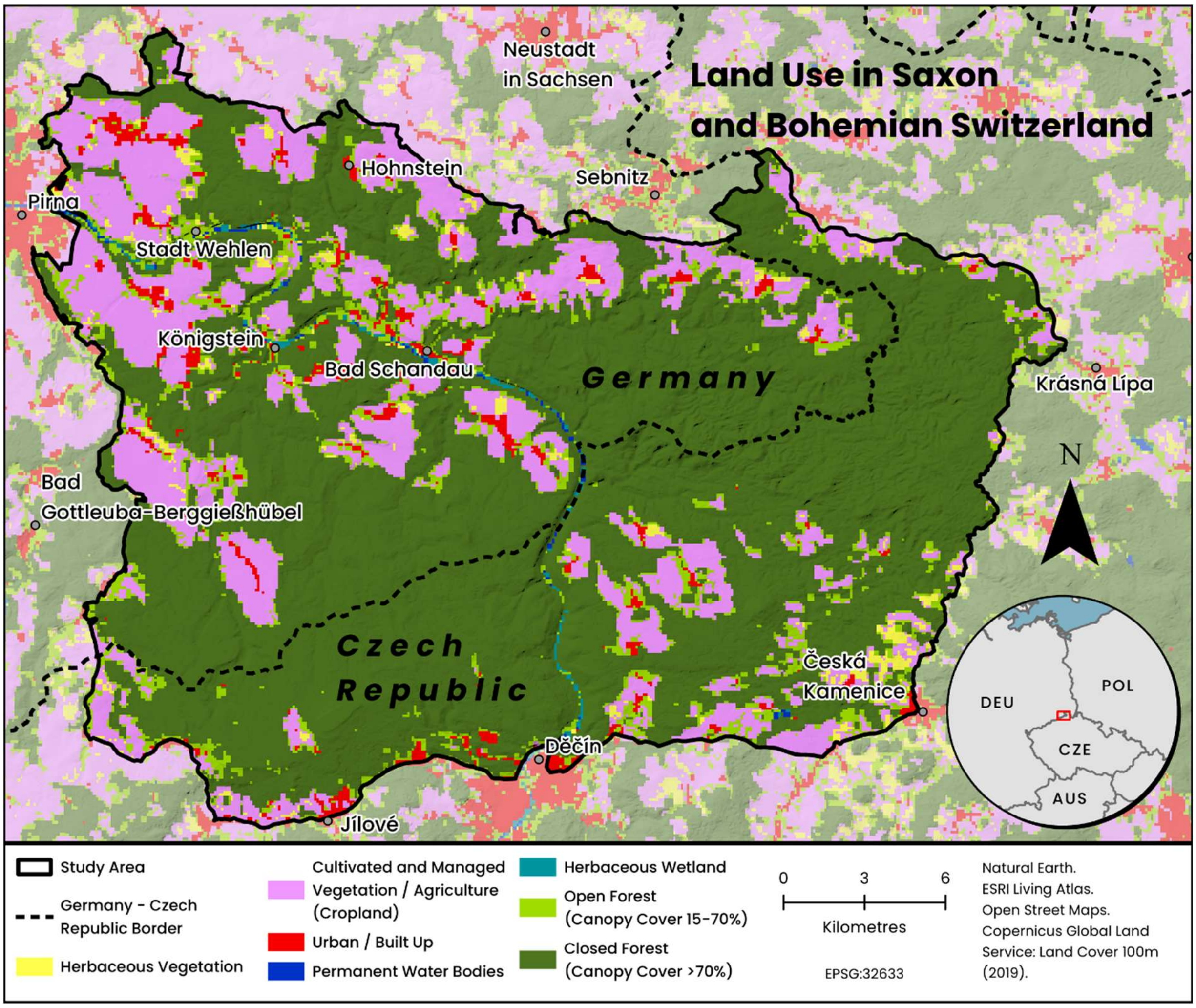


Figure 2: Land Use map for thesis study area. Land Use data derived from (Copernicus Global Land Service, n.d.). Grouping of forest land cover layers based on documentation by (Buchhorn et al., 2020).[2]

To understand how exposed settlements could potentially be to wildfires, it is crucial to model these fires; the appropriate method to achieve this is Fire Modelling (Molina-Terrén et al., 2019).

[2] Terrain Hill-shade derived from ESRI's Living Atlas (ESRI, 2020). Country borders derived from Natural Earth (Natural Earth, 2023). Locations of towns derived from Open Street Maps through Geofabrik (Geofabrik, n.d.).

1.3.5 Fire Modelling

As previously stated (Section 1.3.2), to derive wildfire exposure, it is essential to calculate fire intensity and likelihood metrics, before juxtaposing them with the location of assets (Abrahams et al., 2017). A common way to derive such metrics, is the use of fire modelling; Fire modelling offers an analytical framework for the characterisation and prediction of fire spread and behaviour in varied and intricate fire environments (Van Wagtendonk, 1996 as cited in Jahdi et al., 2016; Stephens, 1998 as cited in Jahdi et al., 2016). This approach has been proven beneficial in the development of suitable wildfire management strategies, in order to mitigate potential disasters and establish effective coping capacities (Alcasena et al., 2017; Moghaddas et al., 2010; Oliveira et al., 2020; 2021; Sá et al., 2022).

There exists a variety of fire modelling software, each with its own strengths, weaknesses, and appropriate use cases; some include the Canadian Forest Fire Danger Rating System (Alexander et al. 1996 in Miller & Ager, 2012), BehavePlus (Andrews 2007 in Miller & Ager, 2012), NEXUS (Scott 1999 in Miller & Ager, 2012) and the Fire and Fuels Extension to the Forest Vegetation Simulator (FVS-FFE) (Reinhardt and Crookston 2003 in Miller & Ager, 2012) to name but a few. Peterson et al., (2007) created a comprehensive consumer guide, detailing fire modelling tools along with many of their characteristics such as recommended spatial scale of use, required level of user knowledge, data requirements, potential model outputs and availability of training and support. What differentiates Peterson et al.'s (2007) work from other examples of research that consider and evaluate fire modelling applications (Ager et al., 2011; C. Miller & Ager, 2012), is that it is far more accessible, paying heed to the non-expert user. Taking this as a foundation, it was initially decided that the most appropriate software to use in this thesis was FlamMap. FlamMap is a fire analysis application developed by the Missoula Fire Sciences Laboratory (Missoula Fire Sciences Laboratory, n.d.-a). FlamMap has the advantage of being able to visualise fire behaviour characteristics directly related to exposure (e.g., Flame Length and Burn Probability, which are the metrics that will be used in this thesis) visualising such characteristics in the form of geolocated rasters, a form which makes easier the prompt deriving of settlements' exposure (D. L. Peterson et al., 2007).

Starting from these two main advantages, a further review of the literature made apparent other qualities; Firstly, FlamMap is an established software often used in studies dealing with wildfire exposure assessment (Ager et al., 2007;2010;2012; Bar Massada et al., 2009; Thompson et al., 2011, 2013a, b;2015; Parks et al., 2012; Haas et al., 2013; Salis et al., 2013;2014;2015; Kalabokidis et al., 2014a; Mitsopoulos et al., 2015; Alcasena et al., 2015 all as cited in Jahdi et al., 2016). Moreover, FlamMap is commonly used to analyse fire behaviour in European settings; Salis et al., (2009) e.g., used FlamMap to assess wildfire severity in Sardinia, Italy, Mitsopoulos et al. (2016) used it for a Greek landscape, Sá et al. (2022) used in for Portugal and Alcasena et al. (2017) for Spain. Though there exists a lack of studies using FlamMap in a Central European setting (Beetz, 2023 being a notable exception), this could be attributed to the research gap in the research of wildfires in that region. Another advantage which was discovered after close inspection of the documentation (*FlamMap Help*, n.d.) was FlamMap's ability to simultaneously model several fires, which as will be shown in Chapter 2, which is an important component in the probabilistic simulation of several simultaneous fires. Finally, FlamMap was the fire modelling software used to successfully test the fuel model of Beetz (2023) in their work. As the very same fuel model is utilised in this thesis, the compatibility between FlamMap and this fuel model – which is perhaps the most difficult-to-derive input data- had already been established.

What lies at the core of every software that models fire behaviour, are mathematical algorithms that calculate different aspects of fire behaviour, based on a specific set of inputs. FlamMap, e.g., incorporates 7 such algorithms -which are known as fire behaviour models-, them being Rothermel's (1972) surface fire spread model, Van Wagner's (1977) crown fire initiation model, Rothermel's (1991) crown fire spread model, Albini's (1979) spotting model, Finney's (1998) or Scott and Reinhardt's (2001) crown fire calculation method and Nelson's (2000) dead fuel moisture model (all as cited in *FlamMap | Missoula Fire Sciences Laboratory*, n.d.)

The specific set of inputs for such algorithms, often takes the form of a fire modelling landscape. A fire modelling landscape is needed in order to simulate potential fire growth and behaviour across a landscape (Scott, 2019). It is a geospatial characterisation in raster-format, of the topography (aspect, slope and elevation) vegetation (stand height and canopy cover) and fuel (canopy bulk density, canopy base height and surface fuel model) of the area in which wildfires will be modelled (Scott, 2019). A conceptual illustration of a fire modelling landscape and its constituent layers can be seen in Figure A.1 in the Appendix. In wildfire modelling software developed by the United States Forest Service, such as FlamMap and FARSITE, the input raster data layers must be of identical resolution, be co-registered (each grid cell in one dataset corresponds to the same geographic location as the corresponding grid cell or pixel in another dataset) and of equal extent (Finney, 2006). The data which will act as input for FlamMap's fire modelling landscape in this thesis, will closely resemble that used in Beetz's (2023). FlamMap simulation, (e.g., canopy cover will be calculated from Copernicus, elevation through LiDAR), making sure to use more contemporary data when available.

One might infer that wildfire modelling is highly dependent on spatial context, as the wildfire simulations, used to compute the characteristics of a wildfire, need to be specifically informed about local conditions (Vacca et al., 2020); For instance, not only are meteorological and climatic conditions vastly different in different regions (e.g., Portugal experiences longer periods of high temperature weather than Germany), but the global distribution of fuel types, as we will see in the following Section, is strongly influenced by geographical context, resulting in different types of fuels being found in distinct regions, affecting wildfire characteristics too (Aragoneses et al., 2022 for example, has an in-depth analysis on fuel-type classification and distribution in Europe while Scott & Burgan (2005), consider a USA context for their fuel models). Moreover, when it comes to the calculation of wildfire exposure, it has been demonstrated that there is significant spatial variation in WUIs per country (Caballero et al., 2007), which means that if, e.g., there exists a pattern of settlements of a specific type and size in a particular area with no adequate fire-escape routes, this pattern will most probably not be replicated in another spatial context. Consequently, it is necessary to independently consider spatial context when modelling wildfires and considering exposure; the modelling results of one area of interest cannot be reused in another. Conversely, new data needs to be acquired for the creation of each new fire landscape. In the following Section we will be taking a closer look at fuel models, an indispensable part of any fire modelling landscape, but a difficult one to acquire, due to the high temporal and spatial variability of fuel components (Brown and See, 1981 (Brown and See, 1981; Keane, 2008 as cited in Keane & Reeves, 2012; Keane, 2008 as cited in Keane & Reeves, 2012).

1.3.6 Fuel Types & Fuel Models

Fuel models were briefly discussed in the previous Section; a fuel model is a vital aspect of any fire modelling landscape. Therefore, a discussion of what fuel models are and how they are derived is in order.

Wildland fuels encompass the entirety of organic material that is capable of facilitating the initiation and perpetuation of fire (Albini, 1976 as cited in Keane & Reeves, 2012; Sandberg et al. 2001 as cited in Keane & Reeves, 2012). More precisely, these fuel components consist of both living and deceased biomass found on the surface and within the canopy, which contribute to the propagation of wildland fires (Keane & Reeves, 2012). Soils can also be part of the fuel load, in the form of peat, which can burn through a slow and flameless smouldering combustion (Rein & Huang, 2021). The fundamental concept of Fire Environment, i.e., 'the conditions, influences, and modifying forces that control the fire behaviour' (Countryman, 1972, p. 1), first promoted by Countryman (1972), dissects fire initiation, propagation and effects into three contributing factors: fuel, topography and weather. Fire dynamics then are intricately connected to the characteristics of fuel, with fuel having the key difference compared to the other two factors, of being able to be managed by humans, in order to reduce fire propagation (Aragoneses et al., 2022). Moreover, fuel characteristics are an integral part of the understanding of the ignitions and intensity of fires (Albini & Reinhardt, 1995), while also being informative of potential fire emissions characteristics (Zheng et al., 2021 as cited in Aragoneses et al., 2022). Hence, the process of mapping the fuels of an area (either in the form of fuel types or models) holds significant importance in the realm of fire risk prevention, planning, and real-time fire management (Keane et al., 2001 as cited in (Aragoneses et al., 2022). This tool enables the spatial depiction of a crucial variable that fire managers possess control over (Keane & Reeves, 2012).

Fuel models are often derived from fuel types. A fuel type refers to a discernible grouping of fuel elements characterised by distinct species, form, size, arrangement, or other distinguishing features that result in a predictable rate of propagation or resistance to containment when subjected to specific weather conditions (Food and Agriculture Organization of the United Nations 1986; National Wildfire Coordinating Group 1996; Canadian Interagency Forest Fire

Centre 2002 all as cited in (Xiao-rui et al., 2005). In other words, a fuel type consists of vegetation types which have been grouped together because of their similar characteristics from a fire behaviour point of view (Aragoneses et al., 2022). Fuel types may refer to either surface or canopy fuels; Low vegetation formations and understorey are classified as surface fuels, whereas elevated fuels, such as forest crowns, are categorised as canopy fuels (Aragoneses et al., 2022). Typically, human-caused fires -the most prevalent cause of wildfires in Central and Southern Europe (Tedim et al., 2015)- originate in surface fuels and may subsequently spread to canopy fuels, resulting in crown fires. These fires are considerably more hazardous than surface fires due to their greater energy release and larger propagation fronts, rendering them more challenging to manage (Scott and Reinhardt, 2001; Aragoneses et al., 2022). Below (Figure 3), the fuel type categorisation that is included in the Canadian Forest Fire Behaviour Prediction (FBP) System is presented as an example:

Group/Identifier	Descriptive name
Coniferous	
C-1	Spruce-lichen woodland
C-2	Boreal spruce
C-3	Mature jack or lodgepole pine
C-4	Immature jack or lodgepole pine
C-5	Red and white pine
C-6[a]	Coniferous plantation
C-7	Ponderosa pine/Douglas-fir
Deciduous	
D-1	Leafless Aspen
Mixedwood	
M-1[b]	Boreal mixedwood-leafless
M-2[b]	Boreal mixedwood-green
M-3[c]	Dead balsam fir mixedwood-leafless
M-4[c]	Dead balsam fir mixedwood-green
Slash	
S-1	Jack or lodgepole pine slash
S-2	White spruce-balsam slash
S-3	Coastal cedar/hemlock/Douglas-fir slash
Open	
O-1a[d]	Matted grass
O-1b[d]	Standing grass

[a]Can vary crown base height.
[b]Must specify percent conifer composition.
[c]Must specify percent dead fir.
[d]Must specify degree of curing and can specify fuel load.

Figure 3: List of fuel types presently included in the Canadian Forest Fire Behaviour Prediction (FBP) System (Wotton et al., 2009, p. 2)

To create a fire modelling landscape which can be used as input in a fire modelling software's fire behaviour model, the fuel of the studied area needs to be introduced in a way that is understandable to the fire behaviour models. The appropriate input for this, are fuel models (Scott & Burgan, 2005). Fuel model are defined by a set of often complex fuel characteristics, such as heat content, mineral content and dead fuel moisture of extinction (Keane, 2015). The fuel models developed by Scott and Burgan (2005) are some of the most commonly used (Keane & Reeves, 2012). These models can be used as input to the Rothermel (1972) surface fire spread model, which in turn is utilised in most US fire behaviour predictions systems, amongst them FlamMap (Keane, 2015).

Creating fuel models for a study area is a demanding process and the task of fuel mapping presents significant challenges owing to the considerable temporal and spatial fluctuations exhibited by fuels (Keane et al., 2001). To address this, numerous fuel classification systems have been devised to address this issue (Arroyo et al., 2008 as cited in Aragoneses et al., 2022). However, the development of these systems has consistently relied upon the expertise of suppression specialists (Keane et al., 2001), primarily due to the extensive range of fuel types, their temporal and spatial variability, and the absence of comprehensive fuel data across different regions (Keane & Reeves, 2012).

The fuel models utilised in this research, were created by (Beetz, 2023), which are also the only fuel models of high enough resolution (10 × 10m) for the entirety of this area. Beetz (2023) first created a fuel type classification system for Saxon and Bohemian Switzerland by combining the fuel type classification of Aragoneses et al. (2022) and that of the Alaska Fuel Model Guide Task Group (Ed.) (2018) -the resulting fuel types map can be found in Figure A.2 of the Appendix-. Beetz (2023) then, transferred derived fuel types to the fuel models of Scott & Burgan (2005), allowing them to be used in fire modelling software like FlamMap. Beetz's (2023) fuel models map of our common study area is shown in Figure 4 below. Note the existence of significant areas that have been infested by bark beetle; these are noted in the fuel models map (Figure 4) with the model ‘Slash-Blowdown 2’, an assignment also employed by the (Alaska Fuel Model Guide Task Group (Ed.) (2018) for bark beetle-infested forests.

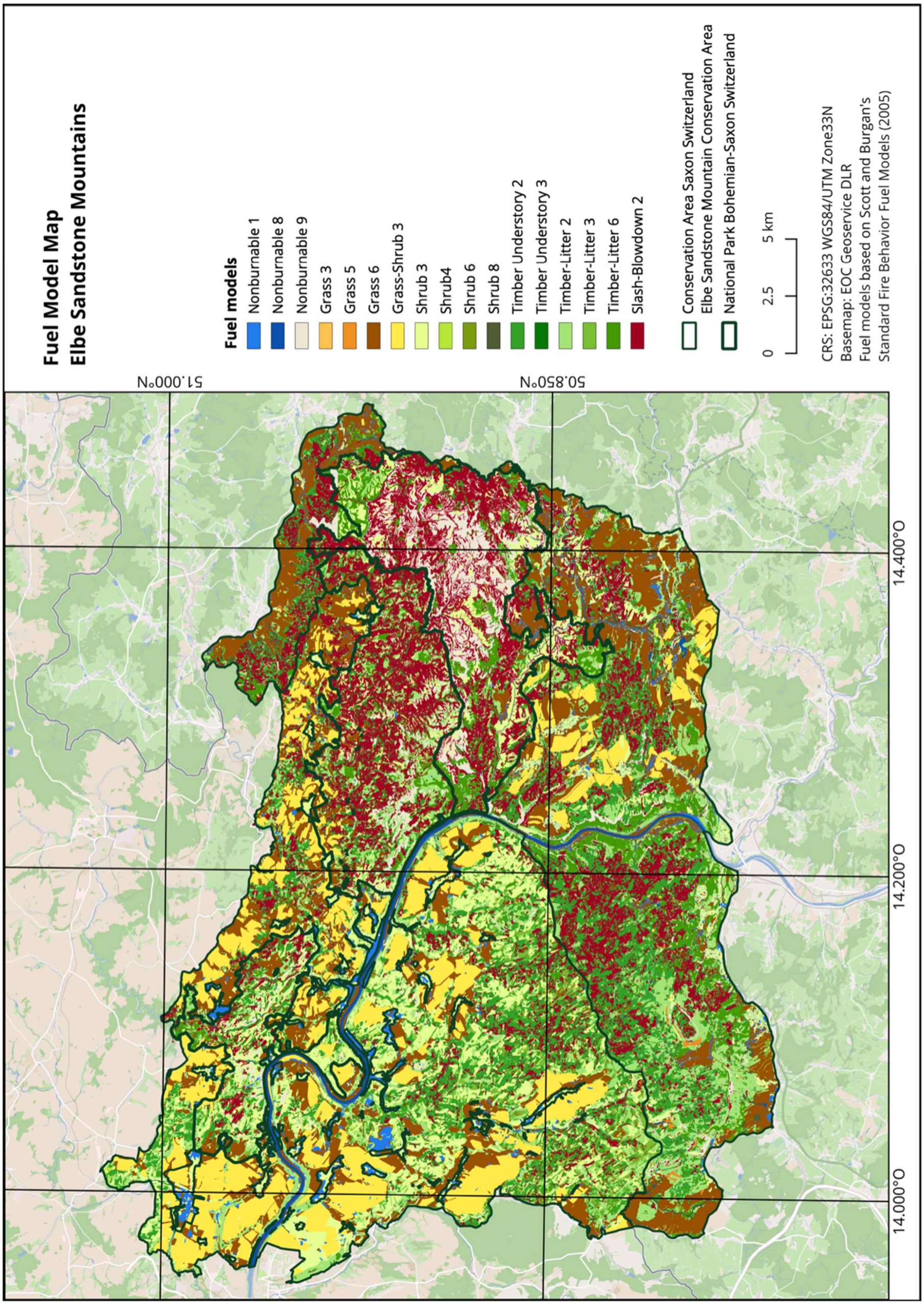


Figure 4: Fuel model map Elbe Sandstone Mountains pre-fire 2022 (Beetz, 2023, p. 42)

Although Beetz (2023) also developed a fuel type and a fuel model map for the study area, after the 2022 fire, this thesis uses the pre-fire ones. This is done in order to evaluate the resulting exposure map, by observing whether the areas that actually burned in 2022, are also highly exposed in the exposure map.

1.4 The Aim of this Study

The thesis' aim is to create an interactive wildfire preparedness map for an area with many examples of WUI, located in Central Europe. More specifically, the map will be a bivariate exposure map which will secondarily include two support capability indicators, namely, the locations of fire stations and local transportation infrastructure. This aim can be condensed into the two following research questions:

Research Question 1: Can the fire modelling tool FlamMap be used to create an accurate Wildfire Exposure map in the designated study area?

Research Question 2: Is an interactive exposure map derived from FlamMap's outputs, usable by the general audience and useful for stakeholders?

2 Method of Work

This chapter examines the methods and data utilised in the creation of the online exposure map.

2.1 Creating the Fire Modelling Landscape

A fire modelling landscape is a necessity for modelling in FlamMap, as was discussed in Section 1.3.5. The input layers need to be co-registered (have the same reference point and units), have identical resolution (cell size must be the same for all layers), have the same extent, and have the same projection and datum (*FlamMap Help*, n.d.). In terms of a common projection, it was determined that the WGS 84 / UTM zone 33N (EPSG: 32633) coordinate reference system would be appropriate due to it providing minimal distortion for the areas mapped (Saxony, northern Czech Republic). Moreover, as the rasters derived from FlamMap modelling inherit the resolution of the input rasters, an input data resolution of 30×30m was determined to be adequate; this allows the detection of individual buildings on the resulting Exposure raster. The following part describes the data sources and methods that were utilised for the creation of all the necessary layers of the fire modelling landscape.

2.1.1 Elevation, Slope and Aspect

1×1m digital ground elevation (DGM) tiles covering the study area were downloaded from the sachsen.de website of the Landesamt für Geobasisinformation Sachsen (Saxony State Office for Basic Geographic Information) (Landesamt für Geobasisinformation Sachsen, n.d.-a). These were then reprojected to EPSG: 32633 and merged in QGIS. Finally, the merged elevation file was resampled to a 30×30m resolution and clipped to the exact borders of the study area using R's terra library. The Slope and Aspect layers, were derived from the respective Slope and Aspect built-in raster geoprocessing functions of ArcGIS Pro (ArcGIS Pro | Documentation, 2023).

2.1.2 Fuel Models Map

The fuel models map used was the same as the ones created by Beetz (2023) and was acquired upon communication with the author. The fuel models map, which had an initial resolution of 10×10m needed to be resampled; this was achieved in R, using the terra package. Two alterations to the original fuel model of Beetz (2023) had to be applied. The first alteration was implemented after a preliminary static version of the map was shown to stakeholders on the 30th of August 2023 at a meeting that took place at Bad Schandau between representatives of the National Parks and the author's supervisors. At that meeting, it was pointed out that the preliminary exposure map, showed low flame lengths in areas where the stakeholders had witnessed high and difficult-to-extinguish flame lengths during the 2022 wildfire suppression efforts. Following this observation, and after communication with Christopher Marrs and Kristina Beetz; it was determined that some areas classified with the NB9 (Bare Ground) fuel model, should be reclassified as SH3 (Moderate Load, Humid Climate Shrub). This was done because according to the Scott & Burgan (2005) fuel models' classification -which were used by Beetz (2023)-, NB9 is a fuel model used to describe land devoid of enough fuel to support wildland fire -i.e., non-burnable areas-, compared to the SH3 which exhibits low flame lengths. The threshold used to determine the NB9 areas that needed to be reclassified, was determined to be an NDVI>0.72, based on a comparison of aerial and satellite images. The Normalized Difference Vegetation Index (NDVI) is the most popular index used for vegetation assessment, and an effective tool in determining vegetation status and properties (Huang et al., 2021). An NDVI value of 0 signifies land with no vegetation on it, while an NDVI value close to 1 signifies the existence of dense, healthy vegetation.

The second alteration was introduced after the realisation that areas mapped by Beetz (2023) with a GS3 fuel model (Moderate Load, Humid Climate Grass-Shrub (Dynamic)), unexpectedly resulted in high flame lengths, even if those areas were dominated by pasture and grasslands. The decision was then taken, with the help of the author's supervisors, to replace all GS3 areas with the GR3 fuel model (Low Load, Very Coarse, Humid Climate Grass (Dynamic)). GR3 is similar to GS3, with the key difference that GS3 can be used to describe areas that have both grass and shrubs, while GS3 is more suited to areas with only grass (such as the areas that had been previously classified as GS3) (Scott & Burgan, 2005). Moreover, areas with GS3 tend to have higher flame lengths than those with GR3 (Scott & Burgan, 2005). Both these fuel models have live herbaceous components (i.e. composed primarily of non-woody plants) and are therefore classified by Scott & Burgan (2005) as dynamic (meaning that their herbaceous load shifts between live and dead depending on the specified live herbaceous moisture content). Figures illustrating these alterations are available in the Appendix (Figure A.3 and Figure A.4).

2.1.3 Canopy Cover

Canopy Cover data was derived from Copernicus' Land Monitoring Service which provides 10×10m resolution rasters with canopy cover density; the latest dataset available dates from 2018 (Copernicus Land Monitoring Service, 2023). The four tiles which were identified as covering the study area were downloaded, re-projected, merged and finally clipped to the study area using R's terra package.

2.1.4 Canopy Height, Crown Base Height and Crown Bulk Density

As opposed to the above layers, Canopy Height, Crown Base Height and Crown Bulk Density are optional for the creation of a fire modelling landscape in FlamMap. Nevertheless, they add more accuracy while modelling fires, as they allow the modelling of torching, spotting, and crown fires, i.e. they add a layer of crown fire activity to the fires, rather than solely considering surface activity (Finney, 2006; *FlamMap Help*, n.d.). The utilisation of these layers is common in fire modelling; Ager et al., (2011), Heisig et al. (2022), and Mitsopoulos et al. (2016) modelled fires with FlamMap and used these layers. However, there are those who do not use them (Alcasena et al., 2021; Sá et al., 2022). This discrepancy could be attributed to the fact that Canopy Characteristics are difficult to estimate, as they require rigorous fieldwork (Heisig et al., 2022) or complex remote sensing methods (Keane et al., 2005).

Initially the inclusion of these three layers was deemed unfeasible, however, after communication with the author, Erico Kutchartt of the University of Padova, made the author aware of a European-wide fuel and canopy dataset developed through the European Commission's FIRE-RES project (Francesco et al., 2023). This dataset contains data on the three canopy layers for the study area, albeit with one significant drawback; the canopy data was acquired in 2020. Bark beetle infestation during these 2-year timespan between the acquiring of this Canopy Data and the fuel modelling, could have significantly deteriorated the canopy of the study area's vegetation. Moreover, a time-consuming in-situ validation of the canopy characteristics, such as the one done by Heisig et al. (2022) was outside the scope of this study. Maps illustrating these inconsistencies can be found in the Appendix (Figure A.5 to Figure A.8)

Unfeasibility of validation through fieldwork, led to the abandonment of the inclusion of the three canopy layers as input to the fire modelling landscape.

2.2 Burn Probability and Flame Length

As discussed in Section 1.3.2, in order to derive exposure for the study area, the spatial juxtaposition of wildfire metrics of both intensity and likelihood, with the area's settlements needs to be calculated. (Abrahams et al., 2017). The variables that were used and which represent intensity and likelihood, are available in FlamMap. These are Flame Length and Burn Probability respectively (FlamMap Help, n.d.).

Burn probability (BP) can be understood as the likelihood that a location (a grid cell in the case of this study) will burn, taking into account the cumulative number of simulated fires (Sá et al., 2022). The BP of cell p can be calculated by the following ratio:

$$BP_p = \left(\frac{F_p}{N_p}\right)$$

wherein F_P denotes the frequency of cell p burning, out of a number of N_p simulated ignitions (Sá et al., 2022, p. 3922). In FlamMap, BP is one of the outputs of the Minimum Travel Time (MTT) Algorithm; The calculation of fire growth in the MTT algorithm involves the exploration of pathways that exhibit the minimum spread time among cells within a two-dimensional gridded landscape, operating at a spatial resolution determined by the user (in this thesis, 30m × 30m) (Finney, 2002 as cited in Sá et al., 2022). Wildfire spread is forecasted by employing Rothermel's model (Rothermel, 1972 as cited in (Finney, 2002 as cited in Sá et al., 2022), which calculates fire characteristics in the direction of the highest rate of spread. It is a commonly used metric, to estimate how exposed areas are to wildfires.

Flame Length, in general refers to the distance between the average flame tip and the middle of the flaming zone located at the base of the fire (*4.1 Flame Length | National Wildfire Coordinating Group*, n.d.). This measurement is taken on a slant when the flames are tilted as a result of the influence of wind and slope (Figure 5). Flame Length serves as a proxy for measuring fire intensity (Finney et al., 2021); longer flames signify a greater release of energy and longer flames lead to more fuel consumed per unit of time (Finney et al., 2021).

Figure 5: Flame Length, retrieved from *4.1 Flame Length | National Wildfire Coordinating Group* (n.d.)

Specifically for FlamMap, Flame Length (FL) is one of the Basic Fire Behaviour outputs; FL like all Basic Fire Behaviour outputs (e.g., Fireline Intensity, Heat per unit Area etc.) is generated for all cells of the fire modelling landscape, only taking into account the constant wind, and the other environmental conditions (e.g. fuel moisture) (Finney, 2006). This means that unlike Burn Probability and other MTT outputs, Flame Length does not consider ignition locations (Finney, 2002).

2.3 Creating Wildfire Scenarios

Three factors need to be considered when modelling fires in FlamMap, namely the ignition locations, the duration of the fires, and the weather in the location where the fires are taking place. These need to be carefully selected to give realistic outputs in terms of BP and FL. Nine different wildfire scenarios were examined in this study, after considering all possible combinations between three different duration scenarios (1, 2, 3 days) and three weather scenarios (winds occurring during periods of middle, high and very high risk of wildfire). Ignition locations as well as initial fuel moistures, were held constant in all nine scenarios.

Figure 6 will serve as a reference for various parts of Section 2.3 and 2.5:

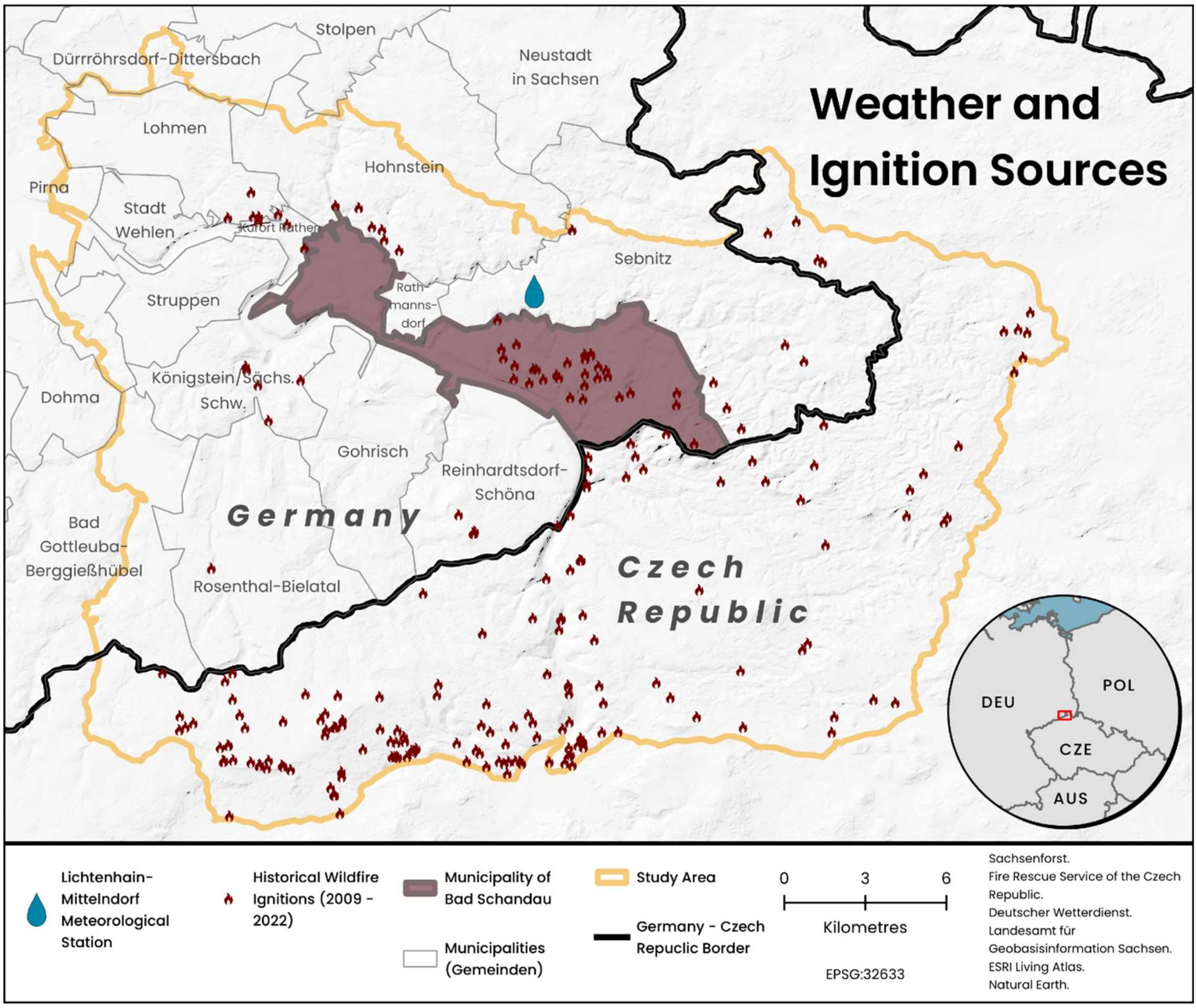


Figure 6: Map showing the ignition locations used in all FlamMap modelling runs. The location of the Lichtenhain-Mittlendorf meteorological station, from which all weather data was derived is also displayed. Finally, the municipalities that are in and around the study area (for each of which a daily Forest Fire Risk Index is calculated), as well as the one chosen to classify winds are visualised.[3]

2.3.1 Fire Duration

The duration of a modelling run in FlamMap is controlled by the Maximum Simulation Time parameter which takes minutes as its units (*FlamMap Help*, n.d.), The three input durations were decided to be 1,440 (1 day), 2,880 (2 days) and 4,320 minutes (3 days). This was done as a compromise between the many short hour wildfires that are assumed to often occur in the area, and the 20-day long 2022 wildfire that occurred in the study area (24.07.2022 – 12.08.2022), which is the only wildfire for whose duration reliable data could be retrieved. Unfortunately, no

[3] Terrain Hill-shade derived from ESRI's Living Atlas (ESRI, 2020). Country borders derived from Natural Earth (Natural Earth, 2023). Czech ignitions derived from the General Directorate of Fire Rescue Service of Czech Republic (data not publicly available) (n.d.). German ignitions derived from the Saxon state company for forests (data not publicly available) (Staatsbetrieb Sachsenforst, n.d.). Municipality borders derived from the Saxony State Office for Geographic Information (Landesamt für Geobasisinformation Sachsen, n.d.-b)

other data could be retrieved indicating the duration of historical fires in the region. Some authors have considered only one duration for their wildfire simulations; Mallinis et al. (2016) considered only one duration (480 min) based on the historical wildfire record of the region, while the one used by Mallinis (2014) was 360 min. Others, such as Sá et al. (2022) considered several (300, 540 and 720 min) durations.

2.3.2 Ignition Locations

Different approaches have been taken to select ignition locations. The simplest method, is to model randomly placed ignitions in a study area; Moghaddas et al. (2010) e.g., considered 1,000 random ignitions while Ager et al. (2011) 50,000. Such practice entails the inherent inaccuracy of ignitions being misplaced at either non-burnable material (e.g., water bodies), or at locations with a low chance of an ignition occurring. This inaccuracy is especially prominent in spatial contexts as the study area, which is located in Central Europe, a setting where the vast majority of wildfires are caused by humans, either as a result of accidents or deliberate acts of arson, and not chaotic phenomena such as lightning (Tedim et al., 2015). To counter this uncertainty, more sophisticated methods have been developed; Ager et al. (2018; 2019) considered historical ignition patterns in the area, while Sá et al. (2022) placed random ignitions after considering the historical probability of ignitions, and then used a fuel model to mask unburnable areas (Sá et al., 2022).

The method employed in this study was to use historical ignitions' locations from state fire services. Historical ignition data for the German part of the study area was acquired from the Saxon state company for forests (data not publicly available) (Staatsbetrieb Sachsenforst, n.d.). Ignition locations from the Czech part, were acquired from the Fire Rescue Service of the Czech Republic (data not publicly available) (The General Directorate of Fire Rescue Service of Czech Republic, n.d.). This data encompassed the locations of 163 ignitions on the Czech side and 60 on the German one. The ignition location of the 2022 fire (on the Czech side) needed to be manually added to the dataset as it had not yet been included in the respective dataset. This brought the total to 224 ignition locations (see Figure 6 for their spatial distribution); the fire of the first ignition started on 10.05.2008 and the fire resulting from the final ignition was extinguished on 12.08.2022 (Národní Park České Švýcarsko & CHKO Labské pískovce, 2022 as cite in Beetz, 2023).

For the fires to be input into FlamMap, they needed to be compiled into a Fire Size List File (*FlamMap Help*, n.d.). A Fire Size List File is a .txt file that is necessary to input multiple ignition locations into FlamMap (for single ignitions a .shp file suffices) and needs to hold the following information:

- FIRE_NUM (integer value used as Fire ID, does not need to be unique or in order)

- XStart (latitude in floating point format using the projection of the fire modelling landscape)

- YStart (longitude in floating point format using the projection of the fire modelling landscape)

To create this file, in ArcGIS Pro, first the Czech and German ignitions .shp files needed to be clipped to the study area and then merged. Then, the geometries (longitude and latitude) of the ignitions needed to be calculated using the ‘Calculate Geometry’ tool of ArcGIS Pro, and input into columns named ‘XStart’ and ‘YStart’ respectively, in ArcGIS Pro’s attribute table format. Finally, the default ‘OBJECTID’ id column needed to be renamed to ‘FIRE_NUM’. After exporting the attribute table of the .shp file as a .txt file, the result was a FlamMap-readable file.

2.3.3 Fire Weather

Fire weather is a term used to describe the dominant weather conditions that impact the behaviour of fires (Pausas & Keeley, 2021). Relative Humidity, cloud cover, precipitation types, wind speed and wind direction are all variables used to predict fire weather (US Department of Commerce - National Weather Service, n.d.). FlamMap provides three methods to model fire weather: wind characteristics (speed and direction), fuel moisture and canopy characteristics. Canopy characteristics -foliar moisture content and crown fire calculation method- do not affect the modelling runs of this study, as they concern canopy fires, which were not considered (due to the lack of canopy layers, as was discussed in Section 2.1.4).

Weather data was derived from the Climate Data Centre (CDC) of the German Meteorological Service (Deutscher Wetterdienst, or DWD for short) (Deutscher Wetterdienst, n.d.-a). The CDC provides access to many different meteorological variables for different intervals and at different stations. The station that was chosen for this study, is the Lichtenhain-Mittelndorf station (station id: 02985) (Figure 6). The selection of this weather station was motivated by the fact that it is the only station located inside the borders of the study area (leading to more accurate data), as well as it being a station that provides hourly data on all the required weather variables (wind speed and direction, but also temperature, relative humidity, precipitation, and cloud cover which were useful for the calculation of fuel moisture).

2.4 Fire Weather (Fuel Moisture)

2.4.1 Fuel moisture Content

Within any given fuel strata, component or particle, wildland fuels can be categorized as either dead or live. Dead fuel refers to the suspended or downed dead biomass, also known as necromass (Prichard et al., 2022). Live fuel encompasses the biomass of living organisms, including vascular plants such as trees, shrubs, and herbs, as well as nonvascular plants like mosses and ground lichens (Prichard et al., 2022). Wildland fires burn fuels that are a mix of live and dead vegetation, whose water content assumes a significant role in influencing the behaviour of a fire (Rothermel, 1983 as cited in Matthews, 2013); Specifically, fuel moisture content (FMC) -which can be understood as the mass of water per unit mass of dry material- influences the heat released when fuel is burned, as energy is required for water to be removed from vegetation for it to be burned (Matthews, 2013). Therefore, the moisture content of both living and dead fuels significantly impacts fuel consumption, energy release rate, fire spread, flame zone characteristics, and combustion occurring behind the flaming zone (Finney et al., 2021).

2.4.2 Dead VS Live Fuels

The distinction between live and dead fuels is primarily based on the difference in fuel moisture dynamics, which determines their combustibility. Both live and dead fuel properties are influenced by antecedent weather conditions, however, live fuel moistures are primarily regulated by factors such as phenology, transpiration, evaporation, and soil water, which are factors that vary among different taxa and across regional climates (Jolly et al., 2014 in (Prichard et al., 2022). In contrast, dead fuel moisture levels are determined by the physical properties of the fuel, such as size, density, and surface area, as well as their interaction with local climate, short-term weather dynamics (such as wind, solar radiation, and vapour pressure deficit), and available soil moisture (Fosberg et al., 1970; Viney, 1991 all as cited in Prichard et al., 2022). Some other differences between the two are displayed in the Figure A.9 of the Appendix.

2.4.3 Fuel Moisture in FlamMap

The state of knowledge regarding the burning and ignition of live fuels has been characterised as ‘abysmally poor’ due to the inherent complexity in understanding the diverse physiological and morphological characteristics of vegetation (Finney et al., 2021). It is perhaps because of this research gap, that live fuel moisture -although in reality fluctuating- is assumed to remain constant throughout a modelling run by FlamMap (*FlamMap Help*, n.d.). In contrast, it is possible to model changes in dead fuel moisture; FlamMap utilises an Initial Fuel Moisture File (.fms) and a Weather Stream File (.wxs) to achieve this. A .fms file is an ASCII text file which represents the starting dead fuel moistures, as well as the -constant- live fuel moistures of different fuels. The initial dead and live fuel moisture values were derived from Kudlackova et al. (2023), who acquired data from a fuel moisture monitoring station located at Mezní Louka, inside the study area borders: Dead fuel located in areas affected by bark beetle were set to values of 6, 7 and 8% for 1-hr, 10-hr, and 100-hr dead fuel, respectively. Initial dead fuel moistures in non-beetle killed areas were set to 3, 4, and 5% for the 1-hr, 10-hr, and 100-hr dead fuel, respectively. 1 hour, 10 hour, 100 hour, and 1000 hour fuel refer to round woody fuels in the diameter ranges of: 0-¼", ¼"-1", 1"-3", and 3"-8" (0-.635cm, 0.635-2.54cm, 2.54-7.62cm, and 7.62-20.32cm) respectively (*FlamMap Help*, n.d.). These durations are called ‘time lags’ and they represent the approximate time it would take for round woody fuels of those diameters to reach 1 – 1/e or 0.6321 (63.21%) of a new equilibrium moisture content (the moisture content within a fuel particle when it is neither gaining moisture from the air nor losing moisture to it) (Fosberg et al. 1970 as cited in Finney et al., 2021). In terms of live fuel moisture, this was set to 60% for the herbaceous vegetation and to 90% for live woody fuels (Kudlackova et al., 2023).

After inputting the initial fuel moistures, the next step was to provide the meteorological variables that represent the changing nature of weather: A .wxs file is also an ASCII file; it comprises of a collection of hourly observations on temperature, humidity, precipitation, wind speed, wind direction, and cloud cover that represent a temporal weather stream (*FlamMap Help*, n.d.). Although the weather stream oversimplifies the actual variation in weather, it serves as a practical means of limiting the amount of weather information for modelling the variation in dead fuel moistures caused by topography and shading (*FlamMap Help*, n.d.). Meteorological data from the Lichtenhain-Mittelndorf weather station were used for the six variables needed; specifically, data for the first three days of the 2022 fire that took place in the study area in 2022 (24.07.2022 – 26.07.2022) were used. Modelling runs utilised 24, 48 or 72 hourly data values depending on whether the modelling run simulated a 1, 2 or 3-day wildfire.

2.5 Fire Weather (Wind)

2.5.1 Wind and Wildfires

Wind is commonly understood to refer to the movements of ambient air that take place in various time intervals and spans across three spatial dimensions (Finney et al., 2021). This weather phenomenon can amplify a wildfire's potential destructive nature; Strong wind can often lead to severe fire weather when coupled with high temperatures and low humidity (Pausas & Keeley, 2021). Moreover, mega-fires, which are wildfires at the extreme of the frequency size distribution for an ecosystem, are often driven by strong winds (Pausas & Keeley, 2021).

Accurately describing the winds that impact wildland fires has been a challenging and enduring task (Beer, 1991; Finney et al., 2021). Many fire models simplify wind as a singular horizontal vector at a specific height above the ground. Consequently, wind speed (measured in metres per second) used in fire modelling smooths out the fluctuations in gusts and lulls, collapsing both vertical and horizontal vectors into a single velocity parallel to the ground surface (Finney et al., 2021). The inherent variability of wind across space and time further complicates its characterisation, even in the absence of fire, however, fires themselves significantly influence the local airflow patterns, making it particularly difficult to characterise wind within the flame zone (Finney et al., 2021). This difficulty arises partly due to the alterations in wind caused by the fire, the burned ground, and the vegetation structure in their immediate vicinity (Finney et al., 2021). Additionally, the inherent variability of wind at various scales adds to the challenge of accurately characterising its behaviour (Finney et al., 2021).

2.5.2 Wind in FlamMap

In FlamMap, a wind speed and direction are used at one point in time to calculate fire behaviour characteristics with no temporal variability considered (*FlamMap Help*, n.d.). Of the four different wind calculation approaches offered in FlamMap (single wind direction in every cell, aspect-derived uphill and downhill winds, and use of gridded winds through WindNinja), the use of WindNinja was deemed the most appropriate. WindNinja is a diagnostic model specifically developed to simulate microscale winds that are influenced by terrain (Forthofer et al., 2009). What WindNinja essentially does, is to consider the input wind speed and direction, as well as the slope of the fire modelling landscape, and to generate high resolution wind vectors, which give a more representative understanding of how terrain influences winds (Missoula Fire Sciences Laboratory, n.d.-b); the chosen resolution for this study was 40×40m.

WindNinja has been proven to be able to accurately depict significant terrain-induced flow characteristics, including the acceleration of wind speeds along ridgelines (Forthofer et al., 2014a as cited in Wagenbrenner et al., 2016). Furthermore, it has been proven to enhance the accuracy of wildfire spread forecasts in intricate topographical conditions (Forthofer et al., 2014b as cited in Wagenbrenner et al., 2016). This make WindNinja even more relevant to this study, as the study area is home to national parks with frequent uneven terrain.

Notwithstanding the added accuracy of Windninja, only one wind speed and direction are permitted per FlamMap modelling run. It is then crucial, to have accurate and representative wind vectors for each of the three desired fire weather scenarios (winds occurring during periods of middle, high and very high risk of wildfire).

2.5.3 Calculating Wind for Different Scenarios

A description of the wind classification method that was employed in this study is described in this Section.

2.5.3.1 Acquiring Wind Data

Similarly to the derivation of dead fuel moistures' weather parameters, hourly wind speed and direction data was derived from the Lichtenhain-Mittelndorf station through CDC (Deutscher Wetterdienst, n.d.-a). Specifically, the two wind variables data was derived from the earliest available day when this data was available for this station (01.11.1991) until the last day of the year the last ignition took place (31.12.2022).

2.5.3.2 Selection of Classification Method

Different authors use different wind classification schemes when modelling wildfires; Alcasena et al. (2017) e.g., considered five wind scenarios, considering the most frequent wind directions (frequency >5% in weather records) during wildfire season, and the respective 97th percentile wind speeds. They considered 16 wind directions. Sá et al. (2022) on the other hand, derived different weather types after classifying 326 fire weather days based on the average values of temperature (T), relative humidity (RH), and wind speed. Each fire weather type (frequent/hotter, drier/windier and cooler/wetter) then had a representative wind based on the average wind speed and the most common out of eight wind directions.

In the case of the present study, the Forest Fire Risk Index (Waldbrandgefahrenindex or 'WBI' for short) used by DWD was used to classify winds. WBI is based on the Canadian Fire Weather Index, while also adopting elements of the German Baumgartner and M68 indexes, and describes the meteorological potential for forest fire hazard risk; it enumerates this potential into 5 levels: 1 'very low risk of fire' up to 5 – 'very high risk of fire' (Deutscher Wetterdienst, n.d.-b). WBI's calculation relies on hourly time series data, encompassing air temperature, relative humidity, wind speed, precipitation and short- and long-wave radiation of the atmosphere (Deutscher Wetterdienst, n.d.-b). It is issued daily (at ~05:00 UTC) for various German state subdivisions (Deutscher Wetterdienst, n.d.-b), and this single value represents the highest hourly value recorded in the period 12-18 UTC (Wittich, n.d.). WBI is used by the state authorities responsible for forest fire prevention to assess the forest fire danger, to issue warnings and it generally serves as the fundamental framework for a standardised presentation of forest fire danger In Germany (Deutscher Wetterdienst, n.d.-c).

2.5.3.3 Wind Data Processing

WBI data for Saxon municipalities is available on the website of the Central German Information Service Agency (Mitteldeutsche Agentur für Informationsservice GmbH or 'mais' for short) (Mitteldeutsche Agentur für Informationsservice GmbH, n.d.). It is important to note at his point, that for unknown reasons, the WBI ranges from 0 to 4 for data downloaded from this website, compared to the 1 to 5 used in the DWD website; for consistency reasons, the highest WBI value shall be referred to as 5. The municipality of Bad Schandau (Region 17 on the mais website) was chosen for three reasons: a) due to it lying entirely in the study area, b) due to its proximity to the meteorological station of Lichtenhain-Mittelndorf, and c) due to it being the location where many ignitions have been recorded (Figure 6). The WBI values of all days between the range of 15.02.2009 (the earliest available date for this municipality) to 12.08.2022 (the day the fire resulting from the final ignition in the data was extinguished) were downloaded, totalling 4042 WBI daily values.

The next step was to categorise these dates according to their WBI. Because three fire weather scenarios are considered in this thesis, only three WBI values were used for categorisation, these being 3 (middle risk), 4 (high risk) and 5 (very high risk). This categorisation resulted in 3 .csv files each with 740 (WBI=3), 445 (WBI=4) and 45 (WBI=5) days.

Using these three files as filters, the hourly wind data for the Lichtenhain-Mittelndorf station was filtered into three new .csv files which hold hourly wind information only for those dates that had a pre-determined WBI value. Hourly values outside the 15.02.2009 – 12.08.2022 span were not used.

For each of these three .csv files holding hourly wind speed and direction data only for those days with a designated WBI value, the prominence of each wind direction was considered; similarly to Sá et al. (2022), eight wind directions were examined. 360° were divided into eight intervals, with each one having an open and a closed endpoint, e.g., for winds to be considered northeast, they would need to have a direction in the range of [22.5 °, 67.5 °). If then a wind direction would fall within a specific interval, it would then be categorized as one of eight representative winds (in the aforementioned example, a wind with a direction 29° would be considered northeast, i.e., 45°). A visualisation of the wind direction division can be seen in Figure A.10 of the Appendix.

The prominence of each wind direction is demonstrated in Figure 7; prominence was derived by counting the number of occurrences of each wind direction per WBI dataset, and dividing this by the total number of hourly wind observations. Higher percentages signify more prominent winds.

		Wind Direction (%)							
		N	NE	E	SE	S	SW	W	NW
WBI Values	3	12.54	9.98	5.41	9.03	24.84	5.04	15.65	17.5
	4	14.17	15.14	9.18	8.5	19.16	2.98	13.26	17.61
	5	6.03	8.89	8.57	17.14	31.75	4.44	13.65	9.52

Figure 7: Prominence of each wind direction for each of the three datasets with hourly winds. The three most prominent wind directions for each WBI value are highlighted.

The mean speed of all co-directional winds, per WBI dataset are shown below.

		Mean Speed (km/h)							
		N	NE	E	SE	S	SW	W	NW
WBI Values	3	13.0	16.01	12.6	7.02	16.65	12.28	14.85	14.93
	4	13.29	16.86	14.94	16.2	10.03	13.21	14.62	17.23
	5	12.64	12.42	12.09	17.4	17.21	11.08	13.59	17.62

Figure 8: The mean speed of every wind direction for each of the three hourly winds' WBI datasets is shown here. The mean speeds of the three most prominent wind directions for each WBI value are highlighted.

Wind roses were also created with the help of the windrose Python (Roubeyrie, n.d.) to visualise the distribution of directions as well as speeds of the winds for each WBI value. The classification of wind speeds is based on the classes of the Beaufort scale (Royal Meteorological Society, n.d.).

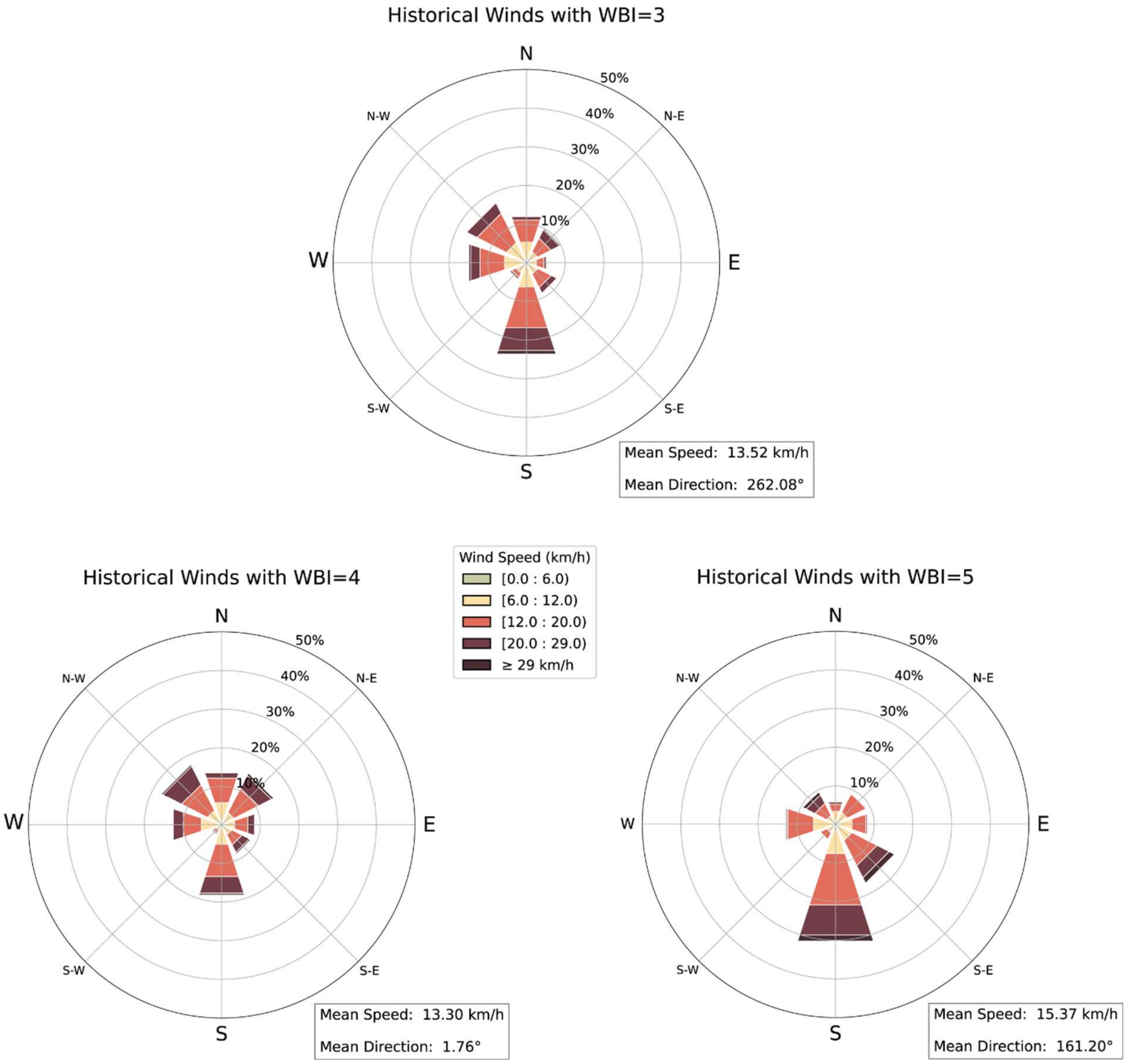


Figure 9: Wind roses for winds that occurred on days with WBI = 3, 4 and 5 in Bad Schandau from 15.02.2009 until 12.08.2022.

After this analysis, we finally had all the data necessary to model the nine wildfire scenarios (three fire weather and three duration scenarios) in FlamMap and to create a bivariate raster for each scenario; a bivariate exposure raster is needed for each scenario's respective exposure map.

2.6 From Modelling Runs to Bivariate Rasters

2.6.1 Workflow Introduction

To create the nine bivariate rasters, twenty-seven modelling runs needed to be executed in total; each of the nine wildfire scenarios (3 durations × 3 WBIs) has three prominent winds, with each wind needing a run of its own -as it was discussed previously, FlamMap can only take one wind per modelling run as input-. Figure 10 below, shows the workflow needed for the derivation of the bivariate raster representing the most extreme wildfire scenario; it models wildfires that lasted 3 days, under conditions of WBI=5.

As seen in Figure 10, for this wildfire scenario, three modelling runs needed to be executed, each for a Southeast (135°, 17.4 km/h), South (180°, 17.21 km/h) and West (270°, 13.59 km/h) wind. It is important to note that initial fuel moistures and ignition locations were common here, but also in all twenty-seven runs; only weather streams differed depending on if the scenario lasted 1, 2, or 3 days as was discussed in Section 2.4.3. Consequently, for the Figure 10 scenario, 3-day long weather streams were utilised for all three runs.

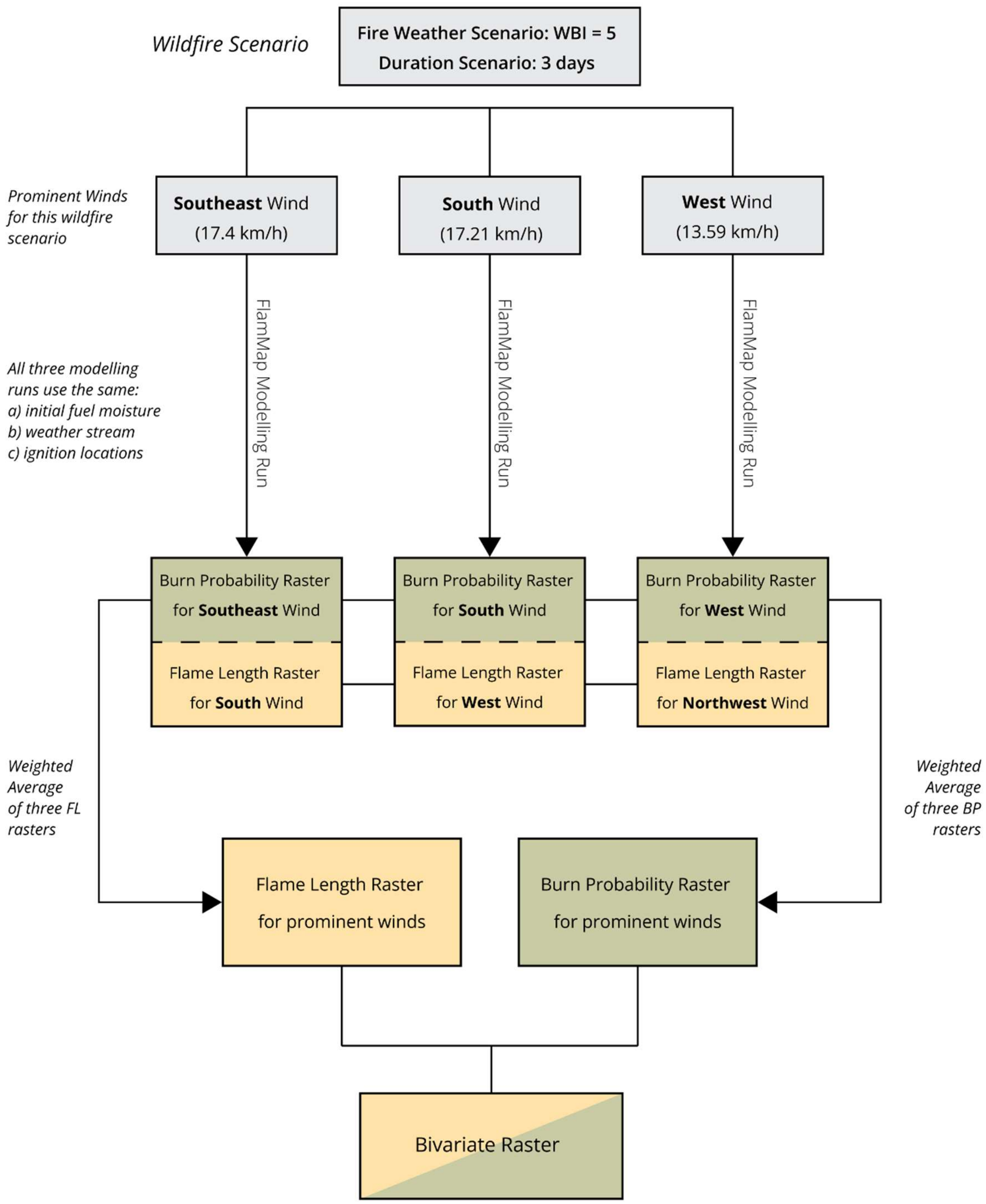


Figure 10: Workflow for the derivation of a bivariate raster for a wildfire scenario. Here, the example of a wildfire taking place under conditions WBI = 5 and which lasted 3 days is presented.

2.6.2 Weighted Mean Rasters

Each run resulted in two rasters; one for Flame Length, and one for Burn Probability, totalling to three FL and three BP rasters per wildfire scenario. The next step was to derive scenario-representative FL and BP rasters. This was achieved by creating weighted mean rasters for each of the two fire behaviour metrics. For each cell of the FL and BP weighted mean rasters, wind prominence percentages were used as weights in order to assign more importance to wind scenarios that occur more often. Specifically, for cell $[i, j]$ of a weighted mean raster WM, resulting from rasters r1, r2 and r3 with respective weights $\mathrm{r1}_{\mathrm{wind}_{\%}}$, $\mathrm{r2}_{\mathrm{wind}_{\%}}$, $\mathrm{r3}_{\mathrm{wind}_{\%}}$, its value was calculated as follows:

$$WM\ Raster\ [i, j] = \frac{\mathrm{r1}[i, j] * \mathrm{r1}_{\mathrm{wind}_{\%}} + \mathrm{r2}[i, j] * \mathrm{r2}_{\mathrm{wind}_{\%}} + \mathrm{r3}[i, j] * \mathrm{r3}_{\mathrm{wind}_{\%}}}{\mathrm{r1}_{\mathrm{wind}_{\%}} + \mathrm{r2}_{\mathrm{wind}_{\%}} + \mathrm{r3}_{\mathrm{wind}_{\%}}}$$

For each run, the values of both the initial six rasters and the resulting two weighted means ones, were classified into five classes. Burn Probability was classified as being either > 0.01, [1, 0.02), [0.02, 0.05), [0.05, 0.1) or ≥ 0.1. The classification was created after the execution of all runs, and after visually determining what classes can effectively represent burn probability without one class being overrepresented over the others. Five classes were created, to match the five classes of the Flame Length classification.

Flame Length's classification was derived from Sá et al. (2022), which in turn is an adaptation of the classification suggested by Alexander and Cruz (2019 as cited in Sá et al., 2022). This classification classifies Flame Length according to the difficulty of fire suppression:

Flame Length (m)	**Fire suppression difficulty**
< 1.5 (very low)	Fire can generally be attacked at the fire head or flanks using hand tools.
1.5 – 2.5 (low)	Fires are too intense for direct attack on the fire head using hand tools. Equipment such as plough, bulldozers, pumpers and retardant aircraft can be effective in suppression.
2.5 – 3.5 (moderate)	Fires may present serious control problems – torching out, crowning and spotting. Control efforts at the fire head will probably be ineffective.
3.5 – 5.5 (high)	Crowning, spotting and major fire runs are frequent. Control efforts at the fire head are ineffective. Aircraft are required for fire suppression.
> 5.5 (very high)	Any combat attempt (even with aircraft) is ineffective.

Figure 11: Flame Length classes and suppression difficulty. Adapted from Sá et al. (2022, p. 3933)

The corresponding Flame Length and Burn Probability rasters of the aforementioned wildfire scenario are shown in Figure 12 and Figure 13 respectively. Note that the local River Elbe was added to the Burn Probability rasters, as it became apparent that fires cannot cross it, creating a natural barrier:

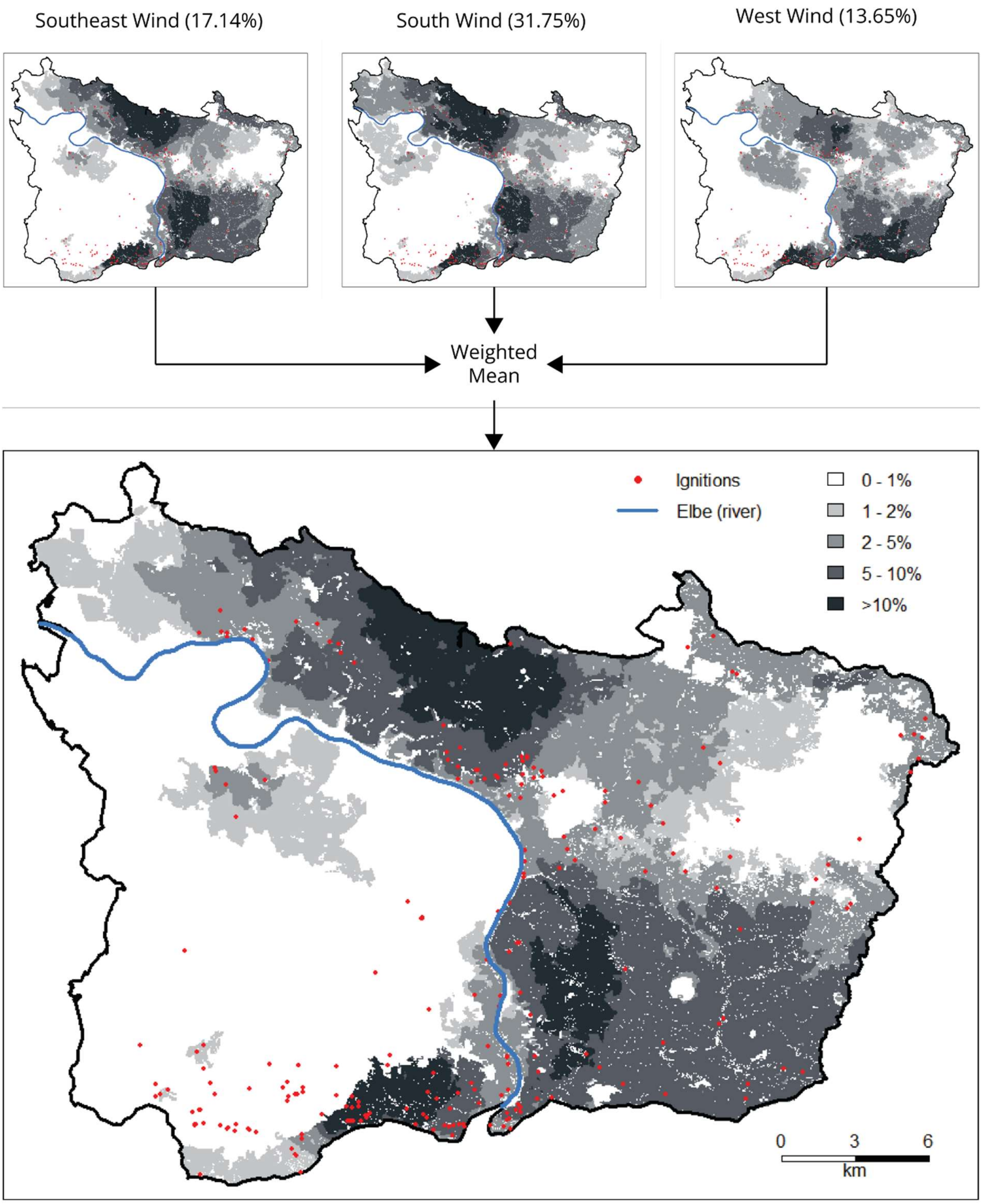


Figure 12: Derivation of weighted mean BP raster from the three BP rasters of prominent winds. This example showcases the scenario of a wildfire lasting 3 days under WBI = 5 conditions.

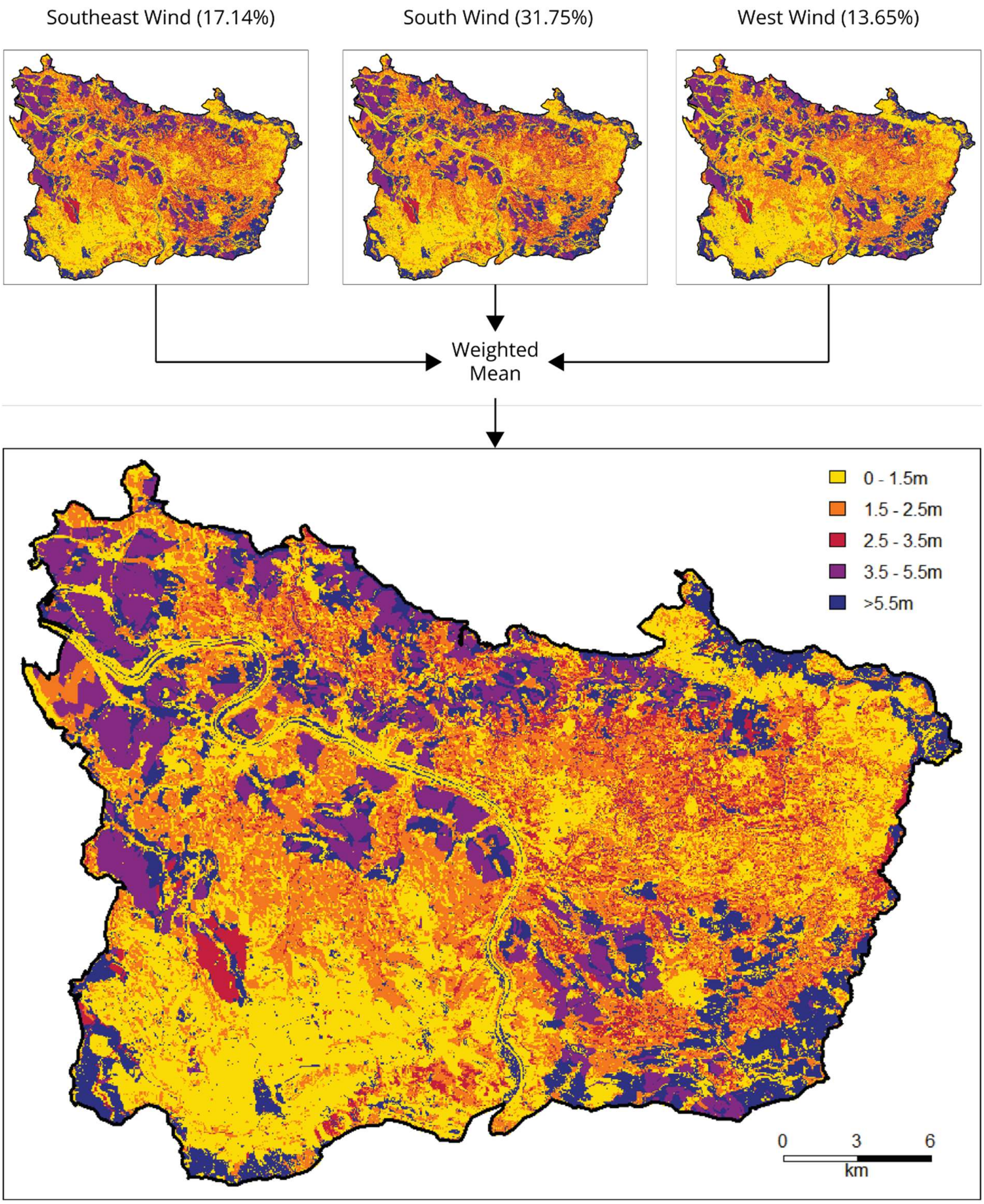


Figure 13: Derivation of weighted mean FL raster from the three FL rasters of prominent winds. This example showcases the scenario of a wildfire lasting 3 days under WBI = 5 conditions.

2.6.3 Bivariate Raster Algorithm

The algorithm which helped create the bivariate raster for each wildfire scenario was programmed in R, and was created based on the following steps:

1. An empty raster (NA values only) is created, of equal resolution, projection and dimensions to the weighted mean Flame Length and Burn Probability ones.
2. The code proceeds to subset cells in the new raster. It does this by selecting only those cells in the new that meet two specified conditions simultaneously. These conditions are based on values from the FL and BP rasters. For example, cells that have FL < 1.5 AND BP < 0.01 are selected: This means that cells in the new raster are only selected if the value in the corresponding cell of the FL raster is less than 1.5 and if the value in the corresponding cell of the BP raster is less than 0.01. If both conditions (FL < 1.5 and BP < 0.01) are met for a particular cell, that cell in the new raster is selected.
3. These selected cells of the new raster are assigned an integer value from 0 to 24 (25 in total).
4. This sub-setting and assigning of values process is repeated for 25 sets of conditions in total. Each pair of conditions defines a unique combination of classes in the BP and FL rasters. These 25 sets of conditions account for all possible combinations of classes, specifically, 5 BP classes multiplied by 5 FL classes. The possible combinations and the resulting value assigned to the new (bivariate) raster are indicated in the table below.

Flame Length (m)	Burn Probability (%)	Bivariate Raster Value
< 1.5	< 0.01	0
< 1.5	0.01 ≤ x < 0.02	1
< 1.5	0.02 ≤ x < 0.05	2
< 1.5	0.05 ≤ x < 0.01	3
< 1.5	≥ 0.1	4
1.5 ≤ x < 2.5	< 0.01	5
1.5 ≤ x < 2.5	0.01 ≤ x < 0.02	6
1.5 ≤ x < 2.5	0.02 ≤ x < 0.05	7
1.5 ≤ x < 2.5	0.05 ≤ x < 0.01	8
1.5 ≤ x < 2.5	≥ 0.1	9
2.5 ≤ x < 3.5	< 0.01	10
2.5 ≤ x < 3.5	0.01 ≤ x < 0.02	11
2.5 ≤ x < 3.5	0.02 ≤ x < 0.05	12
2.5 ≤ x < 3.5	0.05 ≤ x < 0.01	13
2.5 ≤ x < 3.5	≥ 0.1	14
3.5 ≤ x < 5.5	< 0.01	15
3.5 ≤ x < 5.5	0.01 ≤ x < 0.02	16
3.5 ≤ x < 5.5	0.02 ≤ x < 0.05	17
3.5 ≤ x < 5.5	0.05 ≤ x < 0.01	18
3.5 ≤ x < 5.5	≥ 0.1	19
≥ 5.5	< 0.01	20
≥ 5.5	0.01 ≤ x < 0.02	21
≥ 5.5	0.02 ≤ x < 0.05	22
≥ 5.5	0.05 ≤ x < 0.01	23
≥ 5.5	≥ 0.1	24

Figure 14: Combination of FL and BP classes and the respective bivariate raster value that is assigned.

5. The resulting raster has values 0 – 24, but it does not yet look like a bivariate raster. The final step required in transforming it into one, takes place when visualising it; each of

the 25 values, is assigned a colour. This colour simultaneously represents the FL and BP classes it holds. The respective colours of the bivariate raster, as well as the number to which each is assigned to are shown below:

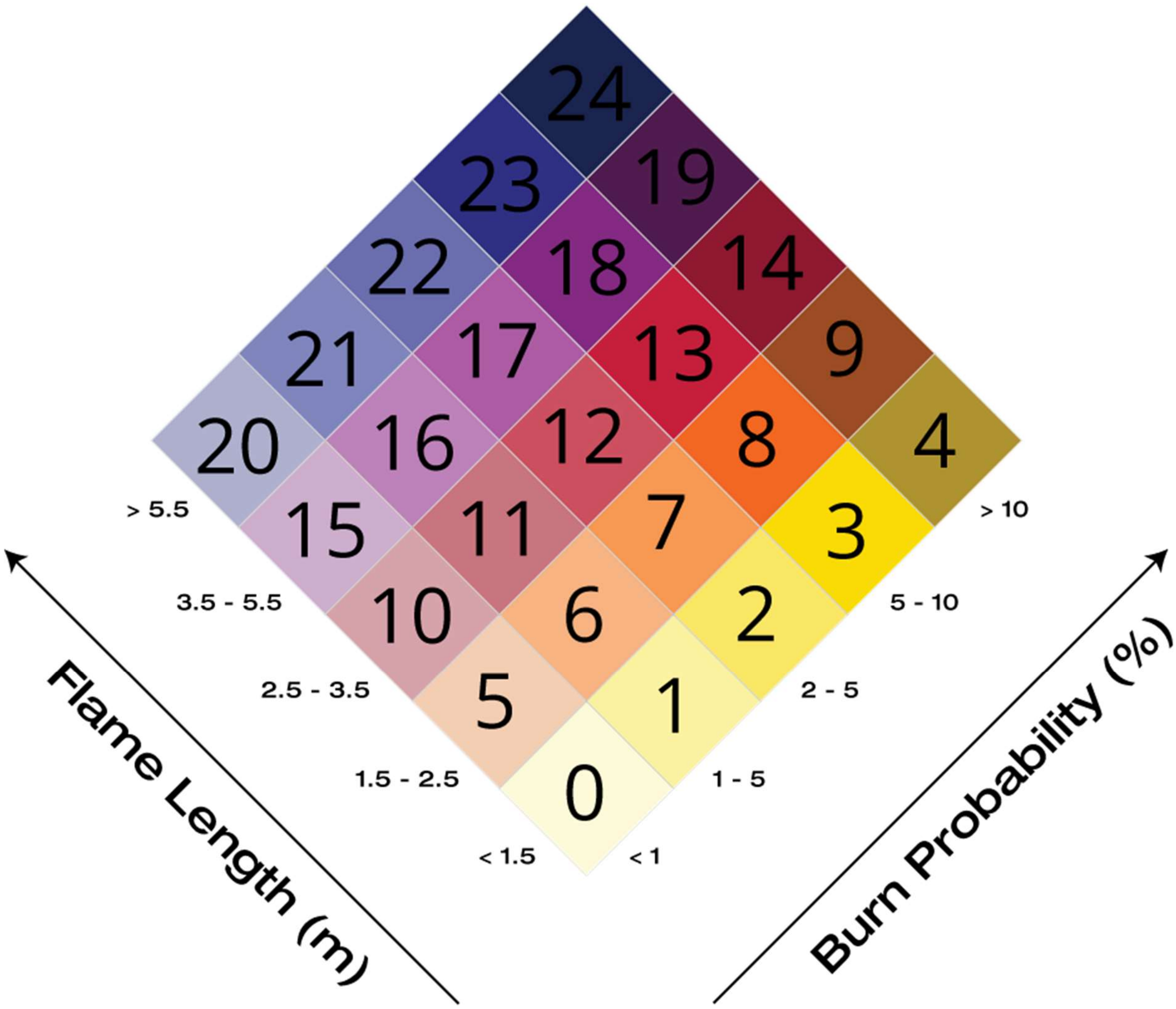


Figure 15: Bivariate raster legend. The bivariate raster's possible cell values are assigned to the respective colours used to represent them.

The bivariate raster algorithm, with its inputs and output is visualised below:

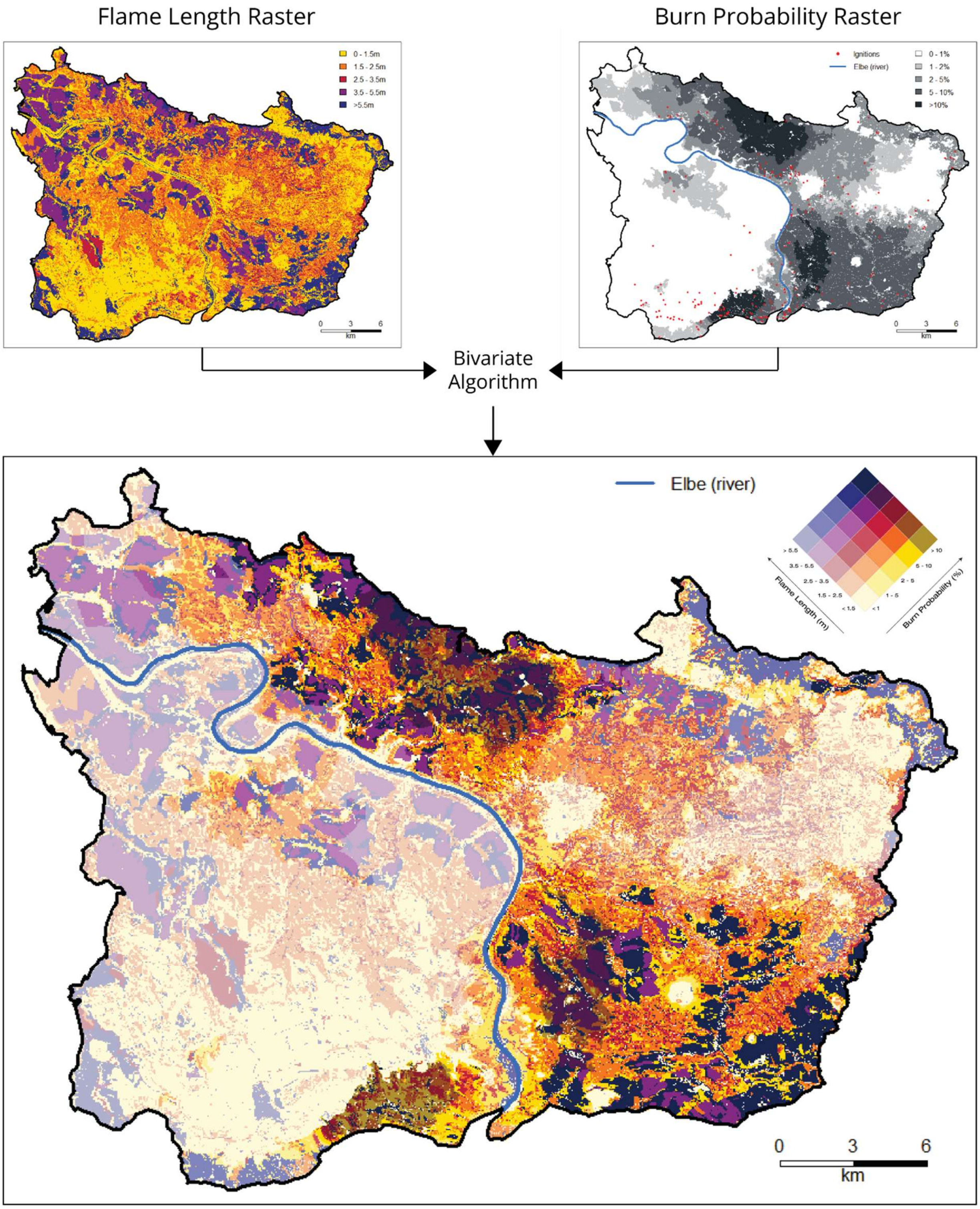


Figure 16: Derivation of bivariate raster from BP and FL rasters. This example showcases the scenario of a wildfire lasting 3 days under WBI = 5 conditions.

2.6.3.1 Selection of Colours

The bivariate raster's colours were created using the HSB (Hue Saturation Brightness) Colour Model. HSB is a way of representing and defining colours in terms of three perceptual properties; Hue refers to dominant visible wavelengths, saturation pertains to the degree to which white light is combined with a particular hue, and brightness refers to the intensity or degree of shading (*Colour Summary | Britannica*, n.d.). The individual colour scales of BP and FL were created based on the principle of holding two of these properties constant and varying the final one. In the case of FL, the varying property is hue; this ranges from yellow (low flames) to blue (high flames). For BP the varying property is saturation; this ranges from saturated shades of colours (low burn probability) to intense ones (high burn probability). The exception to this classification is the colours representing the highest burn probability (4, 9, 14, 19, 24). These colours, when compared to the immediately preceding BP class (3, 8, 13, 18, 23) show not only a (slight, when compared to the other BP classes' differences) increase in saturation, but also a significant decrease in brightness. Finally minimal adjustments were made on all three properties in order to make all 25 colours easily identifiable in case the application of a colouring principle did not result in significant enough colour differentiation. As an example, cells coloured with number 20 have high flame length (blue colour) but low burn probability (saturated colour). Conversely cells numbered 4, have low flame length (yellow colour) but high burn probability (intense and dark colour). The most exposed areas on the raster are assigned the number 24, signifying both high flame length as well as burn probability.

The FL colour scale was based on a colour scale commonly found to visualise meteorological phenomena such as precipitation. The main difference between such meteorological maps and the FL colour scale, is the lack of use of green in the latter; It is imperative to avoid including red and green with comparable luminosity in scientific visualisations as this may result in a significant portion of the audience being unable to differentiate between the two colours (Crameri et al., 2020). This is due to the fact that significant percentages of people suffer from colour vision deficiencies, such as Deuteranomaly and Protanomaly (they affect 5% and 1% of Western males respectively), which prevent the differentiation between red and green (Hunt & Pointer, 2011).

Following discussions with members of the Junior Professorship of TU Dresden as well as guest researchers it was decided to alter that initial bivariate colour scale so that one more hue would be added (blue) and the grey shades would be removed as they were deemed too different compared to the colours (Figure 17).

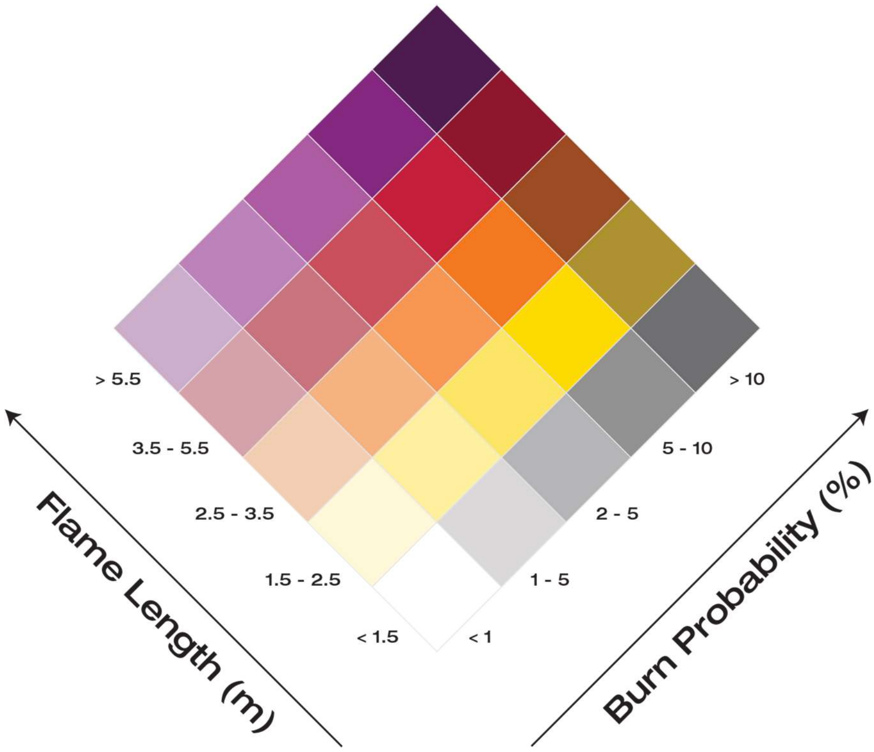


Figure 17: Preliminary version of bivariate raster's legend.

2.7 Adding Exposure and Vulnerability to the Raster

To derive wildfire exposure, the spatial juxtaposition of both wildfire likelihood and intensity metrics, with the location of assets needs to be showcased (Abrahams et al., 2017). The bivariate raster, whose workflow was described in Section 2.6, describes the two necessary wildfire intensity metrics. The next step then, was to integrate information on assets, which in the case of this thesis are considered to be human settlements in the study area. The derived results of this integration process was a preliminary static map, and a web-based interactive one.

2.7.1 Settlements

Settlements of the study area, for both the Czech Republic and Germany were derived from Geofabrik, where Open Street Maps data is available for download, coming in the format of point, line and polygon geolocated data (Geofabrik, n.d.). Only towns (4) and villages (73) were considered and then labelled, in order to not overpopulate the map with hamlets, farms and localities, which although potentially equally exposed, are much smaller and underpopulated when compared to bigger settlements. Some villages were duplicated, and needed to be deleted from one of the two country datasets, i.e., some villages from the German OSM data, were in the Czech side of the border. Apart from settlements, which are essentially a points layer, a polygon layer of buildings was also included. Although these polygons are barely visible in the preliminary static map, in the interactive map, a user may zoom in and observe which buildings of a settlement could be more exposed. This buildings' layer was also retrieved from OSM (Geofabrik, n.d.). With the settlements integrated, the exposure map is ready, however, as was stated in Section 1.4, two further layers were integrated, in order to represent vulnerability (specifically, support capability indicators).

2.7.2 Support Capability Indicators

As was discussed in Section 1.3.3, two variables that have been used to describe support capability in the face of wildfires are transportation network density (Bergonse et al., 2022) and settlements' distance to the nearest fire station (Oliveira et al., 2020). Two similar support capability indicators were likewise integrated into this study's exposure map, namely, the locations of fire stations and that of the local transportation infrastructure. For the location of both of these capabilities' indicators, a 30km circular buffer -from the centroid of the study area- was considered, primarily in order to take into account instances of fire stations outside the study area which are nevertheless nearby enough to provide rapid assistance in the case of a wildfire.

2.7.2.1 Fire Stations

To derive data on the location of German fire stations three sources were utilised; initially OSM, which is the same source used as with the settlements' locations (Geofabrik, n.d.). Secondly, to reinforce the scarce OSM data, fire stations' locations were provided upon personal request, by the District Fire Brigade Association of Saxon Switzerland-Osterzgebirge (*Kreisfeuerwehrverband – Sächsische Schweiz-Osterzgebirge e.V.*, 2023). Finally, the richest source of information was the online Geoportal Sachsenatlas of the Saxony State Office for Geographic Information (Landesamt für Geobasisinformation Sachsen, n.d.-c).

Similarly to Germany, OSM data was the first source used to derive fire stations' locations. for the Czech part of the 30km buffer (Geofabrik, n.d.). Because of the lack of stations in the buffer area, a further source was sought; the web map of the Hasičovo website provided the majority of fires stations' location information (Hasičovo, 2023).

A weakness that was observed in this support capability dataset, is the lack of information, on whether the fire stations were volunteer or professional ones; this distinction could affect the availability of personnel and resources in case of wildfires. All fire stations were eventually added and visualized in one class.

2.7.2.2 Transportation Infrastructure

Data on local transportation infrastructure was derived solely form OSM (Geofabrik, n.d.). OSM data on transportation infrastructure comes into several classes, which needed to be grouped, in order to not overburden the viewer with superfluous information, and to focus on car roads that fire engines can use. Groups were then created, based on the classification and explanation of classes found on OpenStreetMap Wiki, with each group getting a unique symbol (*OpenStreetMap Wiki*, n.d.). All roads classified as 'unclassified' were manually checked with

Google Earth and then reclassified appropriately. Note that the ‘Pedestrian Routes’ class was made exclusively visible in the interactive map upon zooming, as the hiking path network can be too small for the viewer to see on the static map, which was made with a scale of 1: 38 000.

2.8 Creating a Web-Based Interactive Map

2.8.1 Map Type and Tool Selection

What constitutes an interactive map has been a subject of debate; several scholars have argued that map sketches and paper maps should be considered interactive (Bertin, 1983; Dodge et al., 2008; MacEachren and Ganter, 1990; Peterson, 1998; Wood, 1993 all as cited in Roth, 2013) and that human interaction with analogue representations should guide the design of cartographic interfaces (Cartwright, 1999; Gersmehl, 1990; Goodchild, 1999; Kuhn, 1992; Slocum et al., 2001 all as cited in Roth, 2013). Nevertheless, the digital environment offers a broader range of interaction forms for manipulating cartographic representations, with the digital interactive map's interactions limited only by the map user's objectives, the developer's skill set, and the hardware's input, processing, and display capabilities (Gahegan, 1999 as cited in Roth, 2013). The concept of cartographic interaction then, can be understood to refer to the exchange between a human and a map facilitated by a computing device (Roth, 2013). This definition highlights the significance of digital interactions (Beaudouin-Lafon, 2004; Cartwright, 1999; Peterson, 1998; Roth, 2011; Yi et al., 2007 all as cited in Roth, 2013). According to this definition then, the second map (created after the preliminary static map), can be understood to be a digital interactive map.

It was determined that the utilisation of the World Wide Web represented the optimal platform for presenting the exposure information in a digital and interactive format. One notable benefit associated with the utilization of web technologies is the ability to seamlessly incorporate various modes of interaction (Wilkening et al., 2019). This integration empowers users to effortlessly navigate through the displayed dataset, fostering an intuitive exploration experience (Elmqvist et al., 2008 as cited in Wilkening et al., 2019). It was precisely because of this plethora of interaction methods permitted by the utilisation of a web-based map, that the web was chosen as the most suitable environment for this thesis’ digital interactive map. More specifically, the interactive map, was chosen to be created and hosted in ArcGIS Online and published and distributed as an Instant App (a format of online map distribution available on ArcGIS Online) (McPherson, 2021). The reasoning behind this is twofold; firstly, it was empirically verified that typical means of interaction for data exploration such as zooming, panning, and view configuration (Yi et al., as cited in Wilkening et al., 2019) are all featured in ArcGIS Online. Secondly, products developed by Esri (such as ArcGIS Online) are employed by various governmental and research-oriented organizations (Cooke, 2021), at various applications which include managing wildfire risk (A. Miller & Schultz, 2023) rendering a hypothetical integration or adoption of the interactive map by similar institutions potentially smoother.

2.8.2 Interactive Map Features

The first step in creating the interactive map was to publish the layers designed in ArcGIS Pro for the static map, to ArcGIS Online and input them in a new web map. The following eight layers were added:

Layer Name	**Layer Description**
Fire Stations	Layer showing location of fire station in the area contained within a 30km radius from the study area's centroid.
Historical Fires' Ignitions (2009-2022)	Layer presenting the location of all 224 fire ignitions used to derive wildfire likelihood and intensity metrics in FlamMap.
Settlements	Layer containing three sublayers; the first displays buildings' polygons in the study area, the second towns and cities (Ústí nad Labem is the only city; it is located inside the buffer but outside the study area) within the 30km buffer and the third villages inside the study area.
Transportation Networks	Layer encompassing four sublayers, each for a type of transportation route (major paved routes, minor paved routes, unpaved routes, pedestrian routes, and railways)
Burned Area from 2022 Fire	Layer showing the area burned by the 2022 wildfire that occurred in the study area.
Rivers & Canals	Layer displaying major waterways within the 30km buffer.
Borders & Areas	Layer containing seven sublayers; two for the study area's Conservation Areas, two for the study area's National Parks, the Germany-Czech Republic border, the limits of the study area and the limits of the 30km buffer.
Wildfire Exposure Rasters	Layer containing nine bivariate rasters, each for one of the nine wildfire scenarios defined by three different WBI conditions (3, 4, 5) and durations (1, 2, 3 days).

Figure 18: Interactive web map layers and layer descriptions.

Some adjustments needed to be made to the interactive map layers, to increase usability; firstly, the zoom level at which a layer becomes visible needed to be determined. This was done to not overburden the map with information deemed unnecessary at some zoom levels; for example, the 'buildings' sublayer is only visible at scales of 1: 20 000 and higher. Secondly, the style of the map's layers needed to be adjusted to maximise visibility and minimise confusion with other layers when changing the zoom level of the map; for most layers, automatic width adjustment was implemented. Finally, as the concept of WBI may be difficult to understand for new users, 'WBI Level 3', '4' and '5' were replaced in the sidebar by 'Fire Danger = medium', 'high' and 'very high'.

After the completion of the online map, an instant app was developed, in order to distribute it in an intuitive format, and in order to integrate further features. The map's layers were configured to be readily available on the left of the main map view, with the option to turn them visible or invisible with the press of a visibility button. Furthermore, a legend button was added, to help the user understand the meaning behind the bivariate rasters' colours with additional provided examples; the map's legend was designed with the possibility to have it remain open if the user chooses so, to permit a quick reminder of the significance of each colour while the user is simultaneously viewing the exposure rasters and navigating the map. A search bar was also included so that one may search for specific settlements. Additionally, a splash screen was added, which greets the user with a text explaining the background behind the map and its creator, as well as the focus of this thesis and a short explanation of the wildfire exposure rasters. After the user closes the splash screen, this information can be accessed once more with the press of a button. Finally, once the user closes the splash screen, the instant app was configured so that only certain layers are initially visible: the study area border, the border of the 30km buffer, all the transportation sublayers and all the settlements sublayers. This was done to not overwhelm the first-time user with too much information.

2.9 Map Evaluation Questionnaires

To evaluate the interactive map, two questionnaires were created and distributed. Morville (2004) developed the user experience honeycomb, to illustrate the seven facets of user experience (Figure 19). Based on this classification, it was decided that the two separate questionnaires would be developed so that each would evaluate the map in terms of a different user experience facet, namely Usability and Usefulness. The questionnaires were created in and distributed through Google Forms.

Figure 19: User Experience honeycomb developed by Morville (2004)

The usability of a product is determined by its ability to enable users to achieve their objectives with effectiveness, efficiency, and satisfaction within a specified context of use (International Organization for Standardization, 1997 as cited in Bevan, 2009). The attainment of usability is facilitated by adopting a design approach that places users at the centre, ensuring that the product incorporates features that promote usability (Bevan, 2009). To test whether the features of the interactive map where usable, a questionnaire was developed, which is a method commonly utilized to test the usability of interactive maps (by e.g., Flink et al., 2011; Wang, 2014). The questionnaire, which can be seen in Appendix B, can be conceptually divided into four parts: First, the participant was prompted to open the interactive map through the provided link and to read an introductory message explaining the map and its background (the same text utilised in the interactive map's splash page). Secondly, user-profile questions were asked, to determine the participant's familiarity with maps. Thirdly, an activity needed to be completed by the user. This activity contained five tasks, that would encourage the user to interact with the map; the user was then asked to rate the difficulty of completing those tasks. The final questions concerned the design of the exposure rasters, and the understandability of its colours, as well as the overall strengths and weaknesses of the map's design. Likert-scale questions were the preferred question method used, as they were deemed appropriate for classifying, the large number of responses that was expected. The usability questionnaire was distributed to friends, colleagues and family members, and there was an attempt to balance the participation between those who were Cartography students/professionals, and those who were not.

Usefulness has been defined as "the extent to which a system's functions allow users to complete a set of tasks and fulfil specific goals in a particular context of use" (MacDonald & Atwood, 2014, p. 886). In the case of this thesis, a usefulness questionnaire was developed to test whether the developed interactive map could potentially assist stakeholders in their wildfire protection management taking place in the study area. The usefulness questionnaire can be found in Appendix C. The first part of the usefulness questionnaire was identical to the usability one, with the exception that the initial screen provided respondents with the possibility to select the language in which they would like to answer it; Full versions for English and German were implemented, while a Czech version was also an option; it showed a Czech translation of the first part, though it then switched to English for the subsequent parts. The second part included questions regarding the respondents' field of work and their association with the study area, as well as their familiarity with maps. The third part was identical to the third part of the usability questionnaire (activity). The final part asked the respondents to rate the layers of the interactive map with Lickert-scales according to their relevancy to their work, and to consider scenarios where the map would be useful in their work. The usefulness questionnaire was mostly based on open questions with the exception of the Lickert-scale layers' ranking. Nine different stakeholders were identified as having a direct interest in the wildfire management of the study area and were subsequently sent the usefulness questionnaire via email. This group of potential respondents included a local high ranking fire brigade officer, students undertaking theses related to the National Parks, and researchers and administrators associated with both National Parks. A guide to the usage of the interactive map, in German and English was created and then attached to each email sent, to optionally be used as a reference in case the respondent was not familiar with interactive maps.

3 Results and Evaluation

In this chapter, the two created maps will be shown, followed by an evaluation of FlamMap, and the wildfire weather scenarios created, as well as an analysis of the questionnaires' answers.

3.1 Static Map

Before creating the interactive exposure map, a static one was made, as a testbed for the aforementioned layers (see Figure 18) that would be used in the interactive one. The resulting static map is shown in Figure 20; note that only one wildfire scenario can be visualised (here, it is WBI = 5 and duration = 3 days) and as the intended printed size is A0, not all of the information is visible (a zoomed-in detail is included for clarification). Custom ignition and fire station symbols were created in Illustrator. The triangular legend was also developed in Illustrator. The rest of the map design was made in ArcGIS Pro.

What becomes apparent when viewing the map is the large amount of information contained in it, notwithstanding the fact that some layers included in the online interactive map are absent here; these are the national parks'/conservation areas' borders, the burned area from the 2022 fire and pedestrian routes and the 30km buffer's border, which would in any case lie outside the limited extent of the static map. It is precisely because of this large amount of information that it was decided to create the static map with a printed size of A0; it was empirically discovered that anything smaller would compromise the visibility of the included layers.

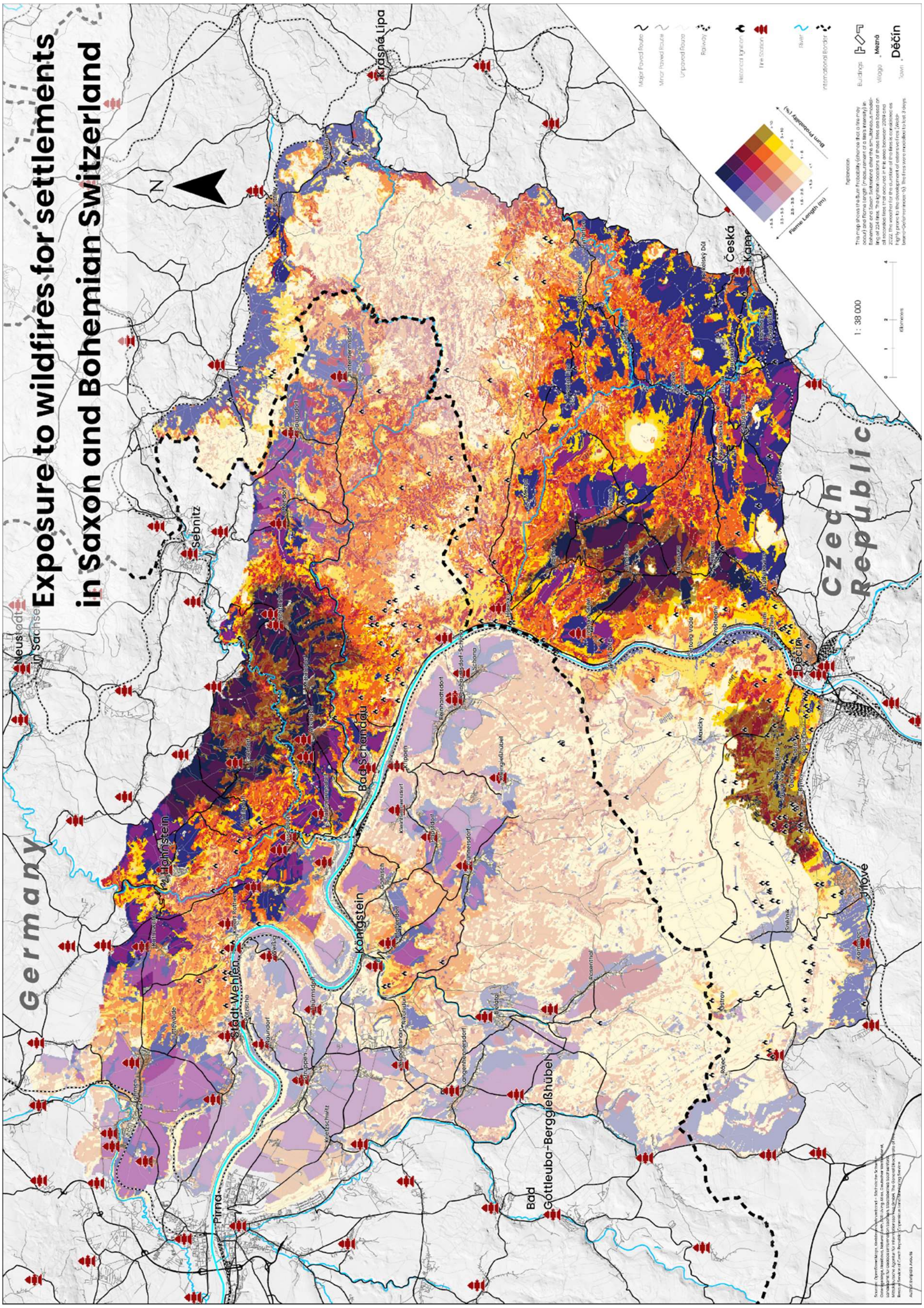


Figure 20: Static exposure map for wildfire scenario WBI = 5, duration = 3 days. Actual map size is A0.

Below is a detail of the static map, showcasing wildfire exposure in the vicinity of the Czech villages of Hřensko, Mezná and Janov. Mezná is the only settlement in the study area which had buildings burned during the 2022 wildfire (Staatsbetrieb Sachsenforst et al., 2022 as cited in Beetz, 2023); of notice here is that for this wildfire scenario, there is a prominence of dark blue areas indicating an area with the highest potential Flame Length class (>5.5) and the second highest Burn Probability (5-10%). Although hard to do, it is possible to see the buildings of these settlements (in Mezná these are located inside the light yellow areas inside the blue area). A river, some major paved routes (solid dark line), minor routes (grey lines), and historical ignition locations are also visible. It can also be inferred that there is a fire station located in the village of Hřensko.

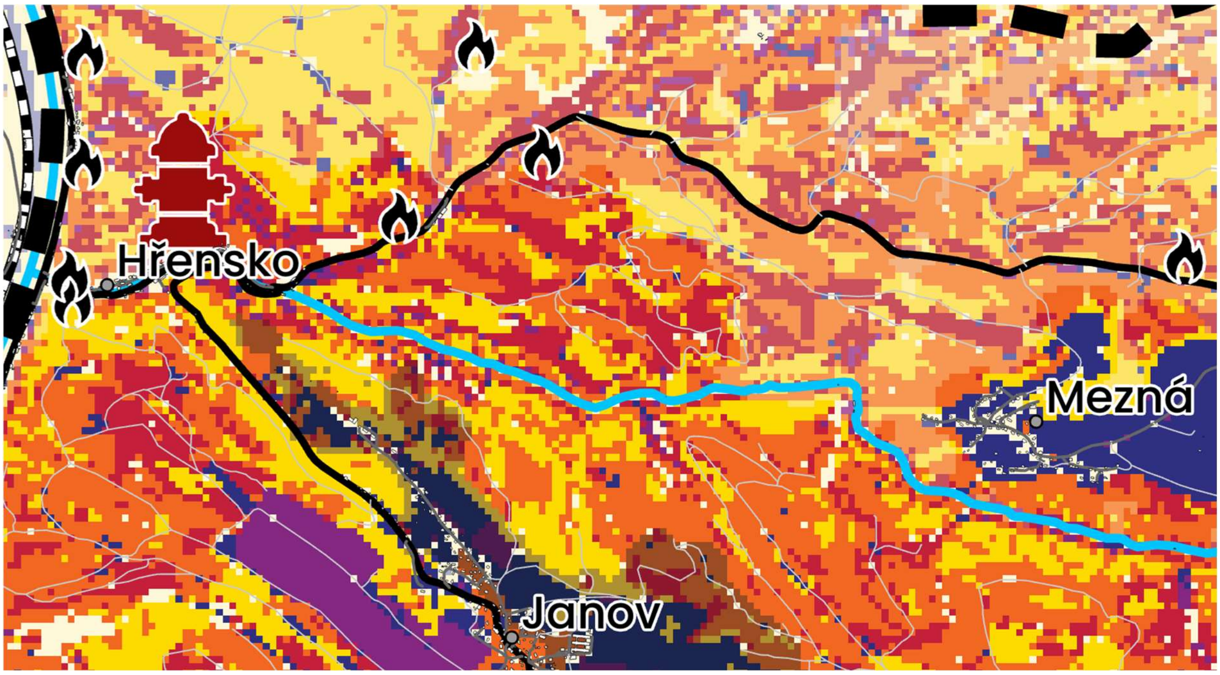


Figure 21: Detail from static map (WBI = 5, duration = 3 days), showing villages of Hřensko, Mezná, Janov and their surroundings.

Below, the static map legend is displayed.

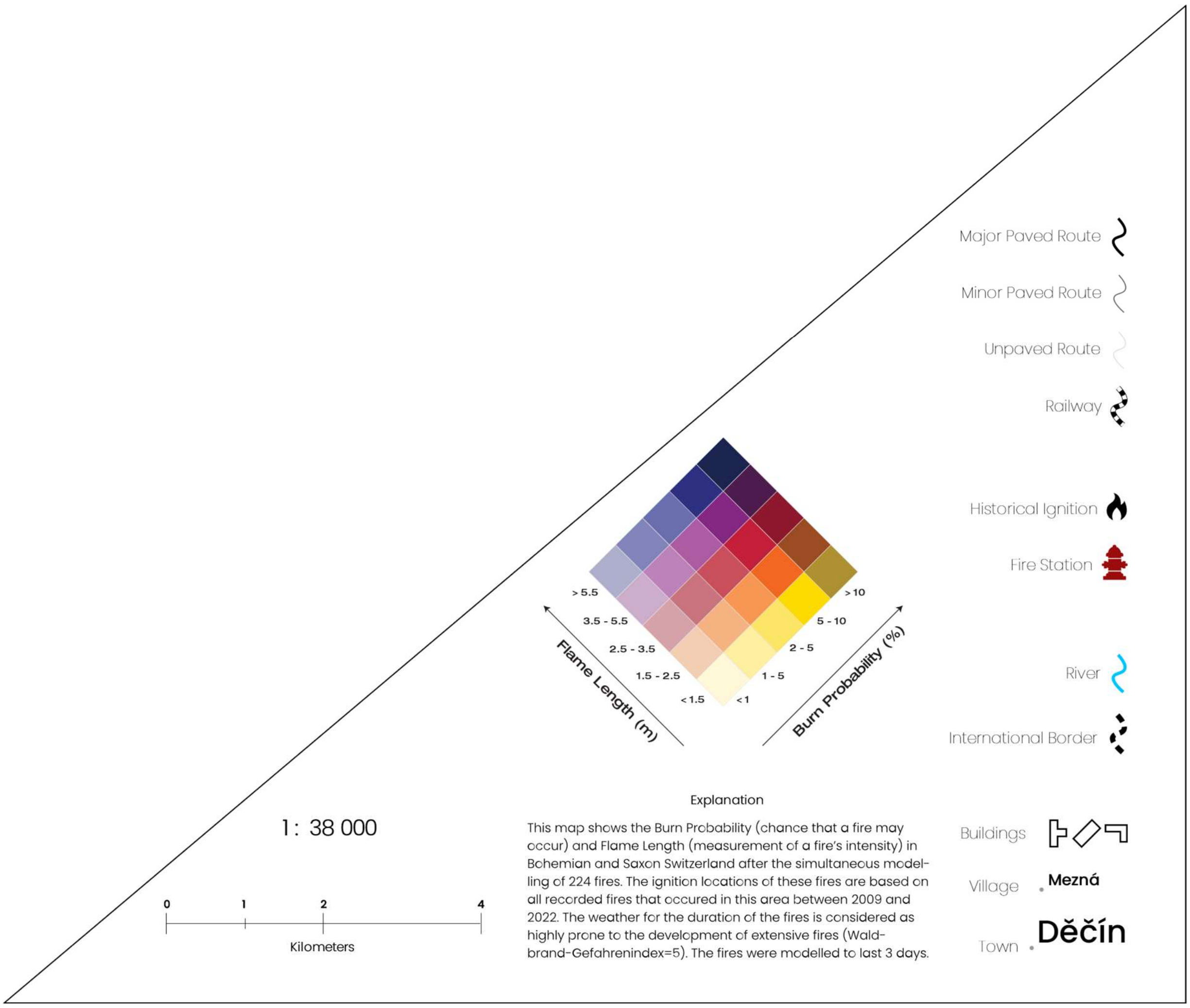


Figure 22: Zoomed-in legend of static map.

3.2 Interactive Map

ArcGIS Online was used to develop the web-based interactive map which was published as an instant app. The map can be accessed here. The main features of the map are marked in Figure 23:

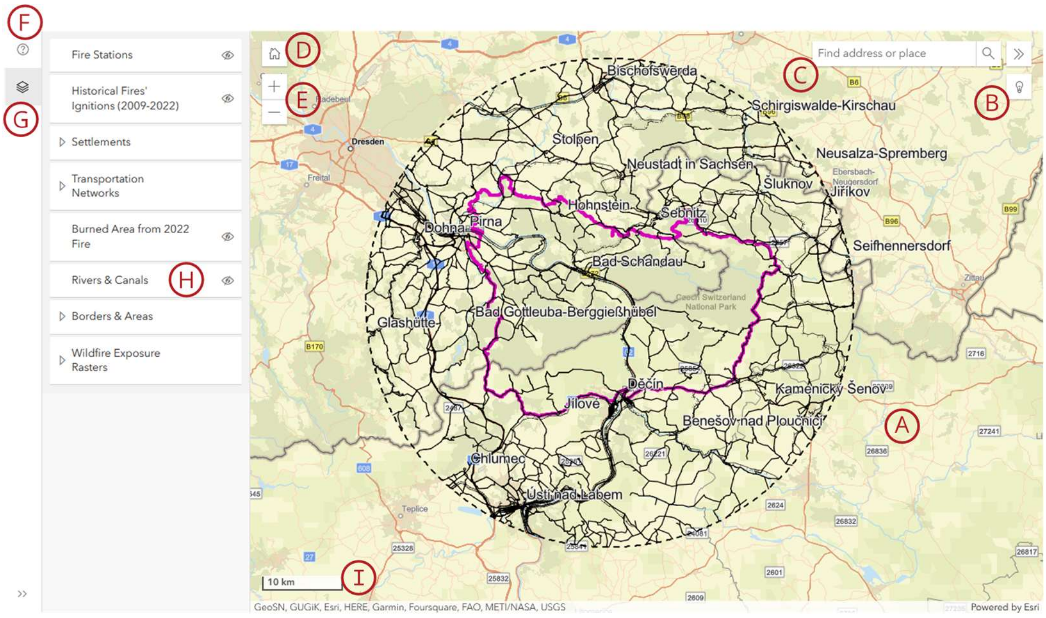


Figure 23: Interactive web map features.

Figure 23 shows the initial map view which appears after closing the splash screen. As was discussed in the previous chapter, initially, only certain layers are available. Here, apart from the basemap, the towns/cities, the Major Paved Roads, the study area borders and the 30km buffer area may be seen in the main window marked with ‘A’. The lighting bulb button ‘B’ may be used to bring up the splash screen once more and the search bar ‘C’ can be used to search for locations in the study area but also outside of it. ‘D’ is the home button which when pressed brings the user to the initial zoom level, and the zoom buttons ‘E’ can be pressed to alter it. The question mark button ‘F’ brings up the legend and the layer button ‘G’ may be used to hide and unhide the left-hand layers menu. ‘H’ is placed on a typical layer; one may press the eye symbol on the left to make the ‘Rivers & Canals’ layer visible. Finally, ‘I’ is placed next to the map’s scale bar, which updates according to the current zoom level.

A potential use case map configuration is shown below. The Wildfire Exposure layer ‘Fire Danger = very high, duration = 3 days’ has been made visible, and the map has been zoomed to the centre of the village of Mezná, to assess which buildings may be more exposed in case of this wildfire scenario. The legend has also been maintained open, to facilitate identification of Flame Length and Burn Probability levels observed. Finally, one may also observe two transportation layers, namely the Minor Paved (in grey) and the Pedestrian Routes (in gold) the in the vicinity.

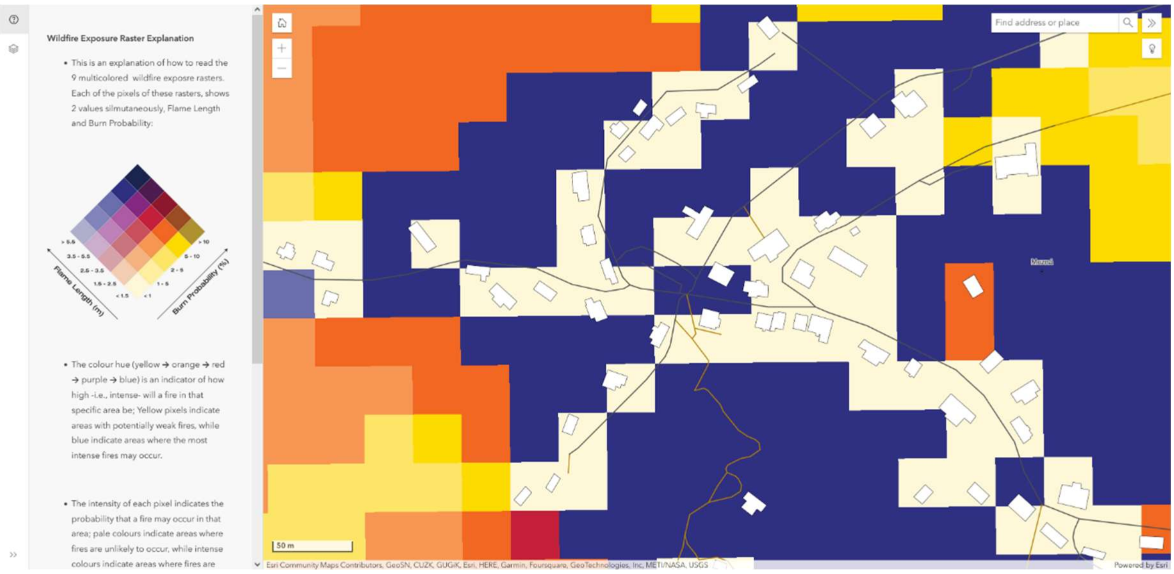


Figure 24: Interactive web-map example usage.

3.3 Modelling Evaluation

Extensive evaluation of models should be considered an essential and vital component of the model development process, particularly when the primary objective of the model is to facilitate decision-making (Jakeman et al., 2006; Alexandrov et al., 2011 both as cited in Alexander & Cruz, 2013). This is relevant to the modelling of hazardous events such as wildfires, specifically, the pursuit of transposing modelling outputs from simulations to specific disaster management applications, as is the case with this thesis (Alexander & Cruz, 2013). It is then crucial to assess the accuracy of the wildfire behaviour characteristics output of this study.

3.3.1 Evaluation of Modelling Scenarios

There exists a number of approaches employed to assess the accuracy of fire modelling: Sá et al. (2022) is an example of a vigorously comprehensive approach; they calibrated their model by adjusting fire durations and frequency until the simulated fires' characteristics accurately described the historical fire size distribution patterns (Figure 25.c below). Moreover, they checked whether high Burn Probability areas in their output, was coincident with parts of their study area that had historically higher ignition probability (Figure 25.a below) and that burned more often (Figure 25.b below).

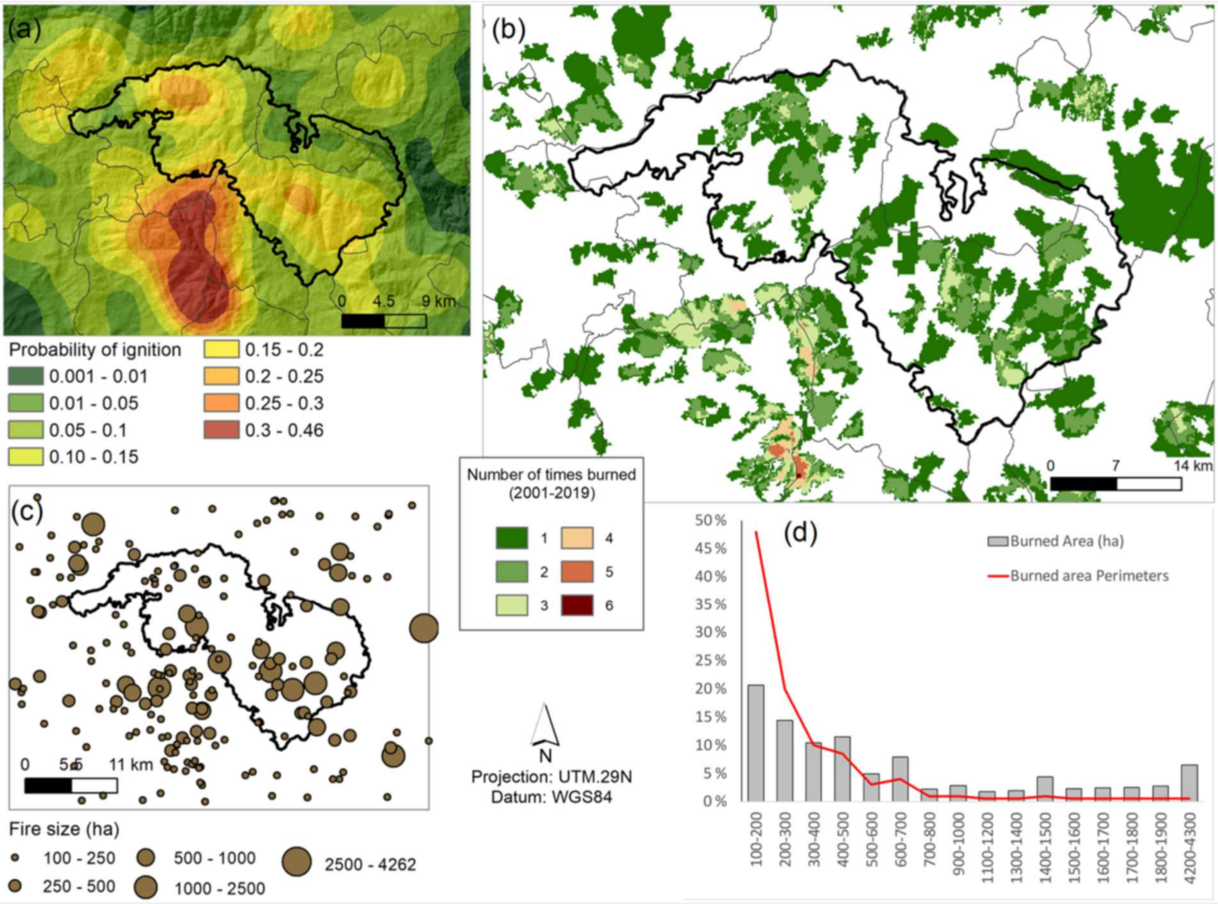


Figure 25: 'Historical wildfire data description for burned area perimeters larger than 100 ha, from 2001 to 2019: (a) probability of ignition, (b) frequency of burning, (c) fire sizes, and (d) percentage of the number of fire perimeters and burned area perimeters by classes of area'. Derived from Sá et al (2022, p. 3920).

The only historical information concerning wildfires for the study area, were historical ignition locations, and the fire perimeter of the 2022 wildfire. The first of the two, were used as input ignition locations in the FlamMap modelling runs (see Section 2.3.2). This left only the 2022 wildfire's fire perimeter to be used as validation data. The evaluation method that was employed to test the accuracy of FlamMap was then decided to be a comparison between the validation fire perimeter, and the nine fire perimeters derived from modelling runs which considered each of the nine wildfire scenarios examined in this thesis; for each of the nine scenarios, three modelling runs were conducted, one for each of the three prominent winds for that scenario (see Figure 7 and Figure 8), and the resulting modelled fire perimeter shows the coinciding areas that burned in all three modelling runs per wildfire scenario. As opposed to the modelling runs that led to the BP and FL outputs -which considered 224 historical ignitions-, a sole ignition was considered this time, that of the 2022 wildfire. What is tested with this evaluation method, is whether the wildfire scenarios that were created in this thesis, could have been able to accurately predict a wildfire's behaviour, given that its ignition location is known.

The selected output was Rate of Spread, an output employing the Minimum Travel Time algorithm, similarly to Burn Probability (*FlamMap Help*, n.d.). Rate of Spread displays the spread rate (in m/min) of the wildfire as it encountered each node in the direction along the minimum travel time path, though when considered as a single-value raster, it returns the overall fire perimeter. The resulting map matrix is shown in Figure 26. In each of the nine maps, the green area indicates places that burned in the model and also during the actual fire, the red area displays locations that burned in the model but not during the actual fire, and the yellow area represents the area that burned during the 2022 wildfire which was not burned in the models. The ignition location is represented by a black flame. Each map is accompanied by a pie chart; it shows the percentage of the modelled fire that correctly (green) and incorrectly (red) lied within the limits of the validation fire perimeter.

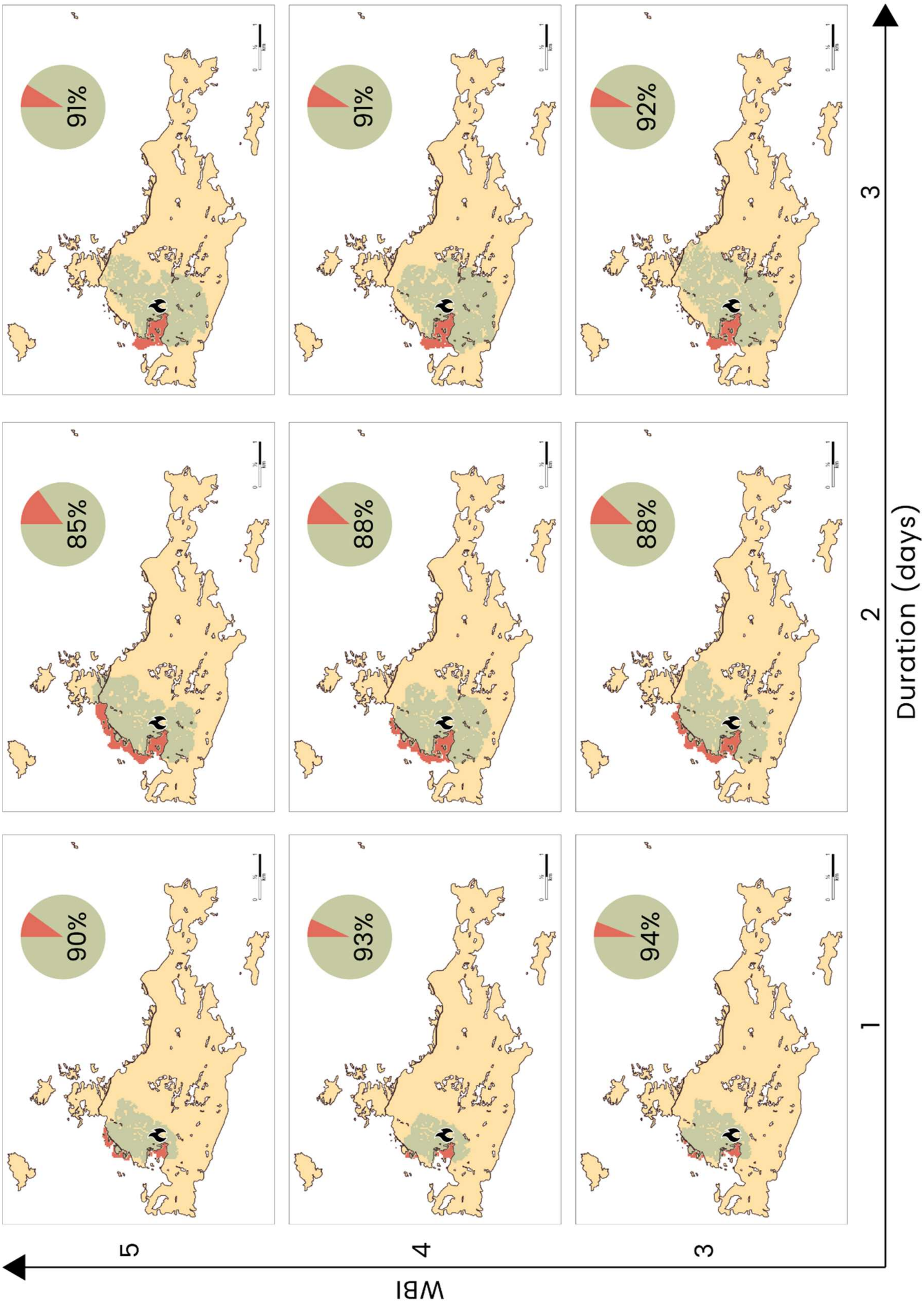


Figure 26: Map matrix comparing the extent of the 2022 study area wildfire, with the extent of nine FlamMap-modelled wildfires, each considering a wildfire scenario devised in this thesis.

Modelling accuracy here ranges from 85% (WBI = 3, duration = 2 days) to 94% (WBI = 3, duration = 1 day) while the total coverage ranges from 8% (WBI = 2, duration = 1) to 24% (WBI = 2,3 both for 3 days). The low coverage can be assigned to the fact that the maximum duration of the modelling scenarios is only 3 days, compared to the 12 days that the 2022 wildfire lasted. However, the areas that did burn in the modelling runs, are accurate, albeit small. It should be mentioned, that although perhaps perplexing at first, it shouldn't come as a surprise that higher WBI scenarios do not necessarily lead to larger burned areas, as WBI is an index indicating risk of a wildfire and not an indicator of a potential wildfire's size (Deutscher Wetterdienst, n.d.-b).

3.3.2 FlamMap Evaluation

A second evaluation was undertaken in order to test the overall ability of FlamMap to accurately model wildfires. For this evaluation, the three first days of the 2022 wildfire were modelled with the utilization of three modelling runs, each lasting one day; the first run used the 2022 wildfire ignition as its ignition location, as well as the mean daily wind and fuel moistures of the first day of the 2022 wildfire (24.07.2022). The second run used a point layer describing the perimeter of the first modelled fire as its multiple ignition locations, as well as the mean daily wind and fuel moistures of the second day of fire (25.07.2022). The third run used a point layer describing the perimeter of the second day modelled fire as its multiple ignition locations, as well as the mean daily wind and fuel moisture of the third day of fire (26.07.2022). The usage of three different runs, was done to counter the inaccuracies that might develop when using one sole wind to represent varying wind conditions that last multiple days, as was the case with the wind conditions of the 2022 wildfire. A time series of the mean daily wind velocities of the 2022 wildfire are displayed below, along with the daily WBI values; notice the constantly changing wind direction:

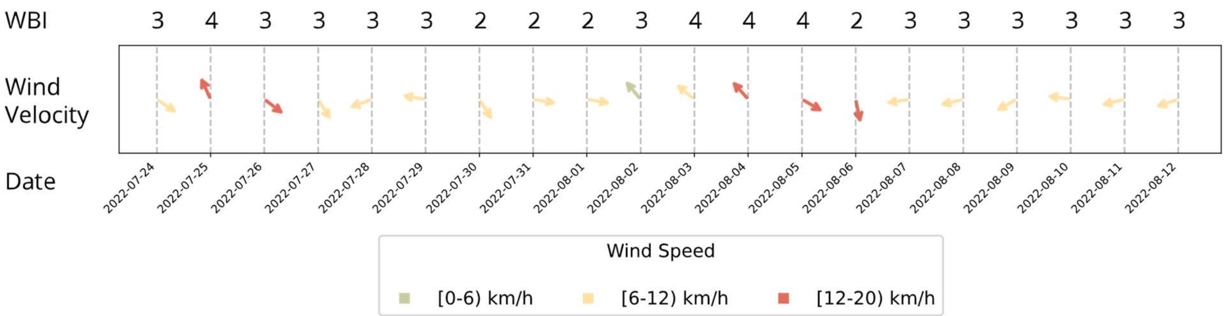


Figure 27: Time series showing wind velocity (speed and direction), as well as daily WBI values throughout the duration of the 2022 study area wildfire.

The results of these three modelling runs, were compared to data derived from active fire detection remote sensing products accessed from NASA's Fire Information for Resource Management System (FIRMS). FIRMS distributes Near Real-Time (NRT) active fire / thermal anomalies data from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua and Terra satellites, and the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard S-NPP and NOAA 20 (formally known as JPSS-1) (*NASA-FIRMS*, n.d.). This data comes into

375m and 1km (at nadir) resolutions (for locations derived from VIIRS and MODIS respectively) (Earth Science Data Systems, NASA, n.d.-a, Earth Science Data Systems, NASA, n.d.-b).

In terms of MODIS-derived data, the thermal anomalies / active fire data, represent the centre of a 1 km pixel that is flagged by the MODIS MOD14/MYD14 Fire and Thermal Anomalies algorithm (Giglio, 2003 as cited in Earth Science Data Systems, NASA, n.d.-a) as containing one or more fires within the pixel. This is the most basic fire product in which active fires and other thermal anomalies, such as volcanoes, are identified (Earth Science Data Systems, NASA, n.d.-a). The VIIRS data exhibits superior sensitivity towards fires of smaller extents and offers enhanced delineation of expansive fire boundaries, in contrast to alternative satellite fire detection products with coarser resolutions (≥1 km) (Earth Science Data Systems, NASA, n.d.-b). As a result, VIIRS data is highly suitable for utilisation in fire management endeavours, such as near real-time alert systems, and also prove valuable for other scientific applications that necessitate enhanced accuracy in fire mapping (Earth Science Data Systems, NASA, n.d.-b).

For this evaluation, the available VIIRS and MODIS detected active fires for the first three days of the 2022 wildfire (24.07.2022 – 26.07.2022), where merged and then classified into three daily layers. These fires where then compared to the fire perimeters derived from the three aforementioned FlamMap modelling runs, which were also done for the first three days of the 2022 wildfire: As can be seen on Figure 28, there is noticeable overlap between the two, especially for the second and third days of the fire, and when considering the accuracy of the combined burned modelled area for all three days:

	Percentage inside FlamMap-modelled burned area for that day
1st day detected fires	11%
2nd day detected fires	52%
3rd day detected fires	69%
Total detected fires	**84%**

Figure 28: Comparison of MODIS and VIIRS-derived fire locations, with FlamMap modelling runs for the same wildfire.

The resulting map showing both the satellite-detected fires as well as the FlamMap-modelled daily fire perimeters, is displayed below:

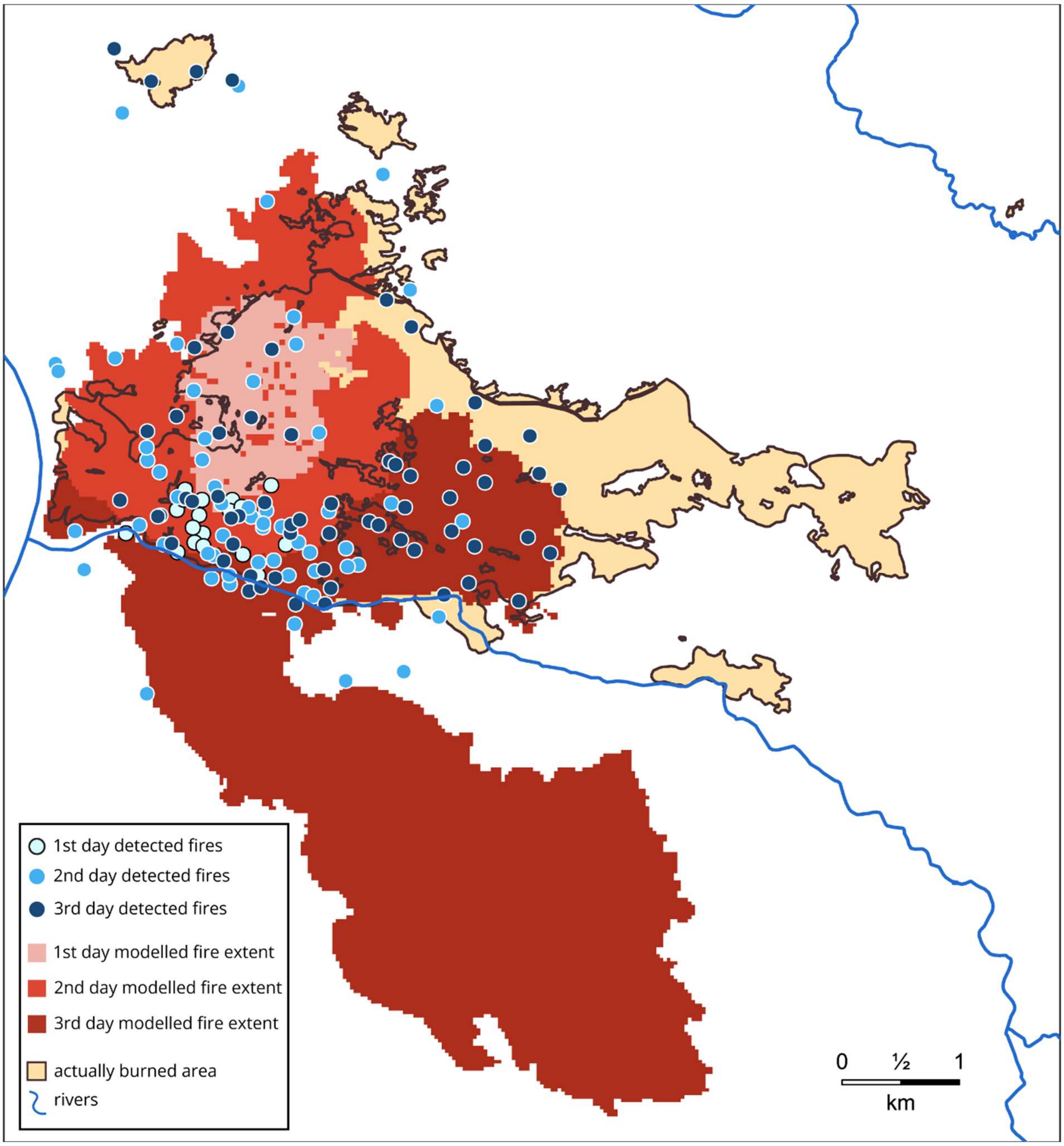


Figure 29: Comparison of three daily FlamMap runs with satellite-detected fires.

When considering the relatively coarse resolution of the satellite-detected active fires, the modelled fire extents overlap substantially with the detected fires. However, the 3rd day modelled fire extent, spreads noticeably beyond the actually burned area's borders. There are two possible justifications to this, apart from the possible FlamMap modelling inaccuracy. As can be seen on the map, there is a river that overlaps with the southwestern border of the actually burned area; this could signify that the river served as a natural boundary to the fire. The fuel models map utilised in this thesis, has a resolution of 30 × 30m, and it could be the case that the raster cells representing the river area where erroneously classified as burnable area. FlamMap allows the usage of barrier files, to act as unburnable fuel, preventing fires from passing through

(*FlamMap Help*, n.d.). However, this feature was not used in this thesis, as it was difficult to determine which rivers could constitute a barrier and which ones not, as data on the width of most rivers could not be retrieved and satellite imagery often shows a thick canopy of trees adjacent to rivers, rendering the detection of rivers' width difficult. Another possible justification is that there could have been firefighting response in the area that was erroneously burned in the modelling. While firefighting response was not integrated into the modelling, as there no data could be retrieved regarding this, it could be that firefighting defence was concentrated along the river, although without further information this possibility cannot be confirmed.

3.4 Questionnaire Results Evaluation

3.4.1 Usability Questionnaire

50 questionnaire responses were collected for the Usability Questionnaire. The results of the 4 profiling questions are shown below. It can be deduced that most participants hold an aptitude for map-reading, due not only to the higher percentage of Cartography professionals/students and GIS users, but also due to the high degree of familiarity with maps; 84% and 86%of respondents indicated a moderate (3) to expert (5) knowledge of static and interactive maps respectively:

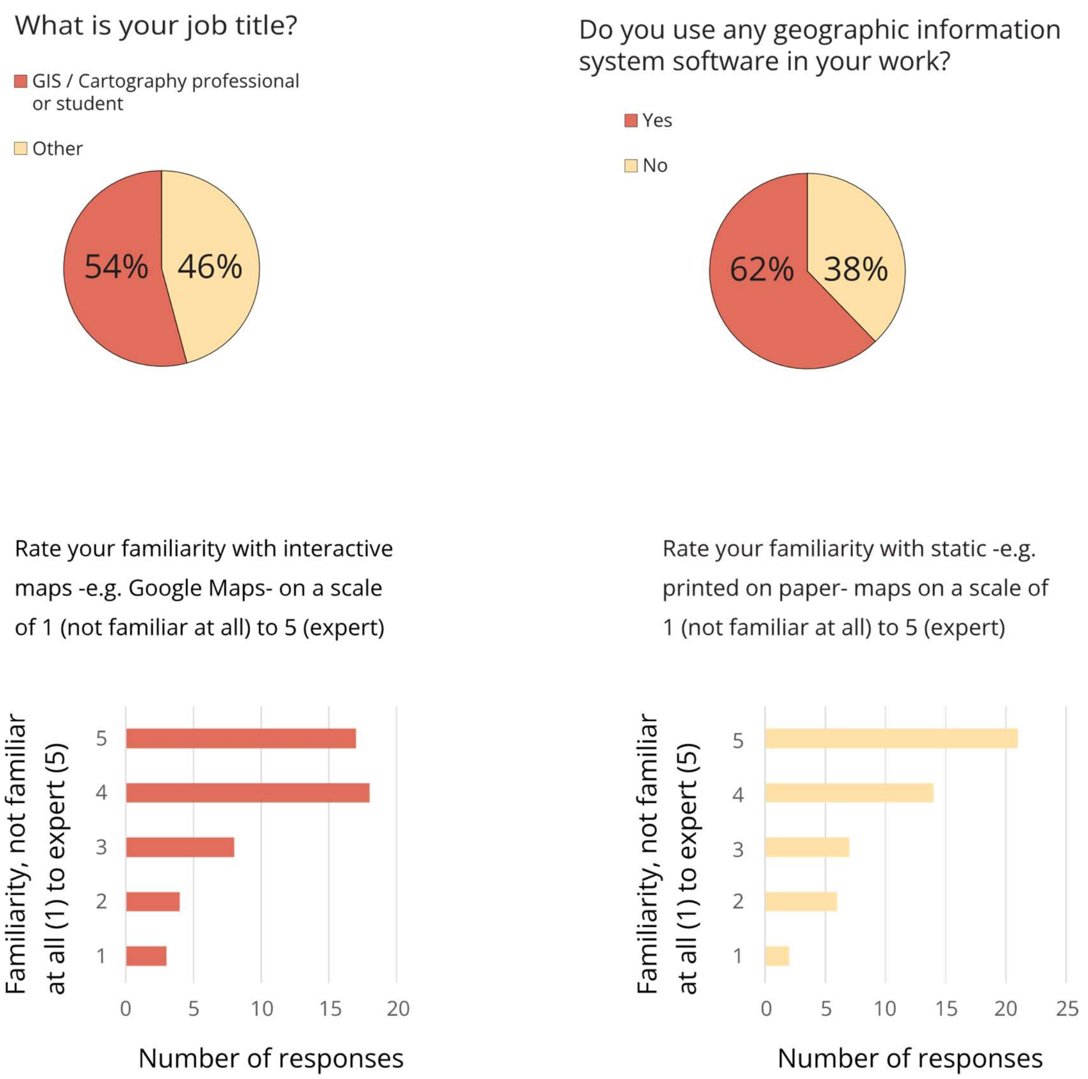


Figure 30: User profiles of usability questionnaire respondents.

In terms of the activity, respondents' answers varied considerably on whether they were using GIS software in their work. On the one hand, those who do not, gave responses that seem to follow a normal distribution, i.e., responses around the mean (difficulty of completion = 3) are more frequent than responses far from the mean (1, 2, 4, 5). On the other hand, the responses by those who do use GIS software at their work, follow a skewed distribution, with responses showing some ease of use being overrepresented; 61% of respondents belonging to this category responded with either 1 or 2 (16% and 45% of the total respectively). This could indicate that either the tasks were too hard for the non-GIS users, or that the interactive map lacked usability when it came to facilitating the completion of the five tasks.

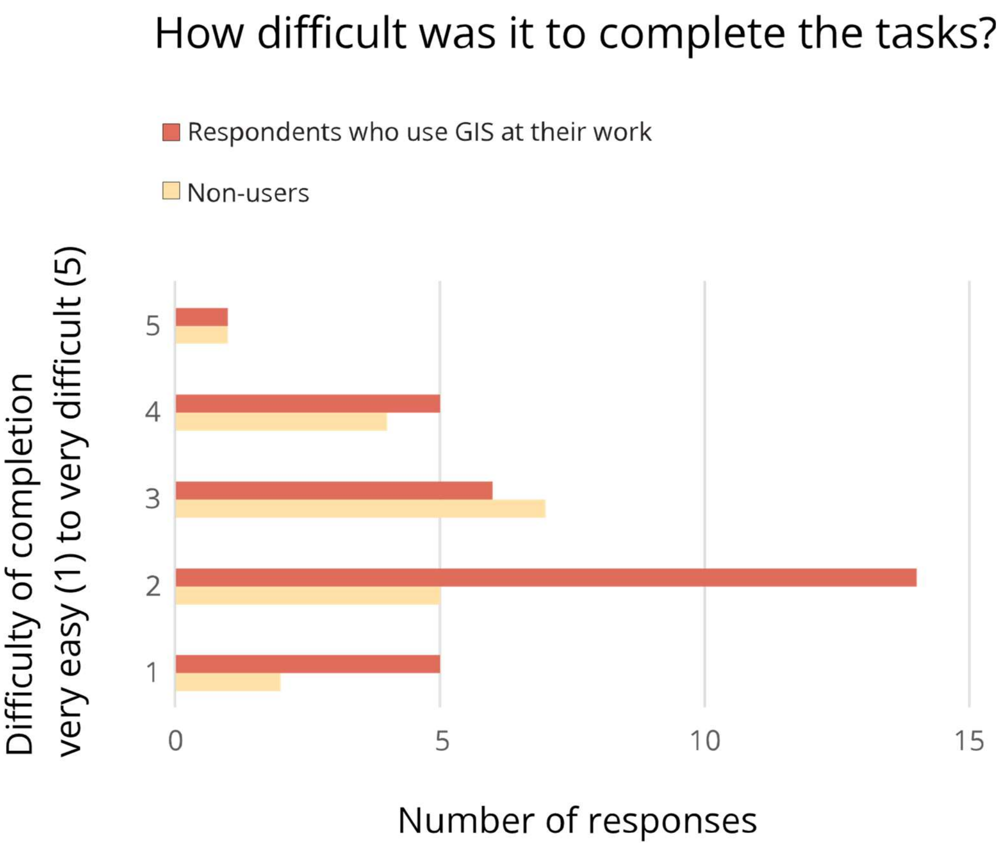


Figure 31: Responses showing difficulty of completion of interactive map activity.

With regards to the interpretation of the legend's colours, which is crucial for the correct understanding of the exposure rasters, a considerable number of responses were correct for both questions (78% for the question regarding blue areas, and 70% for the question regarding colour intensity). This demonstrates a generally clear understanding of the meaning of the legend's colours. Once again, the most prominent user profile factor affecting variability was whether the respondent used GIS in their profession; while the answers of the non-users of GIS had a distribution of 70% – 30% and 37% - 63% correct – false, for the two questions, this distribution was much starker when it came to GIS professional users; 87% and 78% answered the two colour questions correctly. This contrast serves as an indicator to the higher degree of readiness of users to understand this unusual colour scheme, perhaps due to their experience in dealing with non-typical maps in their work environment. Some expertise was therefore proven beneficial to the correct understanding of this map.

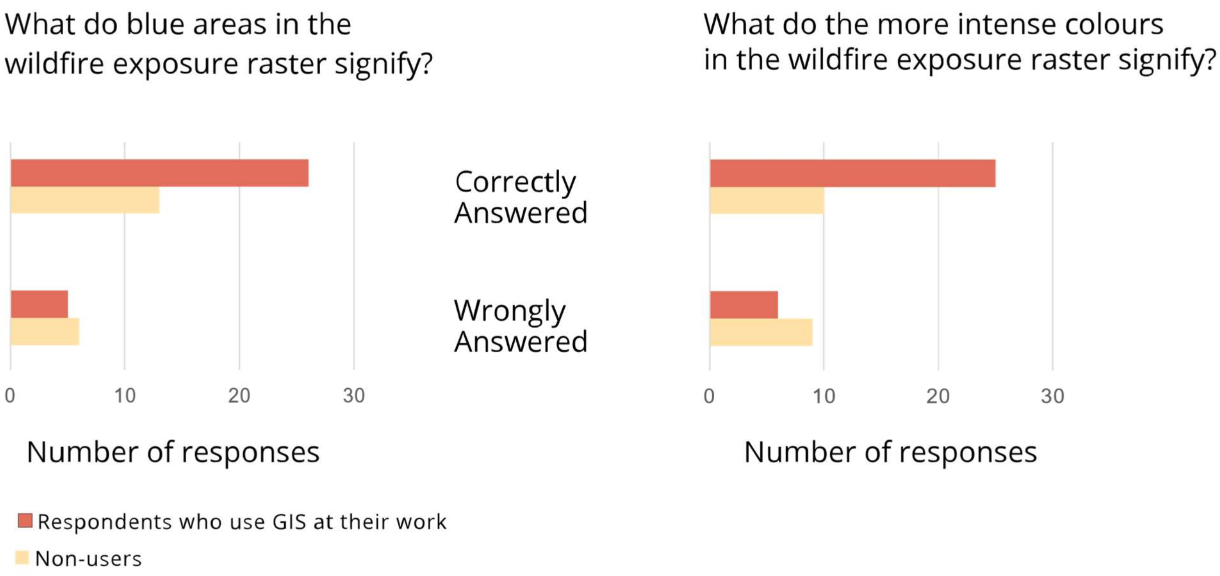


Figure 32: Answers to the questions regarding understanding of the map's colours.

The ease of understanding of the legend, was also demonstrated with the following question, which did not show much variability, no matter the user profile factor considered. Disparity in terms of usage of GIS at work is only shown for continuity reasons.

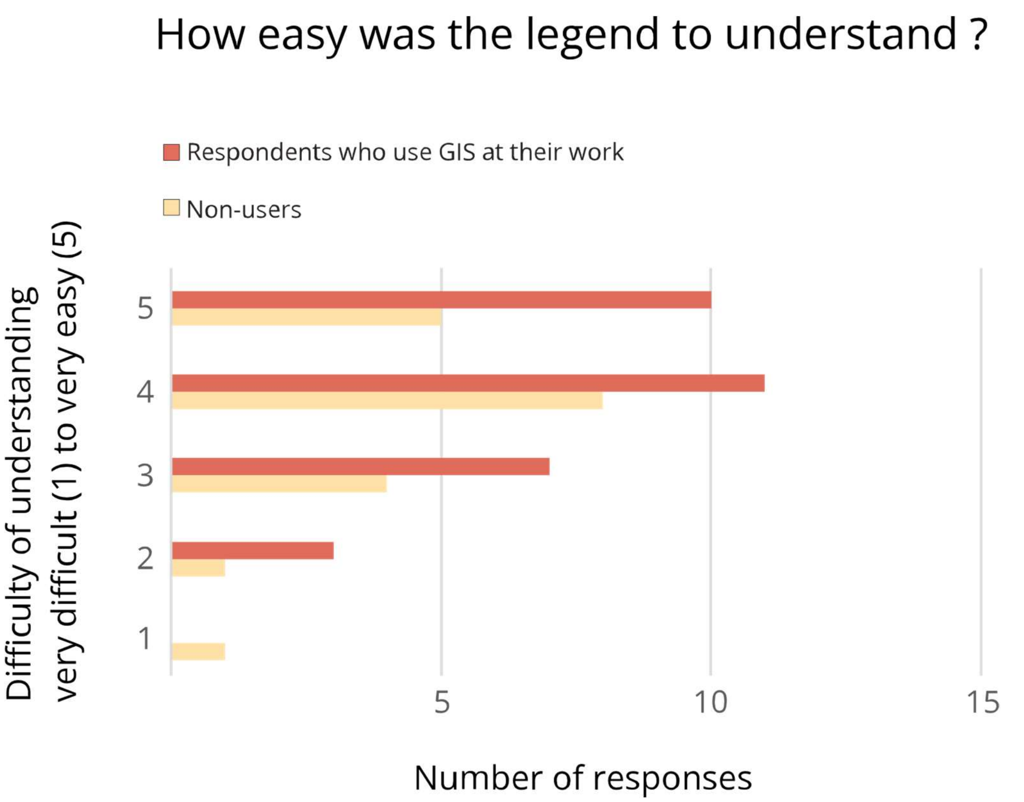


Figure 33: Responses to the question concerning ease of understanding of the legend.

The final two questions gave responders the opportunity to freely express which aspects of the map made it easy to use, as well as suggest what they would change in the design of the map to make it more usable. The five most mentioned user-friendly aspects of the map included:

- The ability to easily turn on and off layers on demand to focus on needed information as well as the ease of use of the taskbar (13 mentions)
- The colour coding, which was found to be easy to understand and made the individual colours distinguishable (6 mentions)
- The overall map design (4 mentions)
- The ease of zooming in and out, and the overall ease of navigation (3 mentions)
- The ability to search locations with the search bar (3 mentions)

The five most mentioned suggestions for making the map more usable included:

- A change in the exposure raster's colour coding: 3 respondents suggested a use of less colours and 5 recommended a change of the existing colours (e.g., a green / yellow / orange / red / brown scale).
- Making the legend more accessible and easier to find (5 mentions). This is tied to the problem some mobile users experienced, where the legend button was not where it was expected to be in mobile devices (as the questionnaire only described the legend button's position on a PC).
- Adding more contrast between the routes and the exposure rasters as they were not clearly visible (5 mentions)
- Change the colour or size of the fire station symbol to make it more visible (4 mentions)
- Adding a transparency control for the raster layers (2 mentions)

3.4.2 Usefulness Questionnaire

Two stakeholders (henceforth identified as 'respondent A' and 'respondent B') completed the usefulness questionnaire; respondent A, is a member of the monitoring department of the Bohemian Switzerland National Park Administration and respondent B is a student who will be dealing with the forest fires in Saxon Switzerland in their MA and who is associated with the Virtual Operations Support Team (VOST) of Germany's Federal Agency for Technical Relief (Bundesanstalt Technisches Hilfswerk) (THW), which is the federal civil protection organisation of Germany. The tasks of THW includes combating disasters, public emergencies and large-scale accidents at the request of the authorities responsible for emergency response

(Bundesministerium der Justiz, n.d.). Respondent A uses interactive maps in their work, for monitoring and orientation in the environment, and indicated that they work with Arc Map, ArcGIS Pro and QGIS. Moreover, they rated their familiarity with interactive maps with a 3 on a scale of 1 (not familiar at all) to 5 (expert) and were able to complete all five of the activity's tasks. Respondent B uses interactive maps in their work at VOST, to create situation reports of the respective operational situation and publish it on social media. They added that they work with ArcGIS Online Apps at VOST. Furthermore, they rated their familiarity with interactive maps with a 4 and were likewise able to complete all five of the activity's tasks.

The respondents ranked the information layers according to their relevance to their work or the use cases of the map as follows:

Interactive map layer	Respondent A ranking	Respondent B ranking
Fire Stations	5	3
Historical Fires' Ignitions (2009-2022)	1	3
Settlements – Villages, Towns and Cities [2 layers]	5	4
Settlements – Buildings	5	4
Transportation Networks	5	3
Burned Area from 2022 Fire	2	3
Rivers & Canals	5	2
Borders & Areas	3	2
Wildfire Exposure Rasters	3	4

Figure 34: Usefulness questionnaire respondents' ranking of interactive map layers.

Additionally, respondent A indicated terrain relief and slope as two layers that should be implemented in the future, to facilitate orientation, and to ascertain the availability and potential of fire spread.

In the next part of the questionnaire, respondents were asked about imagining a scenario where this map would be useful in their work, and to explain a possible use case. Respondent A expressed doubt regarding the accuracy of the Burn Probability of the wildfire exposure layers and pointed out that many of the visualized paths are either long gone, or do not actually connect. This reply can be understood as indicating that the map is inadequate, for respondent A's use cases. Respondent B on the other hand, suggested some potential use cases for the map: According to them, the map could be of interest to the VOST if there are forest fires in this region and they were called into action. Furthermore, since the map was created with ArcGIS Online, it would be advantageous that it would be easy to integrate it into the location map used by VOST, since they also use this technology. However, since the map so far only covers Saxon/Bohemian Switzerland and VOST hasn't had many missions in eastern Germany or forest fires-related missions, respondent B answered that it would currently play a subordinate role in the work undertaken at VOST. Nevertheless, this situation could change, if similar exposure maps were to be developed for other parts of Germany. Respondent B finally suggested that there is a possibility that such maps could prove to be more useful to VOST in the future, as an increasing number of settlements in Germany are affected by fires due to an increasing risk of forest fires and VOST would in response be called into action.

As a suggestion for future work, respondent B pointed that although the map would be easy to integrate to pre-existing maps used by VOST, this would not be the case for other German federal agencies in the THW, which do not hold Esri licenses for using e.g., ArcGIS Online; it would therefore be helpful to make the map more broadly available (either as a static printable map, or as a geopackage / raster data set).

4 Discussion and Future Work

In this chapter, the results and evaluation of this work will be discussed, and suggestions for future work in the same study area will be identified. The research questions of this thesis will also be addressed in this chapter.

4.1 Fuel Models

Yavuz et al. (2018) emphasised that fuel characteristics within a study area undergo dynamic changes from season to season across years, primarily influenced by grazing and human activities occurring within forested lands. Significant and rapid changes have also been observed in the fuels of the study area, particularly because of the bark beetle infestation that has drastically changed the fuel landscape in the span of a few years due to extensive outbreaks in the recent past (Hlásny et al., 2021; Nationalparkverwaltung Sächsische Schweiz & Mayr, 2022). Furthermore, not only can bark beetle infestations affect the fuels of a location, it has been argued by Hood et al., (2018, as cited in Beetz, 2023) that the fuel models developed by Scott and Burgan (2005), which were utilised by Beetz (2023) and consequently in this thesis, cannot effectively represent the fuel changes that occur because of bark beetle outbreaks, which can affect the accuracy of the results. However, it is not only extreme and unprecedented events such as these outbreaks that can cause drastic fuel alterations; Keane et al., (2001) has noted that common meteorological phenomena such as wind or wet snow incidents, can sometimes double or triple dead and downed fuel in a stand, and alter the entire composition of a fuelbed in the surrounding area.

A common countermeasure to such uncertainties is to develop fuel models maps with rigorous input from experts (Keane & Reeves, 2012). Ideal experts constitute fire behaviour analysts who deal with the studied region, and who have significant experience in estimating fire behaviour effects (Keane & Reeves, 2012). Keane & Reeves (2012) have identified six different types of experts whose knowledge can be utilised for different calibration and validation of fuel models' mapping (a detailed description dissemination can be seen in Figure A.12 of the Appendix), and they have also delineated four ways that expert knowledge can be used into the process of fuel mapping (reference, calibration, validation, verification of fuel models). One of these ways, has been employed in this thesis, though indirectly and at a minimal scale: As we saw in Section 2.1.2 local experts were consulted and shown a preliminary version of the wildfire exposure map developed in this thesis. Their input led to the amendment of two fuel models in the study area to accommodate for their input. This involvement can be considered a fuel validation method which is one of the four aforementioned ways with which experts can help in the development of a fire exposure map (Keane & Reeves, 2012).

Future work dealing with wildfire propagation in the study area, should further ascertain their fuel models by making sure that the utilised fuel models, have been developed with more rigorous expert input, when compared to the one undertaken in this thesis. This input should help to minimise as much as possible the inevitable discrepancies between fire modelling landscape, and reality. Further, field work should be conducted in the future, in order to provide ground truths for the validation of the fuel models map (Beetz, 2023). Moreover, a wildfire modelling workflow which is able to effortlessly integrate changes in fuel models and produce equivalent updated results upon request, should also be pursued. It should be noted that, fuel models, is not the only fire modelling landscape layer that undergoes fast enough changes to necessitate field work to validate it: Canopy characteristics also require such an approach.

4.2 Canopy Data and Crown Fires

Crown fires, which are characterised by their intensity, rapid movement, and destructive nature, imply that the potential for damage is significant whenever such fires take place (Scott & Reinhardt, 2001). It is precisely for this reason that crown fire initiation and hazard has been extensively modelled and studied (Alexander, 1998; Van Wagner, 1989; Xanthopoulos, 1990; Rothermel, 1991; Cruz et al., 2002; Albini et al., 1995; Scott and Reinhardt, 2001 all as cited in Perminov, 2003). Moreover, when the necessary data is available, crown fires are commonly modelled with surface fires for more comprehensive and realistic fire behaviour outputs; as was previously discussed (Section 2.1.4), Ager et al., (2011), Heisig et al. (2022), and Mitsopoulos et al. (2016) modelled wildfires with FlamMap and all considered crown fire activity.

The possibility to model crown fires in FlamMap has previously been discussed (Section 2.1.4), as well as the reasoning behind the non-utilisation of the three optional layers necessary for the modelling of crown fires (Canopy Height, Crown Base Height and Crown Bulk Density). Although this has not been calculated in this thesis, it is assumed that the accuracy of all resulting fire modelling outputs is compromised because of this omission. The Canopy data of Figure A.6,Figure A.7 and Figure A.8 of the Appendix, although too outdated -as was just mentioned- to be used in the fire modelling of this thesis, give a basic understanding that the vegetation in the area, has areas with considerable canopy, i.e., considerable potential fuel for crown fires. Future researchers should endeavour to integrate this crucial aspect of fire behaviour in their modelling, by obtaining up-to-date data.

4.3 Wildfire Scenarios and Wildfire Modelling in FlamMap

Two modelling evaluations were conducted in Section 3.3, one to evaluate the nine wildfire modelling scenarios created in this thesis, and one to evaluate the ability of FlamMap to generally model a wildfire in the study area. Given the lack of fire perimeters associated with the 224 ignitions, or any other validation data such as historical fire sizes or probability of ignition, which have been used to accurately evaluate wildfire simulations (Sá et al., 2022), one should consider whether the modelling evaluation results can be considered significant.

The first evaluation (Section 3.3.1) showcased that the devised scenarios can indeed be used to predict wildfire behaviour in the area, albeit with limited confidence as more validation data, such as fire perimeters is needed. The usage of WBI to create wildfire scenarios can therefore be a possibility to be considered for the deriving of fire weather scenarios in the future, keeping in mind the index's limitations; Wittich et al. (2014) have pointed out that topographical effects are not considered in WBI calculations. This assumes (as do more traditional models of fire weather) a quasi-horizontal station environment and is limited to the meteorological conditions measured at the station (Wittich et al., 2014). In this respect, reliable hazard assessments utilizing WBI in varied terrain depend on the density of the measurement network, which might not always be adequate, depending on the study region. Moreover, WBI is an index only used in Germany; in future studies, if a similar approach of using fire weather indices is followed for other regions, one would need to rely on indexes other than WBI, such as McArthur's fire danger index (FDI) for Australia (Khastagir et al., 2018) or the more widely available Canadian forest fire weather index for worldwide applications (e.g., Masinda et al., 2022 used it to estimate forest fire risk in a temperate forest in Northeastern China).

The second evaluation (Section 3.3.2) demonstrated FlamMap's ability to accurately model the first three days of a 12-day wildfire, taking into consideration the area misidentified as being burned, though, as was previously discussed, this could be due either to the existence of a river, or due to firefighting activity, or perhaps a FlamMap modelling error. The important thing to note here, is that this fire was modelled not by using FlamMap's wildfire features as intended; FlamMap is designed to model wildfires with a single wind speed and direction for the duration of the wildfire, no matter how long the wildfire may be (*FlamMap Help*, n.d.). Therefore, for the second evaluation, a workaround needed to be implemented to counter this inability, and to be able to model each individual day with its own wind velocity (transforming the fire perimeter layer to a points layer, using this point layer as new ignition points for the next day etc.). Though this has not been statistically established, it has been empirically determined after the many modelling runs undertaken during this thesis, and can be assumed, that the more enduring the wildfire, the less accurate the single wind used to represent the entirety of the weather conditions taking place during the wildfire will be, as that wind will need to represent several differing winds; as was observed with the wind velocities of the 2022 wildfires (Figure 27), wind directions during a wildfire can drastically change from one day to another. Further, it should be noted that the modelling runs used to create the FL and BP rasters that in turn created the wildfire exposure rasters, used the standard modelling configuration (single wind) and not the alternative one used for this evaluation. Notwithstanding this potential inaccuracy, there exists research where FlamMap was used to model wildfires with single winds, with the results shown to be accurate when compared to historical data, although calibration with historical fire behaviour characteristics needed to be implemented (Sá et al., 2022).

Notwithstanding these potential inaccuracies, it may be asserted that FlamMap was well-equipped, after appropriate input data was found (with the notable exception of canopy data necessary for crown fire modelling), to provide the needed BP and FL layers for creating an exposure map of the study area. However, there is a significant degree of uncertainty when it comes to accurately evaluating the modelling outputs. This lack of validation data though, is not an issue of FlamMap per se, but rather, perhaps of the state authorities responsible for acquiring and distributing this information. Nevertheless, from the scarce validation data that was acquired, results are encouraging, and they hardly constitute a sign that FlamMap is inappropriate for the creation of wildfire exposure maps in the study area. However, caution should be taken when inputting winds in FlamMap, in order to make sure that the most representative wind for the considered wildfire scenario is used as input. From this discussion, one may only partially answer the first research question of this study (‘Can the fire modelling tool FlamMap be used to create an accurate Wildfire Exposure map in the designated study area?’): Indeed, FlamMap can be used to create the FL and BP layers necessary for calculating Wildfire Exposure in the study area, however, more validation data would be greatly beneficial for the assessment of the accuracy of the results.

4.4 Usability, Usefulness, and Involving Local Stakeholders

Though the number of participants to the usefulness questionnaire is not enough to draw definitive conclusions, the responses to the usability questionnaire indicated that the interactive map can be understood to be easy to use, relative to the complexity of information presented. Some level of expertise (usage of GIS at work) was shown to be beneficial to better understand the map, especially when it came to completing the map-interaction activities. Another important outcome of the usability questionnaire was the plethora of recommendations about what to change in the future, some of them could be employed to make the map easier to use in future iterations: the taskbar and the feature of turning on/off layers at will received particular praise, with lesser recognition being given to other aspects of interactivity such as the ability to zoom and to search for locations. A point of contention amongst respondents proved to be the colouring scheme of the wildfire exposure rasters; although six of them found it to be understandable and helpful in distinguishing individual colours, eight also suggested either lessening the number of colours or replacing them. Other suggested improvements also concerned colour improvement such as making the contrast between various layers easier. These comments serve as an indicator that the whole colouring scheme employed in the thesis should be improved for better clarity.

The usefulness questionnaire asked participants to detail their involvement with interactive maps and the study area, as well as to identify use cases of the map for their work. Even if the questionnaire collected qualitative rather than quantitative data, and was focused on the individuality of each respondent, a higher number of respondents would have been desirable in order to understand the needs of more stakeholders; in the end, two out of the total nine contacted stakeholders replied. Nevertheless, the two collected responses gave valuable information on how the map achieves some level of usefulness, or how it may be improved to become even more useful in the future. Respondent B, for example, indicated that the preliminary static map which was developed (but not tested) in this thesis, could prove useful for some use cases, as Esri products are not ubiquitously available, even between agencies of the same civil protection organisation (THW), creating a usage niche for static wildfire exposure maps employed by such organisations. They furthermore responded that such an interactive online map could be proven useful to VOST in the future, and their replies can be understood to express a general positive attitude towards the potential usefulness of the map by this organisation in the future. In terms of respondent A, it is deemed noteworthy that they chose to rank the two included vulnerability layers (fire stations and transportation networks) with a rank of 5, meaning that they found them extremely relevant to their work. This is an encouraging indicator for future work, as respondent A works at the Bohemian Switzerland National Park Administration. However, when it comes to the improvement of these layers to better suit the needs of the administration of the National Park, further contact needs to be established with the administration.

After discussing the results of these questionnaires, the answer to the second Research Question ('Is an interactive exposure map derived from FlamMap's outputs, usable by the general audience and useful for stakeholders?') becomes more apparent: The interactive map that was based on FlamMap's outputs is indeed usable by the general audience, though familiarity with GIS and with interactive maps makes the map more usable. In terms of usefulness for stakeholders, there is more uncertainty; Respondent A exhibited reluctance in adopting the map in their work, while respondent B indicated more optimism. More stakeholders should test the interactive map, in order to be certain about the answer to the second part of the research question.

Overall, a general recommendation for future wildfire research in this thesis' or any other study area, is to establish good communication with the local expert and stakeholder community. As was discussed, expert knowledge is invaluable in developing accurate fuel models maps, while stakeholders, as potential users, should be consulted in various parts of the wildfire research process, and not only towards the end. For example, respondent A indicated erroneous transportation network data used; this error could have been avoided had a stakeholder been consulted beforehand. Moreover, firefighting response, which could be integrated into FlamMap in the form of barriers, could have been better understood had good communication with the fire local fire brigades of Germany and Czech Republic been established; this would have perhaps resulted in more accurate wildfire modelling. Ultimately, integrating either stakeholders' (Al-Manji et al., 2021) or experts' knowledge (Riley et al., 2018) is a common method utilised in disaster-related mapping and future research in the study area, should adhere to this approach.

5 Conclusions

This thesis has followed the development of a wildfire preparedness map, in a transboundary area of Germany and Czech Republic consisting of two National Parks and two Conservations Areas. Such mapping in that area is still at a relatively early stage, but it is an area where wildfires are expected to become an ever increasing threat due to climate change. Wildfire scenarios were devised based on local historical weather and classified based on WBI values and wildfire duration. These scenarios where then converted to exposure rasters, showcasing which human settlements are most potentially exposed to wildfires in the study area. The modelling results were then integrated into a web-based interactive map, which was then evaluated both for its accuracy and its usability/usefulness. The results of the usability evaluation have shown that the design workflow of the interactive map is promising, and that the resulting product, though it presents complex information, shows its information in an understandable way. The usefulness questionnaire revealed the need to include stakeholders in such research in different ways, and to generally include local stakeholders and experts early, and throughout the research process. Moreover, significant work remains to be done, in order for future research to have access to adequate historical wildfire data, indispensable for testing the accuracy of the resulting exposure maps. Finally, this thesis has demonstrated the importance of interdisciplinarity in disaster-related mapping; Cartography, and Environmental Remote Sensing, when combined can create pioneering results when it comes to developing accurate and effective disaster-preparedness mapping.

References

4.1 Flame Length | National Wildfire Coordinating Group. (n.d.). Retrieved 15 October 2023, from https://www.nwcg.gov/course/ffm/vert-horiz-and-slope/41-flame-length

Abrahams, J., Anacia, A., Beavers, R., Gabriel Andrés, B., Caffrey, M., Omar Darío, C., Ciotti, M., Derrough, T., Douris, J., Espinosa, L., Fraser, G., G. Goldammer, J., Gudnason, T., Gyenes, Z., Hainsworth, A., Krausmann, E., Loughlin, S., Løvholt, F., Mallinis, G., … Woolf, M. (2017). Words into Action guidelines: National disaster risk assessment, Parth Three: Hazard specific Risk Assessment. United Nations Office for Disaster Risk Reduction. https://www.undrr.org/media/20847/download?startDownload=true

Ager, A. A., Palaiologou, P., Evers, C. R., Day, M. A., & Barros, A. M. G. (2018). Assessing Transboundary Wildfire Exposure in the Southwestern United States. Risk Analysis, 38(10), 2105–2127. https://doi.org/10.1111/risa.12999

Ager, A. A., Palaiologou, P., Evers, C. R., Day, M. A., Ringo, C., & Short, K. (2019). Wildfire exposure to the wildland urban interface in the western US. Applied Geography, 111, 1–13. https://doi.org/10.1016/j.apgeog.2019.102059

Ager, A. A., Vaillant, N. M., & Finney, M. A. (2011). Integrating Fire Behavior Models and Geospatial Analysis for Wildland Fire Risk Assessment and Fuel Management Planning. Journal of Combustion, 2011, 19. https://doi.org/10.1155/2011/572452

Alaska Fuel Model Guide Task Group (Ed.). (2018). Fuel model guide to Alaska vegetation (p. 105) [Unpublished Report]. Alaska Wildland Fire Coordinating Group, Fire Modeling and Analysis Committee. https://www.frames.gov/catalog/56055

Albini, F. A., & Reinhardt, E. D. (1995). Modeling Ignition and Burning Rate of Large Woody Natural Fuels. International Journal of Wildland Fire, 5(2), 81–91. https://doi.org/10.1071/wf9950081

Alcasena, F., Ager, A., Le Page, Y., Bessa, P., Loureiro, C., & Oliveira, T. (2021). Assessing Wildfire Exposure to Communities and Protected Areas in Portugal. Fire, 4(4), 82. https://doi.org/10.3390/fire4040082

Alcasena, F., Salis, M., Ager, A., Castell, R., & Vega-García, C. (2017). Assessing Wildland Fire Risk Transmission to Communities in Northern Spain. Forests, 8(2), 30. https://doi.org/10.3390/f8020030

Alexander, M. E., & Cruz, M. G. (2013). Are the applications of wildland fire behaviour models getting ahead of their evaluation again? Environmental Modelling & Software, 41, 65–71. https://doi.org/10.1016/j.envsoft.2012.11.001

Al-Manji, S., Lovett, J., & Mitchell, G. (2021). Factors Affecting Disaster Resilience in Oman: Integrating Stakeholder Analysis and Fuzzy Cognitive Mapping. Risk, Hazards & Crisis in Public Policy, 12(1), 29–50. https://doi.org/10.1002/rhc3.12201

Aragoneses, E., García, M., Salis, M., Ribeiro, L. M., & Chuvieco, E. (2022). Classification and mapping of European fuels using a hierarchical-multipurpose fuel classification system [Preprint]. ESSD – Land/Land Cover and Land Use. https://doi.org/10.5194/essd-2022-184

ArcGIS Pro | Documentation. (2023). List of raster functions. https://pro.arcgis.com/en/pro-app/latest/help/analysis/raster-functions/list-of-raster-functions.htm

Attinà, F. (2012). Disaster and Emergency Policies at the International and Global System Levels. In F. Attinà (Ed.), The Politics and Policies of Relief, Aid and Reconstruction: Contrasting Approaches to Disasters and Emergencies (pp. 21–41). Palgrave Macmillan UK. https://doi.org/10.1057/9781137026736_2

Beer, T. (1991). The interaction of wind and fire. Boundary-Layer Meteorology, 54(3), 287–308. https://doi.org/10.1007/BF00183958

Beetz, K. (2023). Forest fires in the Bohemian-Saxon Switzerland in 2022: Mapping and analysis of fuel types, fire dynamics and severity using remote sensing data [Unpublished master's thesis]. TU Dresden.

Berčák, R., Holuša, J., Kaczmarowski, J., Tyburski, Ł., Szczygieł, R., Held, A., Vacik, H., Slivinský, J., & Chromek, I. (2023). Fire Protection Principles and Recommendations in Disturbed Forest Areas in Central Europe: A Review. Fire, 6(8), Article 8. https://doi.org/10.3390/fire6080310

Bergonse, R., Oliveira, S., Santos, P., & Zêzere, J. L. (2022). Wildfire Risk Levels at the Local Scale: Assessing the Relative Influence of Hazard, Exposure, and Social Vulnerability. Fire, 5(5), Article 5. https://doi.org/10.3390/fire5050166

Bevan, N. (2009). Usability. In L. LIU & M. T. ÖZSU (Eds.), Encyclopedia of Database Systems (pp. 3247–3251). Springer US. https://doi.org/10.1007/978-0-387-39940-9_441

Bohemian National Park Region – Nationalpark Sächsische Schweiz. (n.d.). Retrieved 14 April 2023, from https://www.nationalpark-saechsische-schweiz.de/boehmische-nationalparkregion/?lang=en

Bowman, D. M. J. S., Williamson, G. J., Abatzoglou, J. T., Kolden, C. A., Cochrane, M. A., & Smith, A. M. S. (2017). Human exposure and sensitivity to globally extreme wildfire events. Nature Ecology & Evolution, 1(3), 0058. https://doi.org/10.1038/s41559-016-0058

Buchhorn, M., Smets, B., Bertels, L., Roo, B. D., Lesiv, M., Tsendbazar, N.-E., Li, L., & Tarko, A. (2020). Copernicus Global Land Service: Land Cover 100m: version 3 Globe 2015-2019: Product User Manual (Dataset v3.0, doc issue 3.3). Zenodo. https://doi.org/10.5281/ZENODO.3938963

Bundesministerium der Justiz. (n.d.). THWG - Gesetz über das Technische Hilfswerk. Retrieved 5 November 2023, from https://www.gesetze-im-internet.de/thw-helfrg/BJNR001180990.html

Burkett, V. R. (2013). Coping Capacity. In P. T. Bobrowsky (Ed.), Encyclopedia of Natural Hazards (pp. 119–121). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_75

Caballero, D., & Beltrán, I. (2003). Concepts and ideas of assessing settlement fire vulnerability in the W-UI zone. International Workshop Forest Fires in the Wildland-Urban Interface and Rural Areas in Europe Athens, Greece 15-16 May 2003.

Caballero, D., Beltrán, I., & Velasco, A. (2007). Forest Fires and Wildland-Urban Interface in Spain: Types and Risk Distribution. IV International Wildfire Conference, 1–15.

Cannon, T. (1994). Vulnerability Analysis and The Explanation Of 'Natural' Disasters. Disasters, Development and Environment.

Chuvieco, E., Aguado, I., Jurdao, S., Pettinari, M. L., Yebra, M., Salas, J., Hantson, S., de la Riva, J., Ibarra, P., Rodrigues, M., Echeverría, M., Azqueta, D., Román, M. V., Bastarrika, A., Martínez, S., Recondo, C., Zapico, E., & Martínez-Vega, F. J. (2014). Integrating geospatial information into fire risk assessment. International Journal of Wildland Fire, 23(5), 606. https://doi.org/10.1071/WF12052

Chuvieco, E., Aguado, I., Salas, J., García, M., Yebra, M., & Oliva, P. (2020). Satellite Remote Sensing Contributions to Wildland Fire Science and Management. Current Forestry Reports, 6(2), 81–96. https://doi.org/10.1007/s40725-020-00116-5

Colour Summary | Britannica. (n.d.). Retrieved 30 October 2023, from https://www.britannica.com/summary/color

Cooke, K. (2021). Five Best Planning and Community Development Success Stories of 2021. Industry Blogs. https://www.esri.com/en-us/industries/blog/articles/five-best-planning-and-community-development-success-stories-of-2021/

Copernicus Emergency Management Service. (n.d.). EMSR610: Wildfire in Saxony, Germany. Copernicus Emergency Management Service - Mapping. Retrieved 23 October 2023, from http://emergency.copernicus.eu/mapping/list-of-components/EMSR610

Copernicus Global Land Service. (n.d.). Global Land Cover Viewer. Global Land Cover Viewer. Retrieved 7 October 2023, from http://lcviewer.vito.be/

Copernicus Land Monitoring Service. (2023). Tree Cover Density 2018 (raster 10 m and 100 m), Europe, 3-yearly. https://land.copernicus.eu/en/products/high-resolution-layer-tree-cover-density/tree-cover-density-2018

Countryman, C. M. (1972). The fire environment concept. USDA Forest Service, Pacific Southwest Range and Experiment Station. https://www.frames.gov/catalog/8189

Crameri, F., Shephard, G. E., & Heron, P. J. (2020). The misuse of colour in science communication. Nature Communications, 11(1), Article 1. https://doi.org/10.1038/s41467-020-19160-7

Cui, X., Alam, M. A., Perry, G. LW., Paterson, A. M., Wyse, S. V., & Curran, T. J. (2019). Green firebreaks as a management tool for wildfires: Lessons from China. Journal of Environmental Management, 233, 329–336. https://doi.org/10.1016/j.jenvman.2018.12.043

Czaja, M. R. (2015). Wildland Fire Management: Movement Towards Enabling Resiliency? In A. Masys (Ed.), Disaster Management: Enabling Resilience (pp. 287–315). Springer International Publishing. https://doi.org/10.1007/978-3-319-08819-8_14

Degel, D., Wiesche, L., Rachuba, S., & Werners, B. (2014). Reorganizing an existing volunteer fire station network in Germany. Socio-Economic Planning Sciences, 48(2), 149–157. https://doi.org/10.1016/j.seps.2014.03.001

Deutscher Wetterdienst. (n.d.-a). CDC (Climate Data Center). Retrieved 26 October 2023, from https://www.dwd.de/EN/ourservices/cdc_portal/cdc_portal.html

Deutscher Wetterdienst. (n.d.-b). Erläuterungen zum Waldbrandgefahrenindex. Retrieved 27 October 2023, from https://www.dwd.de/DE/fachnutzer/landwirtschaft/dokumentationen/allgemein/basis_waldbrandgefahrenindex_doku.html?nn=16102

Deutscher Wetterdienst. (n.d.-c). Waldbrandgefahrenindex. Retrieved 26 October 2023, from https://www.dwd.de/DE/leistungen/waldbrandgef/waldbrandgef.html

Disaster | Definition & Types | Britannica. (2023, September 21). https://www.britannica.com/science/disaster

Disaster | UNDRR. (2007, August 30). http://www.undrr.org/terminology/disaster

Earth Science Data Systems, NASA. (n.d.-a). MCD14DL-NRT | Earthdata [Basic Page]. Earth Science Data Systems, NASA. Retrieved 4 November 2023, from https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms/mcd14dl-nrt

Earth Science Data Systems, NASA. (n.d.-b). VNP14IMGTDL_NRT | Earthdata [Basic Page]. Earth Science Data Systems, NASA. Retrieved 4 November 2023, from https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms/vnp14imgtdlnrt

Enia, J. (2020). Is there an international disaster risk reduction regime? Does it matter? Progress in Disaster Science, 7, 1–5. https://doi.org/10.1016/j.pdisas.2020.100098

ESRI. (2020). Terrain: Hillshade. https://www.arcgis.com/home/item.html?id=d2f3e6dbfd7c457fa275dfb5a282523b

European Civil Protection and Humanitarian Aid Operations. (2023). Wildfires: Biggest rescEU aerial firefighting operation in Greece. https://civil-protection-humanitarian-aid.ec.europa.eu/news-stories/news/wildfires-biggest-resceu-aerial-firefighting-operation-greece-2023-08-29_en

Falaras, T., Tselka, I., Papadopoulos, I., Nikolidaki, M., Karavias, A., Bafi, D., Petani, A., Krassakis, P., & Parcharidis, I. (2022). Operational Mapping and Post-Disaster Hazard Assessment by the Development of a Multiparametric Web App Using Geospatial Technologies and Data: Attica Region 2021 Wildfires (Greece). Applied Sciences, 12(14), Article 14. https://doi.org/10.3390/app12147256

Finney, M. A. (2002). Fire growth using minimum travel time methods. Canadian Journal of Forest Research, 32(8), 1420–1424. https://doi.org/10.1139/x02-068

Finney, M. A. (2006). An Overview of FlamMap Fire Modeling Capabilities. In: Andrews, Patricia L.; Butler, Bret W., Comps. 2006. Fuels Management-How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 213-220, 041. https://www.fs.usda.gov/research/treesearch/25948

Finney, M. A., McAllister, S. S., Grumstrup, T. P., & Forthofer, J. M. (2021). Wildland fire behaviour: Dynamics, principles and processes. CSIRO publishing. https://www.publish.csiro.au/book/7817

FlamMap Help. (n.d.). Retrieved 7 October 2023, from https://owfflammaphelp62.firenet.gov/Flammap2.htm#FileTypes/PU_Custom_Fuel_Model_File.htm

Flink, H.-M., Oksanen, J., Pyysalo, U., Rönneberg, M., & Sarjakoski, L. T. (2011). Usability Evaluation of a Map-Based Multi-Publishing Service. In A. Ruas (Ed.), Advances in Cartography and GIScience. Volume 1: Selection from ICC 2011, Paris (pp. 239–257). Springer. https://doi.org/10.1007/978-3-642-19143-5_14

Forthofer, J., Shannon, K., & Butler, B. (2009). Simulating diurnally driven slope winds with WindNinja. In: Proceedings of 8th Eighth Symposium on Fire and Forest Meteorology; 2009 October 13-15; Kalispell, MT. Boston, MA: American Meteorological Society. 13 p. Online: Https://Ams.Confex.Com/Ams/8Fire/Techprogram/Paper_156275.Htm. https://www.fs.usda.gov/research/treesearch/61476

Francesco, P., Kutchartt, E., Gonzalez Olabarria, J. R., & Granja, L. M. (2023). Fuel model input raster data EU [dataset]. https://doi.org/10.5281/zenodo.8420046

Gao, H., Barbier, G., & Goolsby, R. (2011). Harnessing the Crowdsourcing Power of Social Media for Disaster Relief. IEEE Intelligent Systems, 26(3), 10–14. https://doi.org/10.1109/MIS.2011.52

Geofabrik. (n.d.). Europe. Retrieved 23 October 2023, from http://download.geofabrik.de/europe.html

Gizzi, F. T. (2022). "Natural Disaster(s)": Going Back to the Roots of Misleading Terminology. Insights from Culturomics. GSA Today, 33(3–4). https://www.geosociety.org/GSA/GSA/GSAToday/groundwork/G532GW/article.aspx

Glade, T., & Alexander, D. E. (2013). Classification of Natural Disasters (P. T. Bobrowsky, Ed.; pp. 78–82). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_61

Grodzki, W., & Fronek, W. G. (2019). The European spruce bark beetle (L.) in wind-damaged stands of the eastern part of the Tatra National Park – the population dynamics pattern remains constant. Folia Forestalia Polonica, 61(3), 174–181. https://doi.org/10.2478/ffp-2019-0017

Guo, H., Ma, J., Zhang, B., Li, Z., Huang, J., & Zhu, L. (2010). Damage consequence chain mapping after the Wenchuan Earthquake using remotely sensed data. International Journal of Remote Sensing, 31(13), 3427–3433. https://doi.org/10.1080/01431161003727648

Hasičovo, F. F., a s. (2023). Mapa sborů. https://www.hasicovo.cz/cs/hasicuv-svet/mapa-sboru

Heisig, J., Olson, E., & Pebesma, E. (2022). Predicting Wildfire Fuels and Hazard in a Central European Temperate Forest Using Active and Passive Remote Sensing. Fire, 5(1), 29. https://doi.org/10.3390/fire5010029

Hlásny, T., Zimová, S., Merganičová, K., Štěpánek, P., Modlinger, R., & Turčáni, M. (2021). Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. Forest Ecology and Management, 490, 1–13. https://doi.org/10.1016/j.foreco.2021.119075

Huang, S., Tang, L., Hupy, J. P., Wang, Y., & Shao, G. (2021). A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. Journal of Forestry Research, 32(1), 1–6. https://doi.org/10.1007/s11676-020-01155-1

Hunt, R. W. G., & Pointer, M. (2011). Colour Vision. In Measuring Colour (pp. 1–17). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119975595.ch1

Jahdi, R., Salis, M., Darvishsefat, A. A., Alcasena, F., Mostafavi, M. A., Etemad, V., Lozano, O. M., & Spano, D. (2016). Evaluating fire modelling systems in recent wildfires of the Golestan National Park, Iran. Forestry: An International Journal of Forest Research, 89(2), 136–149. https://doi.org/10.1093/forestry/cpv045

Kalabokidis, K., Palaiologou, P., Kostopoulou, E., Zerefos, C., Gerasopoulos, E., & Giannakopoulos, C. (2014). Effect of climate projections on the behavior and impacts of wildfires in Messenia, Greece. COMECAP 2014 E-Book of Proceedings, 1, 395–400.

Kalabokidis, K., Xanthopoulos, G., Moore, P., Caballero, D., Kallos, G., Llorens, J., Roussou, O., & Vasilakos, C. (2012). Decision support system for forest fire protection in the Euro-Mediterranean region. European Journal of Forest Research, 131(3), 597–608. https://doi.org/10.1007/s10342-011-0534-0

Kautz, M., Delb, H., Hielscher, K., Hurling, R., Lobinger, G., Niesar, M., Otto, L.-F., & Thiel, J. (2023). Borkenkäfer an Nadelbäumen—Erkennen, Vorbeugen, Bekämpfen (12. Auflage 2023, Webversion; p. 56). Fachagentur Nachwachsende Rohstoffe e. V. (FNR). https://mediathek.fnr.de/broschuren/borkenkafer-an-nadelbaumen-erkennen-vorbeugen-bekampfen.html

Keane, R. E. (2015). Wildland Fuel Fundamentals and Applications (1st ed.). Springer Cham. https://doi.org/10.1007/978-3-319-09015-3

Keane, R. E., Burgan, R. E., & Wagtendonk, J. W. V. (2001). Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. International Journal of Wildland Fire, 10(4), 301–319. https://doi.org/10.1071/WF01028

Keane, R. E., & Reeves, M. (2012). Use of Expert Knowledge to Develop Fuel Maps for Wildland Fire Management. In A. H. Perera, C. A. Drew, & C. J. Johnson (Eds.), Expert Knowledge and Its Application in Landscape Ecology (pp. 211–228). Springer. https://doi.org/10.1007/978-1-4614-1034-8_11

Keane, R. E., Reinhardt, E. D., Scott, J., Gray, K., & Reardon, J. (2005). Estimating forest canopy bulk density using six indirect methods. Canadian Journal of Forest Research, 35(3), 724–739. https://doi.org/10.1139/x04-213

Khastagir, A., Jayasuriya, N., & Bhuyian, M. A. (2018). Assessment of fire danger vulnerability using McArthur's forest and grass fire danger indices. Natural Hazards, 94(3), 1277–1291. https://doi.org/10.1007/s11069-018-3476-8

Kreisfeuerwehrverband – Sächsische Schweiz-Osterzgebirge e.V. (2023, June 2). https://kfv-soe.de/

Kudlackova, L., Podebradska, M., Monika, B., Cienciala, E., Beranova, J., McHugh, C., Finney, M., Novotny, J., Zahradnicek, P., Stepanek, P., Vebrova, D., Mozny, M., Surovy, P., Zalud, Z., & Trnka, M. (2023). Using Flammap to Assess Wildfire Behavior in Bohemian Switzerland National Park. https://doi.org/10.21203/rs.3.rs-3157719/v1

Kunreuther, H., & Michel-Kerjan, E. (2013). Costs (Economic) of Natural Hazards and Disasters. In P. T. Bobrowsky (Ed.), Encyclopedia of Natural Hazards (pp. 125–129). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_78

Landesamt für Geobasisinformation Sachsen. (n.d.-a). Download, Dienste und Testdaten. sachsen.de. Retrieved 19 October 2023, from https://www.landesvermessung.sachsen.de//download-offene-geodaten-und-testdaten-8647.html

Landesamt für Geobasisinformation Sachsen. (n.d.-b). Downloadbereich Verwaltungsgrenzen. sachsen.de. Retrieved 17 October 2023, from http://www.geodaten.sachsen.de/downloadbereich-verwaltungsgrenzen-4344.html

Landesamt für Geobasisinformation Sachsen. (n.d.-c). Geoportal Sachsenatlas.

Lukeš, M. (2022). EXPERIENCE ON THE RESPONSE TO THE 2022 FOREST FIRE SEASON Czech Republic—Forest Fire in the National Park Czech Switzerland. FirEUrisk Symposium, Dresden, Germany.

MacDonald, C. M., & Atwood, M. E. (2014). What does it mean for a system to be useful? An exploratory study of usefulness. Proceedings of the 2014 Conference on Designing Interactive Systems, 885–894. https://doi.org/10.1145/2598510.2598600

Mallinis, G. (2014). STSM Report. University of Sassari, Department of Science for Nature and Environmental Resources. https://www.eurocoppice.uni-freiburg.de/intern/pdf/stsm/stsmreport-giorgos-mallinis-rev.pdf

Mallinis, G., Mitsopoulos, I., Beltran, E., & Goldammer, J. (2016). Assessing Wildfire Risk in Cultural Heritage Properties Using High Spatial and Temporal Resolution Satellite Imagery and Spatially Explicit Fire Simulations: The Case of Holy Mount Athos, Greece. Forests, 7(2), Article 2. https://doi.org/10.3390/f7020046

Masinda, M. M., Li, F., Qi, L., Sun, L., & Hu, T. (2022). Forest fire risk estimation in a typical temperate forest in Northeastern China using the Canadian forest fire weather index: Case study in autumn 2019 and 2020. Natural Hazards, 111(1), 1085–1101. https://doi.org/10.1007/s11069-021-05054-4

Matthews, S. (2013). Dead fuel moisture research: 1991–2012. International Journal of Wildland Fire, 23(1), 78–92. https://doi.org/10.1071/WF13005

McKenney, M., & Schneider, M. (2016). Concepts of Maps. In M. McKenney & M. Schneider (Eds.), Map Framework: A Formal Model of Maps as a Fundamental Data Type in Information Systems (pp. 1–14). Springer International Publishing. https://doi.org/10.1007/978-3-319-46766-5_1

McPherson, K. (2021). Introducing ArcGIS Instant Apps. ArcGIS Blog. https://www.esri.com/arcgis-blog/products/instant-apps/mapping/introducing-arcgis-instant-apps/

Migoń, P. (2013). Cultural Heritage and Natural Hazards. In P. T. Bobrowsky (Ed.), Encyclopedia of Natural Hazards (pp. 135–140). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_82

Miller, C., & Ager, A. A. (2012). A review of recent advances in risk analysis for wildfire management. International Journal of Wildland Fire. 22: 1-14., 1–14.

Miller, & Schultz, J. (2023). A Holistic Approach to Managing Wildland Fire Risk with ArcGIS. Industry Blogs. https://www.esri.com/en-us/industries/blog/articles/a-holistic-approach-to-managing-wildland-fire-risk-with-arcgis/

Missoula Fire Sciences Laboratory. (n.d.-a). FlamMap. Retrieved 17 April 2023, from https://www.firelab.org/project/flammap

Missoula Fire Sciences Laboratory. (n.d.-b). WindNinja. https://www.firelab.org/project/windninja

Mitsopoulos, I., Mallinis, G., Karali, A., Giannakopoulos, C., & Arianoutsou, M. (2016). Mapping fire behaviour under changing climate in a Mediterranean landscape in Greece. Regional Environmental Change, 16(7), 1929–1940. https://doi.org/10.1007/s10113-015-0884-0

Mitteldeutsche Agentur für Informationsservice GmbH. (n.d.). Waldbrandgefährdung. Retrieved 26 October 2023, from https://www.mais.de/php/sachsenforst.php?n=3

Moghaddas, J. J., Collins, B. M., Menning, K., Moghaddas, E. E. Y., & Stephens, S. L. (2010). Fuel treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada. Canadian Journal of Forest Research, 40(9), 1751–1765. https://doi.org/10.1139/X10-118

Mohamed Shaluf, I. (2007). Disaster types. Disaster Prevention and Management: An International Journal, 16(5), 704–717. https://doi.org/10.1108/09653560710837019

Molina-Terrén, D. M., Xanthopoulos, G., Diakakis, M., Ribeiro, L., Caballero, D., Delogu, G. M., Viegas, D. X., Silva, C. A., & Cardil, A. (2019). Analysis of forest fire fatalities in Southern Europe: Spain, Portugal, Greece and Sardinia (Italy). International Journal of Wildland Fire, 28(2), 85. https://doi.org/10.1071/WF18004

Morville, P. (2004). User Experience Design. User Experience Design. https://semanticstudios.com/user_experience_design/

Müller, J., Bußler, H., Goßner, M., Rettelbach, T., & Duelli, P. (2008). The European spruce bark beetle Ips typographus in a national park: From pest to keystone species. Biodiversity and Conservation, 17(12), 2979–3001. https://doi.org/10.1007/s10531-008-9409-1

NASA-FIRMS. (n.d.). Retrieved 4 November 2023, from https://firms.modaps.eosdis.nasa.gov/map/

Nationalparkverwaltung Sächsische Schweiz, & Mayr. (2022). FAQ - Waldbrand im Nationalpark Sächsische Schweiz vom 25.07. Bis 26.08.2022. https://www.nationalpark-saechsische-schweiz.de/wp-content/uploads/2022/10/FAQ- Waldbrand-2022.pdf

Natural Earth. (2023). 1:10m Cultural Vectors. https://www.naturalearthdata.com/downloads/10m-cultural-vectors/

Natural Hazards | National Risk Index. (n.d.). Retrieved 4 October 2023, from https://hazards.fema.gov/nri/natural-hazards

O'Keefe, P., Westgate, K., & Wisner, B. (1976). Taking the naturalness out of natural disasters. Nature, 260(5552), 566–567. https://doi.org/10.1038/260566a0

Oliveira, S., Gonçalves, A., Benali, A., Sá, A., Zêzere, J. L., & Pereira, J. M. (2020). Assessing Risk and Prioritizing Safety Interventions in Human Settlements Affected by Large Wildfires. Forests, 11(8), 859. https://doi.org/10.3390/f11080859

Oliveira, S., Rocha, J., & Sá, A. (2021). Wildfire risk modeling. Current Opinion in Environmental Science & Health, 23, 100274. https://doi.org/10.1016/j.coesh.2021.100274

OpenStreetMap Wiki. (n.d.). Retrieved 31 October 2023, from https://wiki.openstreetmap.org/wiki/Main_Page

Pausas, J. G., & Keeley, J. E. (2021). Wildfires and global change. Frontiers in Ecology and the Environment, 19(7), 387–395. https://doi.org/10.1002/fee.2359

Perminov, V. (2003). Mathematical Modeling of Crown Forest Fires Initiation. In V. Kumar, M. L. Gavrilova, C. J. K. Tan, & P. L'Ecuyer (Eds.), Computational Science and Its Applications—ICCSA 2003 (pp. 549–557). Springer. https://doi.org/10.1007/3-540-44839-X_59

Petersen, K. (2014). Producing space, tracing authority: Mapping the 2007 San Diego wildfires. The Sociological Review, 62(S1), 91–113. https://doi.org/10.1111/1467-954X.12125

Peterson, D. L., Evers, L., Gravenmier, R. A., & Eberhardt, E. (2007). A consumer guide: Tools to manage vegetation and fuels. (PNW-GTR-690; p. 158). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://doi.org/10.2737/PNW-GTR-690

Prichard, S. J., Rowell, E. M., Hudak, A. T., Keane, R. E., Loudermilk, E. L., Lutes, D. C., Ottmar, R. D., Chappell, L. M., Hall, J. A., & Hornsby, B. S. (2022). Fuels and Consumption. In D. L. Peterson, S. M. McCaffrey, & T. Patel-Weynand (Eds.), Wildland Fire Smoke in the United States: A Scientific Assessment (pp. 11–49). Springer International Publishing. https://doi.org/10.1007/978-3-030-87045-4_2

Raikes, J., Smith, T. F., Baldwin, C., & Henstra, D. (2022). The influence of international agreements on disaster risk reduction. International Journal of Disaster Risk Reduction, 76, 1–11. https://doi.org/10.1016/j.ijdrr.2022.102999

Rein, G., & Huang, X. (2021). Smouldering wildfires in peatlands, forests and the arctic: Challenges and perspectives. Current Opinion in Environmental Science & Health, 24, 100296. https://doi.org/10.1016/j.coesh.2021.100296

Riley, K. L., Thompson, M. P., Scott, J. H., & Gilbertson-Day, J. W. (2018). A Model-Based Framework to Evaluate Alternative Wildfire Suppression Strategies. Resources, 7(1), Article 1. https://doi.org/10.3390/resources7010004

Roth, R. E. (2013). Interactive maps: What we know and what we need to know. Journal of Spatial Information Science, 2013(6), 59–115. https://doi.org/10.5311/JOSIS.2013.6.105

Roubeyrie, L. (n.d.). Windrose (1.9.0) [Python; OS Independent]. Retrieved 27 October 2023, from https://github.com/python-windrose/windrose

Royal Meteorological Society. (n.d.). The Beaufort Wind Scale. Retrieved 27 October 2023, from https://www.rmets.org/metmatters/beaufort-wind-scale

Sá, A. C. L., Aparicio, B., Benali, A., Bruni, C., Salis, M., Silva, F., Marta-Almeida, M., Pereira, S., Rocha, A., & Pereira, J. (2022). Coupling wildfire spread simulations and connectivity analysis for hazard assessment: A case study in Serra da Cabreira, Portugal. Natural Hazards and Earth System Sciences, 22(12), 3917–3938. https://doi.org/10.5194/nhess-22-3917-2022

Safaie, S., Stepanyan, M., Houdijk, R., & Onur, T. (2017). Words into Action guidelines: National disaster risk assessment, Parth One: Main Body. United Nations Office for Disaster Risk Reduction. https://www.undrr.org/media/20847/download?startDownload=true

Sagara, J., & Saito, K. (2013). Risk Assessment and Hazard Mapping (Brief 79387). World Bank. http://hdl.handle.net/10986/16146

Salis, M., Arca, B., Bacciu, V., Duce, P., & Spano, D. (2009, October 1). Assessment of Fire Severity in a Mediterranean Area using FlamMap Simulator.

Scott, J. H. (2019). Glossary of wildfire hazard and risk. Pyrologix. http://pyrologix.com/downloads/

Scott, J. H., & Burgan, R. E. (2005). Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model (RMRS-GTR-153; p. RMRS-GTR-153). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-153

Scott, J. H., & Reinhardt, E. D. (2001). Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p., 29. https://doi.org/10.2737/RMRS-RP-29

Sendai Framework Terminology on Disaster Risk Reduction | UNDRR. (2023, March 9). http://www.undrr.org/terminology

Shamsipour, A. A., & Shekhi, M. (2010). Zoning of Sensitive Area and Environment Vulnerable in West of Fars Province using Fazzy and AHP Claassification. Physical Geography Research Quarterly, 42(73), 53–67.

Shao, J., Tang, L., Liu, M., Shao, G., Sun, L., & Qiu, Q. (2020). BDD-Net: A General Protocol for Mapping Buildings Damaged by a Wide Range of Disasters Based on Satellite Imagery. Remote Sensing, 12(10), Article 10. https://doi.org/10.3390/rs12101670

Staatsbetrieb Sachsenforst. (n.d.). Staatsbetrieb Sachsenforst. Retrieved 24 October 2023, from https://www.sbs.sachsen.de/index.html

Tacnet, J.-M., & Curt, C. (2013). Expert (Knowledge-Based) Systems for Disaster Management. In P. T. Bobrowsky (Ed.), Encyclopedia of Natural Hazards (pp. 300–305). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_125

Tedim, F., Xanthopoulos, G., & Leone, V. (2015). Chapter 5 - Forest Fires in Europe: Facts and Challenges. In J. F. Shroder & D. Paton (Eds.), Wildfire Hazards, Risks and Disasters (pp. 77–99). Elsevier. https://doi.org/10.1016/B978-0-12-410434-1.00005-1

The General Directorate of Fire Rescue Service of Czech Republic. (n.d.). Fire rescue service of the Czech republic. Retrieved 24 October 2023, from https://www.hzscr.cz/hasicien/

Tsou, M.-H., Jung, C.-T., Allen, C., Yang, J.-A., Han, S. Y., Spitzberg, B. H., & Dozier, J. (2017). Building a Real-Time Geo-Targeted Event Observation (Geo) Viewer for Disaster Management and Situation Awareness. In M. P. Peterson (Ed.), Advances in Cartography and GIScience (pp. 85–98). Springer International Publishing. https://doi.org/10.1007/978-3-319-57336-6_7

Tzavella, K., Skopeliti, A., & Fekete, A. (2022). Volunteered geographic information use in crisis, emergency and disaster management: A scoping review and a web atlas. Geo-Spatial Information Science, 0(0), 1–32. https://doi.org/10.1080/10095020.2022.2139642

US Department of Commerce - National Weather Service, N. (n.d.). Fire Weather Definitions. NOAA's National Weather Service. Retrieved 27 October 2023, from https://www.weather.gov/gum/fireweatherdefinitions

Ushashidi. (2023). Ushahidi. https://www.ushahidi.com//

Vacca, P., Caballero, D., Pastor, E., & Planas, E. (2020). WUI fire risk mitigation in Europe: A performance-based design approach at home-owner level. Journal of Safety Science and Resilience, 1(2), 97–105. https://doi.org/10.1016/j.jnlssr.2020.08.001

Wagenbrenner, N. S., Forthofer, J. M., Lamb, B. K., Shannon, K. S., & Butler, B. W. (2016). Downscaling surface wind predictions from numerical weather prediction models in complex terrain with WindNinja. Atmospheric Chemistry and Physics, 16(8), 5229–5241. https://doi.org/10.5194/acp-16-5229-2016

Waltz, A. E. M., Stoddard, M. T., Kalies, E. L., Springer, J. D., Huffman, D. W., & Meador, A. S. (2014). Effectiveness of fuel reduction treatments: Assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. Forest Ecology and Management, 334, 43–52. https://doi.org/10.1016/j.foreco.2014.08.026

Wang, C. (2014). Usability Evaluation of Public Web Mapping Sites. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL–4, 285–289. https://doi.org/10.5194/isprsarchives-XL-4-285-2014

Watt, K., & Weinstein, P. (2013). Casualties Following Natural Hazards. In P. T. Bobrowsky (Ed.), Encyclopedia of Natural Hazards (pp. 59–64). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4399-4_58

Wildfire | Definition & Facts | Britannica. (2023). https://www.britannica.com/science/wildfire

Wilkening, J., Han, K., & Jahnke, M. (2019). Creating and evaluating web-based visualizations of multi-dimensional spatiotemporal data. Proceedings of the ICA, 2, 1–8. https://doi.org/10.5194/ica-proc-2-145-2019

Wittich, K.-P. (n.d.). Der Waldbrandgefahrenindex WBI des Deutschen Wetterdienstes.

Wittich, K.-P., Bock, L., & Zimmermann, L. (2014). Der WBI und dessen Anwendung auf bayerische Waldbrände. AFZ/Der Wald, Allgemeine Forst Zeitschrift für Waldwirtschaft und Umweltvorsorge, 69(9), 22–25.

Wotton, B. M., Alexander, M. E., & Taylor, S. W. (2009). Updates and revisions to the 1992 Canadian Forest Fire Behaviour Prediction System (Information Report. GLC-X Series0832-7122GLC-X-10E). Canada. Natural Resources Canada. Canadian Forest Service. https://publications.gc.ca/site/eng/9.619157/publication.html

Xanthopoulos, G., Viegas, D. X., & Caballero, D. (2009). The fatal fire entrapment of Artemida (Greece) 2007. Recent Forest Fire Related Accidents in Europe, 65–75.

Xiao-rui, T., McRae, D. J., Li-fu, S., & Ming-yu, W. (2005). Fuel classification and mapping from satellite imagines. Journal of Forestry Research, 16(4), 311–316. https://doi.org/10.1007/BF02858198

Yamano, N., Kajitani, Y., & Shumuta, Y. (2007). Modeling the Regional Economic Loss of Natural Disasters: The Search for Economic Hotspots. Economic Systems Research, 19(2), 163–181. https://doi.org/10.1080/09535310701330191

Yao, J., Zhang, X., & Murray, A. T. (2019). Location optimization of urban fire stations: Access and service coverage. Computers, Environment and Urban Systems, 73, 184–190. https://doi.org/10.1016/j.compenvurbsys.2018.10.006

Yavuz, M., Sağlam, B., Kucuk, O., & Tufekcioglu, A. (2018). Assessing forest fire behavior simulation using FlamMap software and remote sensing techniques in Western Black Sea Region, Turkey. 18, 171–188. https://doi.org/10.17475/kastorman.459698

Yeboah, G., & Park, P. Y. (2018). Using survival analysis to improve pre-emptive fire engine allocation for emergency response. Fire Safety Journal, 97, 76–84. https://doi.org/10.1016/j.firesaf.2018.02.005

Appendix A: Illustrations

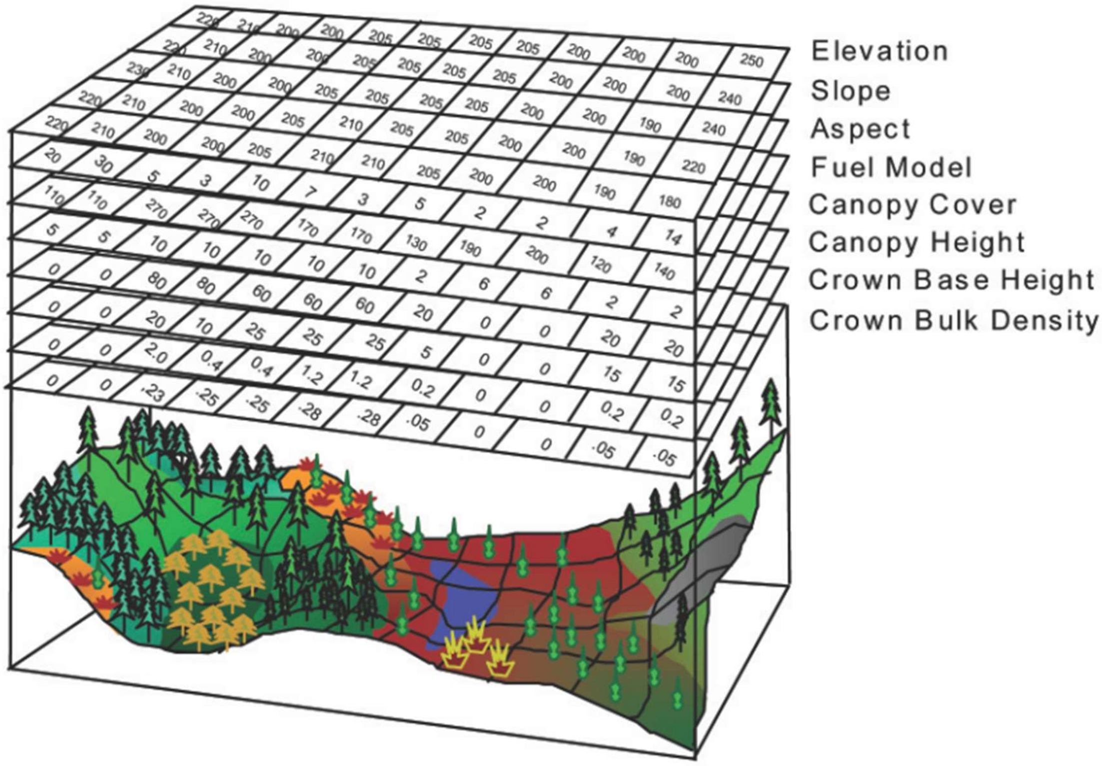


Figure A.1: Typical layers used for the creation of a fire modelling landscape in FlamMap and FARSITE (Finney, 2006, p.214).

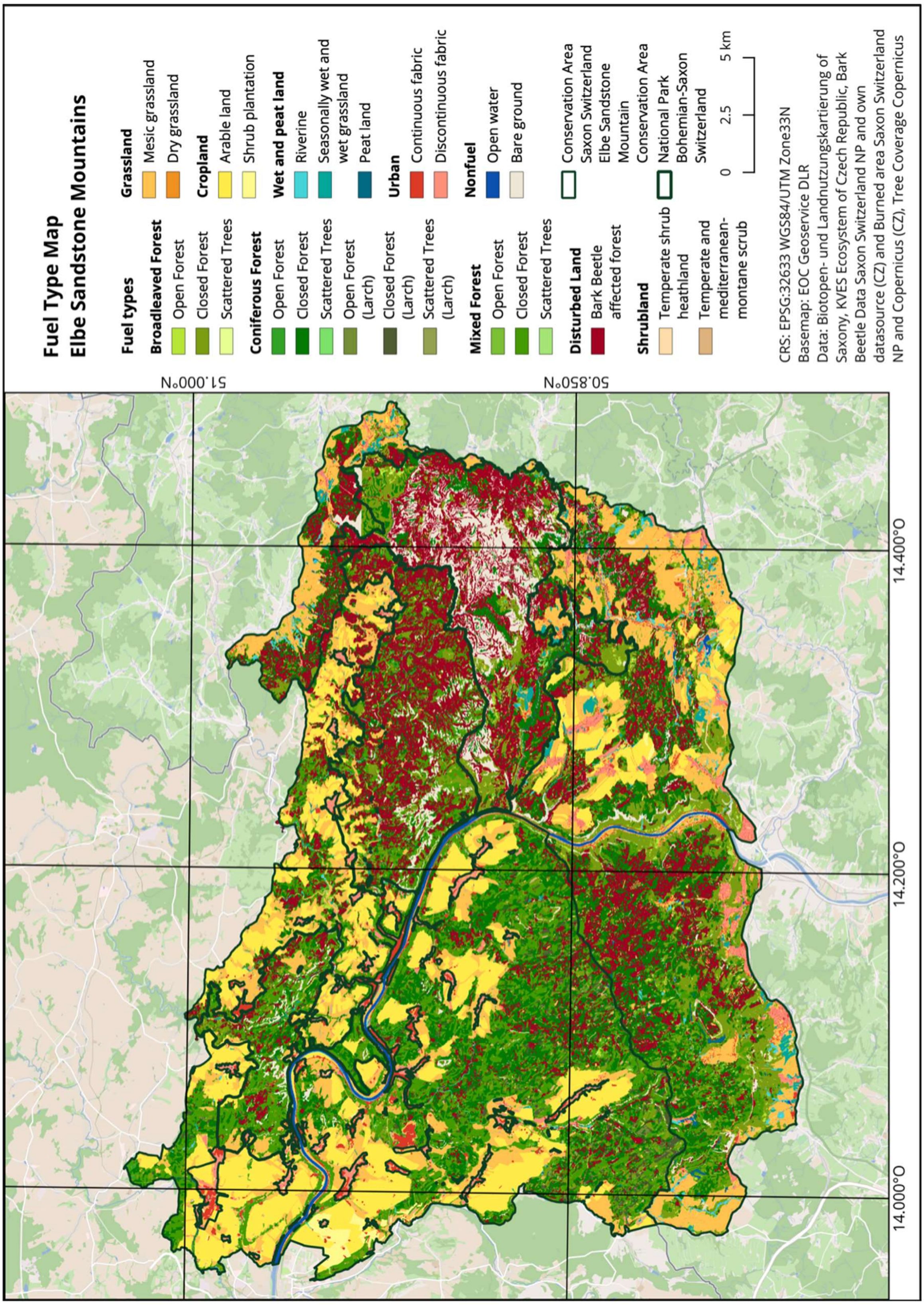


Figure A.2: Fuel type map Elbe Sandstone Mountains pre-fire 2022 (Beetz, 2023, p. 36)

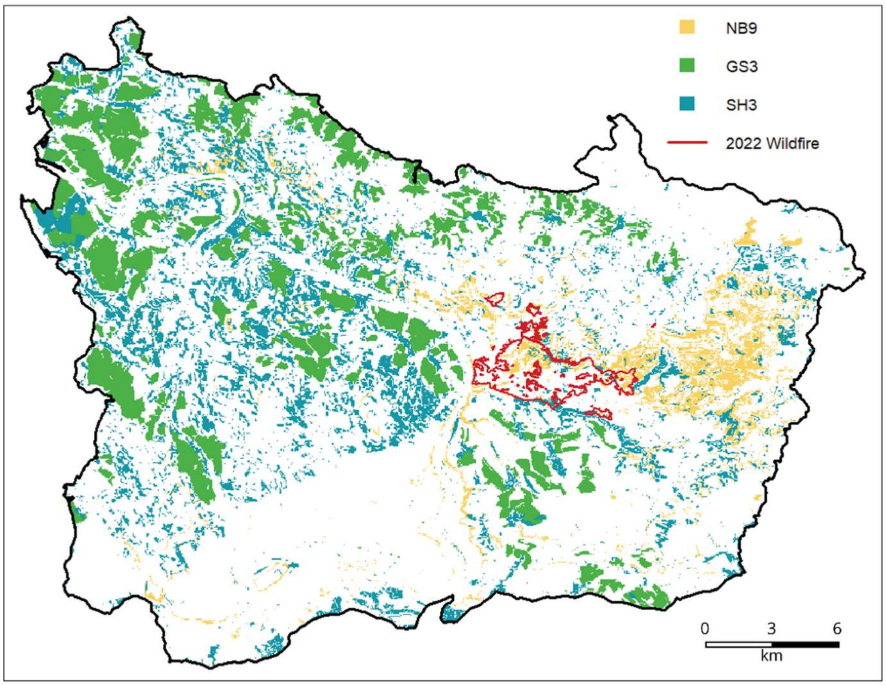


Figure A.3: Original Fuel Models map derived from Beetz (2023), showcasing the three fuel models that were altered.

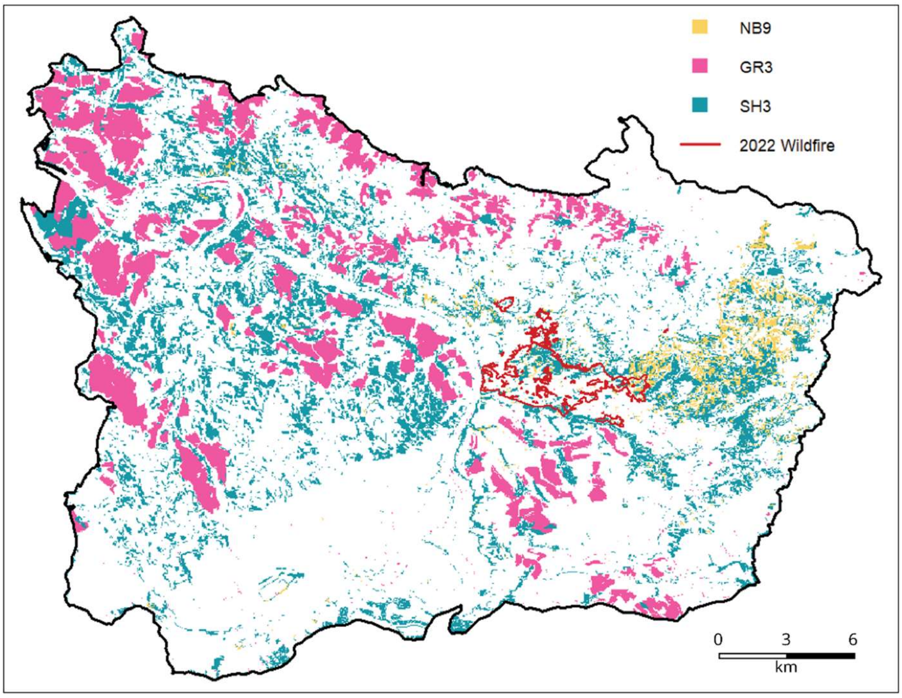


Figure A.4: This map shows the updated fuel models map, after the two aforementioned alterations; Notice the replacement of the NB9 (yellow area) with SH3 (blue) inside the limits of the 2022 wildfire, as well as the complete replacement of GS3 (green areas in the previous Figure) by GR3 (magenta).

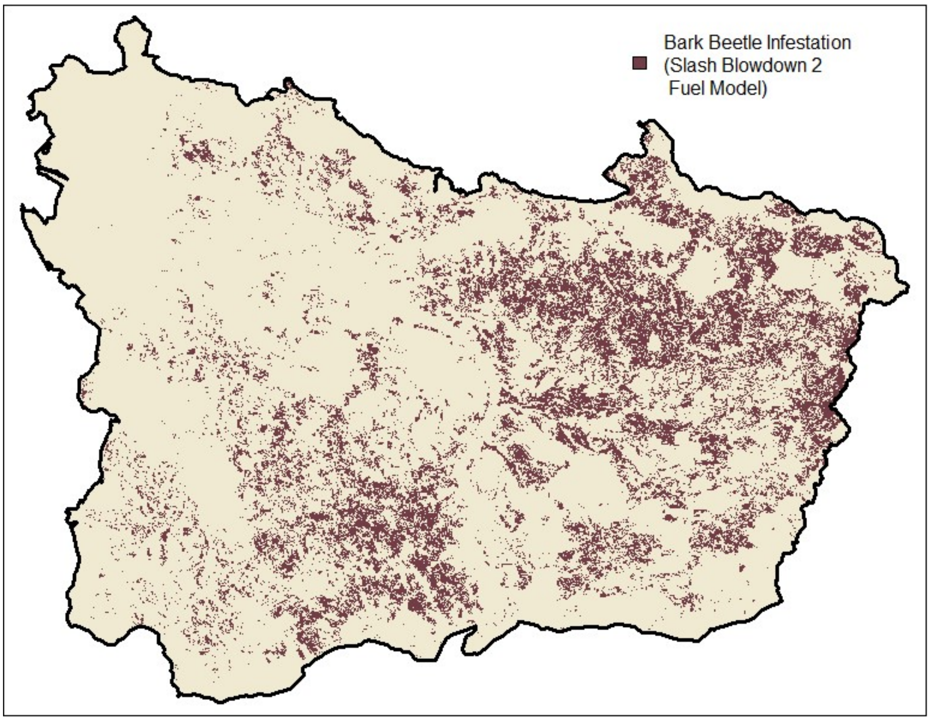


Figure A.5: Parts of the study area infested by Bark Beetle. These are areas classified by Beetz (2023) as belonging to fuel model 'Slash Blowdown 2' according to the fuel models of Scott & Burgan (2005).

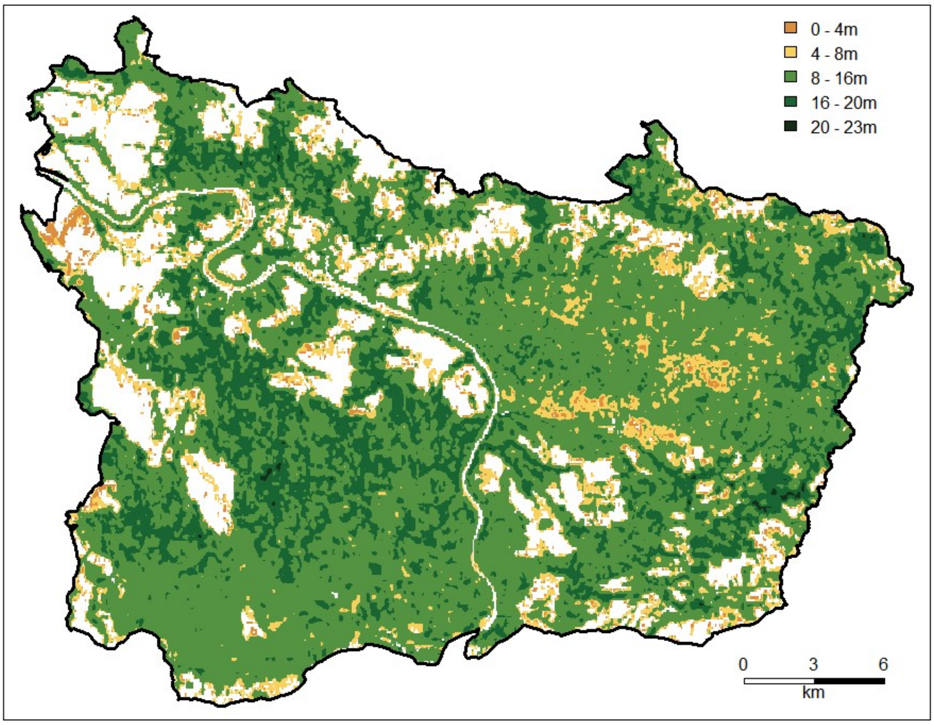


Figure A.6: 2020 Canopy Base Height in the Study Area (Francesco et al., 2023).

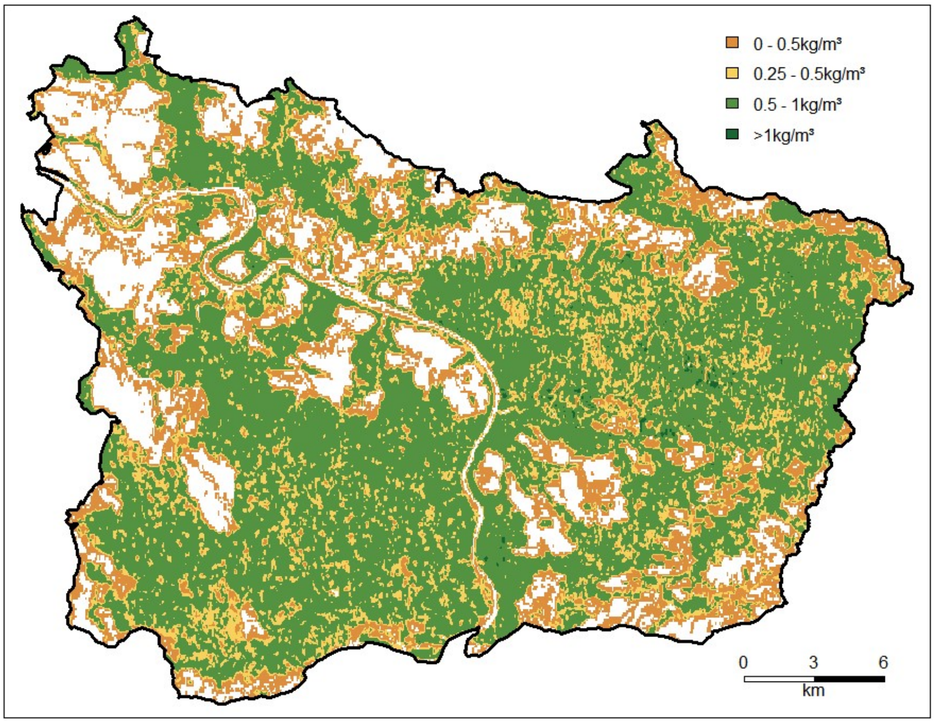


Figure A.7: 2020 Canopy Bulk Density in the Study Area (Francesco et al., 2023).

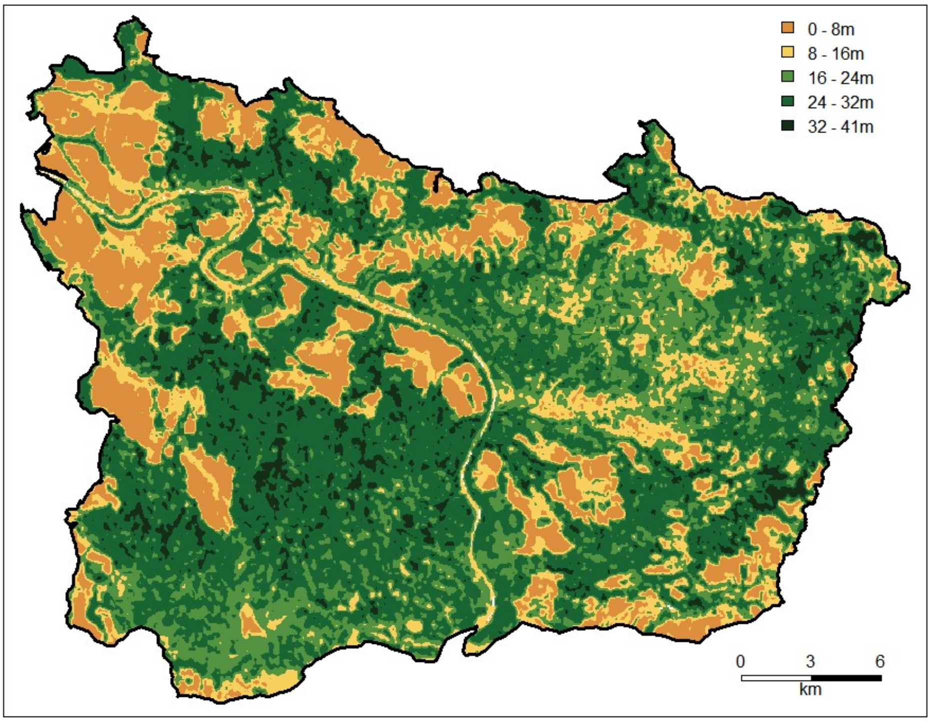


Figure A.8: 2020 Canopy Height in the Study Area (Francesco et al., 2023).

Fuel characteristic	Dead	Live
Range of moisture contents	2–30%	50% to more than 300%
Method of moisture loss	Diffusion of water vapour	Explosive release
Ignition time with moisture	Increases	Generally increases, but may decrease in some species under some conditions
Sustained burning	Occurs on individual particles	Occurs in clumps or groups of particles
Primary constituents	Structural carbohydrates (cellulose, hemicellulose, lignin)	Includes structural and non-structural carbohydrates (sugars, starches, pectin), waxes, resins, terpenes
Seasonal dynamics	Respond to short- and long-term ambient moisture. Foliage is added to dead fuels, begins decay.	Dry mass and moisture content change with plant phenology. Foliage moisture varies depending on age.
Particle geometry	Highly varied	Highly varied
Plant species	May include decayed or partially decayed material	Highly varied physiology and chemical constituents

Figure A.9: 'Comparison of live v. dead fuel properties and their effects on fire behaviour in spreading fires', from Finney et al. (2021, p.153).

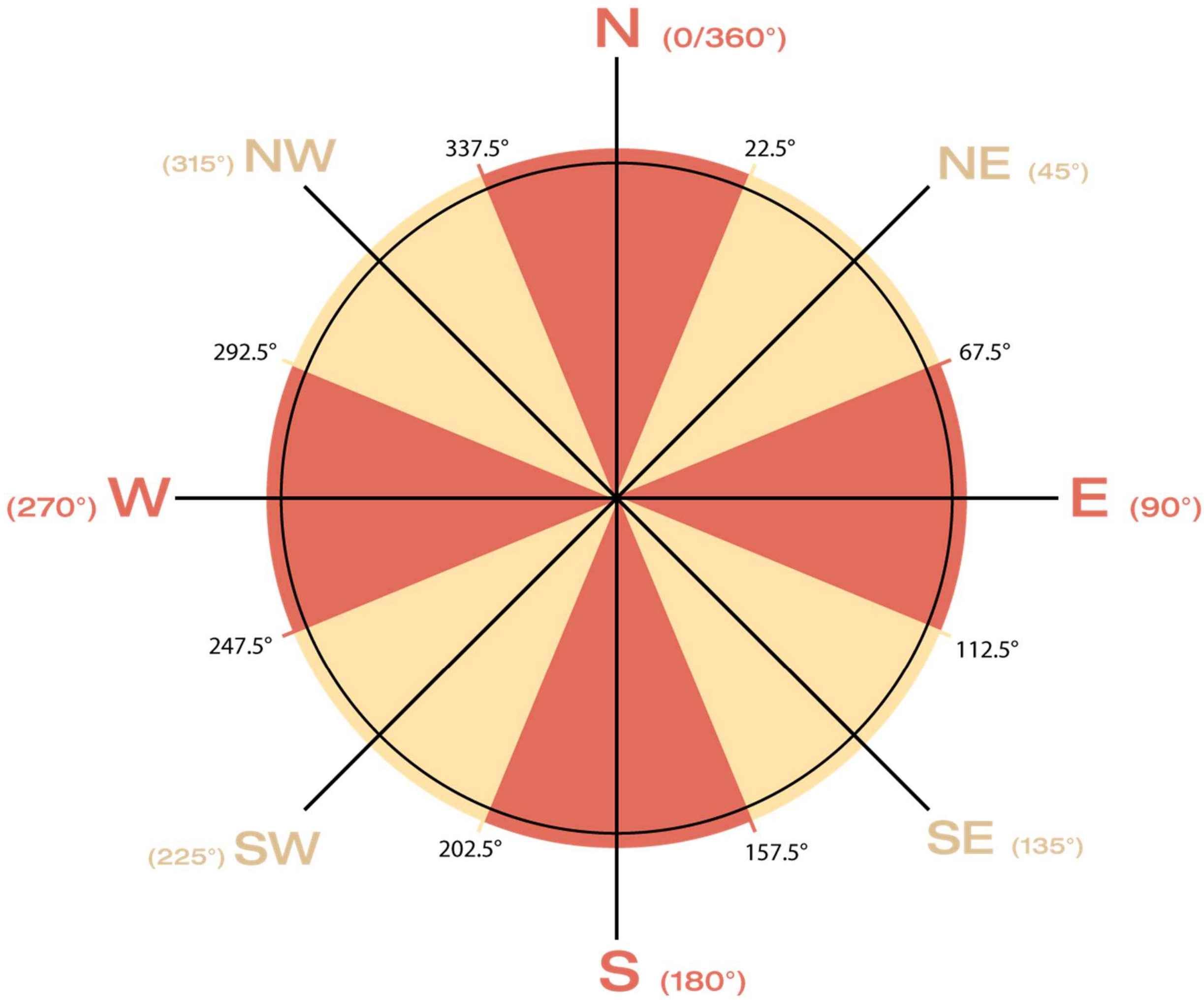


Figure A.10: Eight-fold division of hourly winds based on their direction. Notice the closed and open intervals signified by circle radii coloured with the same or different colour of each wedge.

Input Transportation Classes	Resulting Group
Motorway / Motorway Link *(restricted access major divided highway)* Trunk / Trunk Link *(most important roads in a country's system that aren't motorways)* Primary / Primary Link *(the next most important roads in a country's system after trunk)* Secondary / Secondary Link *(the next most important roads in a country's system after primary)* Tertiary / Tertiary Link *(the next most important roads in a country's system after secondary)*	Major Paved Routes (major car roads)
Service *(Access roads to, or within an industrial estate, camp site, business park, car park, alleys, etc.)* Residential *(Roads which serve as an access to housing, without function of connecting settlements)* Living Street *(Residential streets where pedestrians have legal priority over cars)* Track Grade 1 *(Solid Road. Usually a paved surface (called also 'Sealed Road')*	Minor Paved Routes (minor car roads)
Track *(Roads for mostly agricultural or forestry uses)* Track Grade 2 *(Mostly solid.* *Usually an unpaved track with surface of gravel mixed with a varying amount of sand, silt, and clay)* Track Grade 3 *(Even mixture of hard and soft materials. An unpaved track)* Track Grade 4 *(Mostly soft. An unpaved track prominently with soil/sand/grass, but with some hard or compacted materials mixed in)*	Unpaved Routes (unpaved car roads, no asphalt)

Track Grade 5 *(An unimproved track lacking hard materials)*	
Footway *(For designated footpaths, i.e., mainly/exclusively for pedestrians)* Steps *(For flights of steps -stairs- on footways)* Pedestrian *(For roads used mainly/exclusively for pedestrians in shopping and some residential areas)* Path *(A non-specific path)*	Pedestrian Routes (mostly hiking paths)
Rail *(rails for full sized passenger or freight trains in the typical gauge of the country or state)*	Railway

Figure A.11: Grouping of OSM classes based on OSM documentation (*OpenStreetMap Wiki*, n.d.).

Title	Main job	Potential knowledge	Potential mapping tasks
Fire behavior analyst	Predicting fire behavior	FBFM sampling; fire behavior simulation, collecting fuel information as inputs	FBFM assignment and calibration; map validation and verification
Fuel specialist	Sampling, estimating, and treating wildland fuels	FBFM identification; fuel sampling; defining the biophysical context for fuels; prediction of fire effects	Collection of reference field data, estimation and verification of fuel loads
Fire manager	Managing fire in specific areas using fuel treatments, prescribed burning, and controlled wildfires	Local knowledge of wildland fuel characteristics; prediction of fire behavior and effects	Calibration, validation, and verification of local area references
Fire suppression specialist	Suppression of fires	FBFM identification and use; prediction of fire behavior	FBFM calibration; map validation
Fire scientist	Conducting fire and fuel research	Depends on the scientist and their field of study	Fuel collection, sampling, and identification; map validation and calibration
Fire prevention specialist	Fire danger warnings, public information, preventing unwanted ignitions	General fuel information	Map validation and verification

These titles vary among countries and government agencies, and many of these experts have multiple titles and perform multiple duties. *FBFM* fire behavior fuel model

Figure A.12: 'A summary of the potential experts whose knowledge can be used to more effectively map wildland fuels' (Keane & Reeves, 2012, p. 216).

Appendix B: Usability Questionnaire

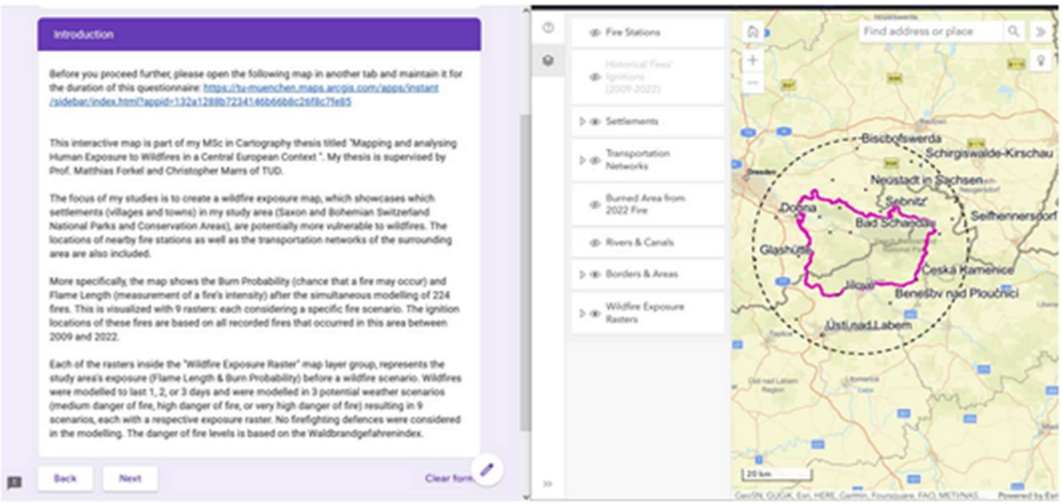
Interactive Wildfire Exposure Map - Usability Questionnaire (~ 10 mins)

evripidis.avouris@gmail.com Switch account

Not shared

Preliminary Step

Before you proceed further, please open the following map in another tab and maintain it next to the questionnaire while answering the following questions: https://tu-muenchen.maps.arcgis.com/apps/instant/sidebar/index.html?appid=132a1288b7234146b66b8c26f8c7fe85



Back Next Clear form

Introduction

This interactive map is part of my MSc in Cartography thesis titled "Mapping and analysing Human Exposure to Wildfires in a Central European Context ". My thesis is supervised by Prof. Matthias Forkel and Christopher Marrs of TUD.

The focus of my studies is to create a wildfire exposure map, which showcases which settlements (villages and towns) in my study area (Saxon and Bohemian Switzerland National Parks and Conservation Areas), are potentially more exposed to wildfires. The locations of nearby fire stations as well as the transportation networks of the surrounding area are also included.

More specifically, the map shows the Burn Probability (chance that a fire may occur) and Flame Length (measurement of a fire's intensity) after the simultaneous modelling of 224 fires. This is visualized with 9 rasters: each considering a specific fire scenario. The ignition locations of these fires are based on all recorded fires that occurred in this area between 2009 and 2022.

Each of the rasters inside the "Wildfire Exposure Raster" map layer group, represents the study area's exposure (Flame Length & Burn Probability) before a wildfire scenario. Wildfires were modelled to last 1, 2, or 3 days and were modelled in 3 potential weather scenarios (medium danger of fire, high danger of fire, or very high danger of fire) resulting in 9 scenarios, each with a respective exposure raster. No firefighting defenses were considered in the modelling. The danger of fire levels is based on the Waldbrandgefahrenindex.

Back Next Clear form

Participant Profile

What is your job title? *

- GIS / Cartography Professional or Student
- Other

Do you use any geographic information system software in your work? *

- Yes
- No

Rate your familiarity with interactive maps -e.g. Google Maps- on a scale of 1 (not familiar at all) to 5 (expert). *

	1	2	3	4	5	
Not familiar at all	○	○	○	○	○	Expert

Rate your familiarity with static -e.g. printed on paper- maps on a scale of 1 (not familiar at all) to 5 (expert). *

	1	2	3	4	5	
Not familiar at all	○	○	○	○	○	Expert

Back Next Clear form

Activity

Please take a few minutes to interact with the map, try to do the following tasks:

1. Make sure that the only Wildfire Exposure Raster visible, is that for the scenario of Fire Danger = medium and duration = 3 days. Also make sure the "Fire Stations" layer is on.

2. Using the search bar, search for the village of Mezna.

3. What values of Flame Length and what values of Burn Probability can you observe around the buildings of this village for this specific scenario (Fire Danger = medium, duration = 3 days)? The legend of the map can be opened on the top left, indicated with a "?" button. To make the buildings layer visible, you need to zoom in to the location.

4. Can you locate where is the closest fire station to Mezna?

5. Can you trace a path from the nearest fire station to Mezna?

How difficult was it to complete the tasks? *

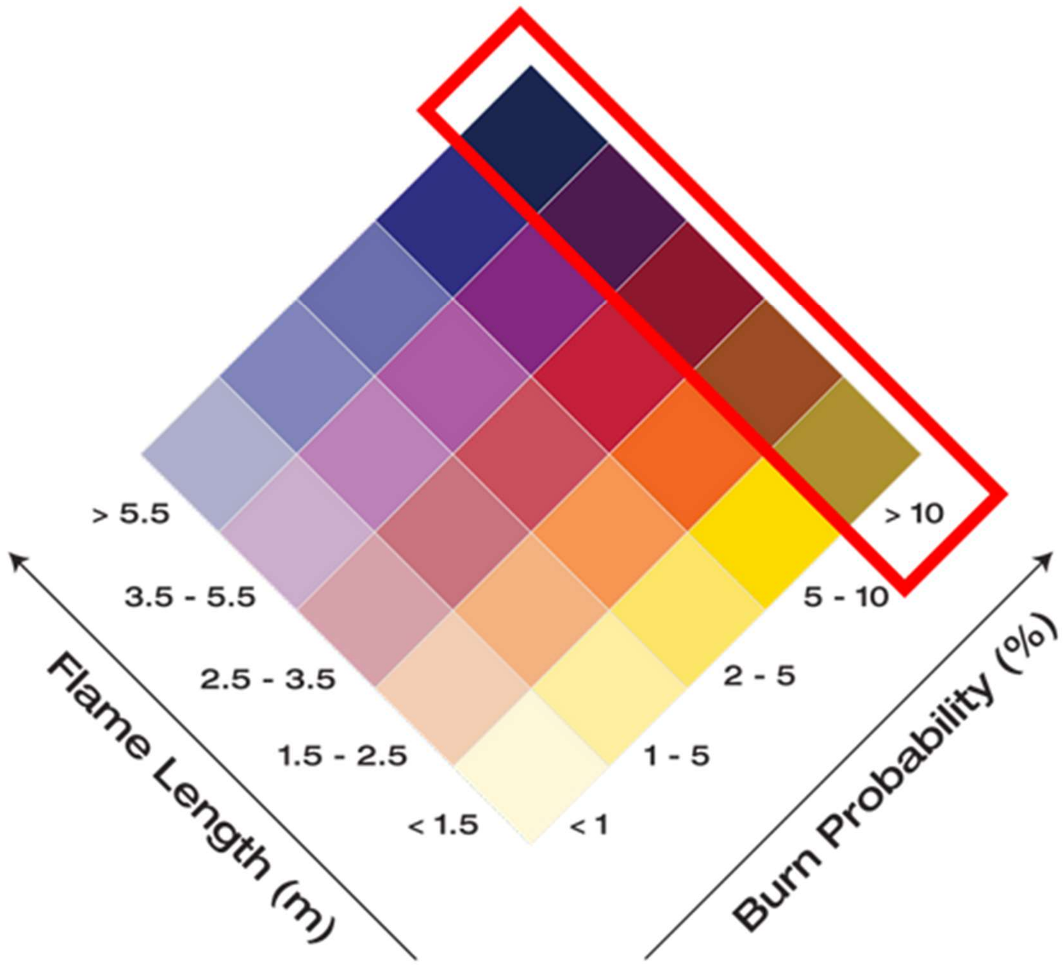
	1	2	3	4	5	
Very easy	○	○	○	○	○	Very difficult

Back Next Clear form

Design Questions

In the following questions you will be asked about the map legend, here it is as a reminder.

What do the more intense colours (see indication below) in the wildfire exposure raster signify? *



Your answer

What do blue areas in the wildfire exposure raster signify? *

Your answer

How easy was the legend to understand ? *

	1	2	3	4	5	
Very difficult	○	○	○	○	○	Very easy

Would you change anything in the design of the map to make it easier to use?

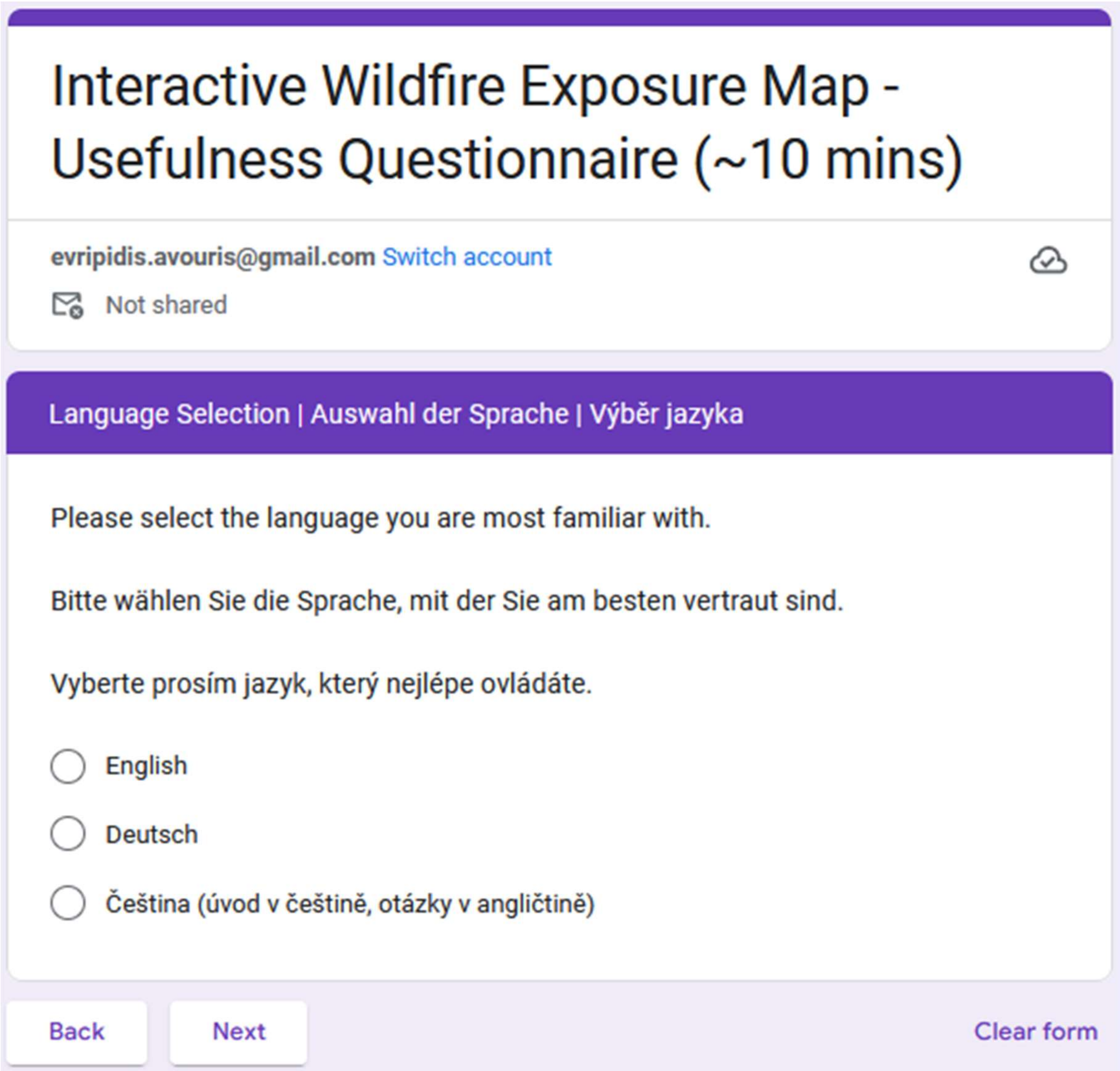
Your answer

What makes the map easy to use?

Your answer

Back Next Clear form

Appendix C: Usefulness Questionnaire (English Version)



Interactive Wildfire Exposure Map - Usefulness Questionnaire (~10 mins)

evripidis.avouris@gmail.com Switch account

Not shared

Language Selection | Auswahl der Sprache | Výběr jazyka

Please select the language you are most familiar with.

Bitte wählen Sie die Sprache, mit der Sie am besten vertraut sind.

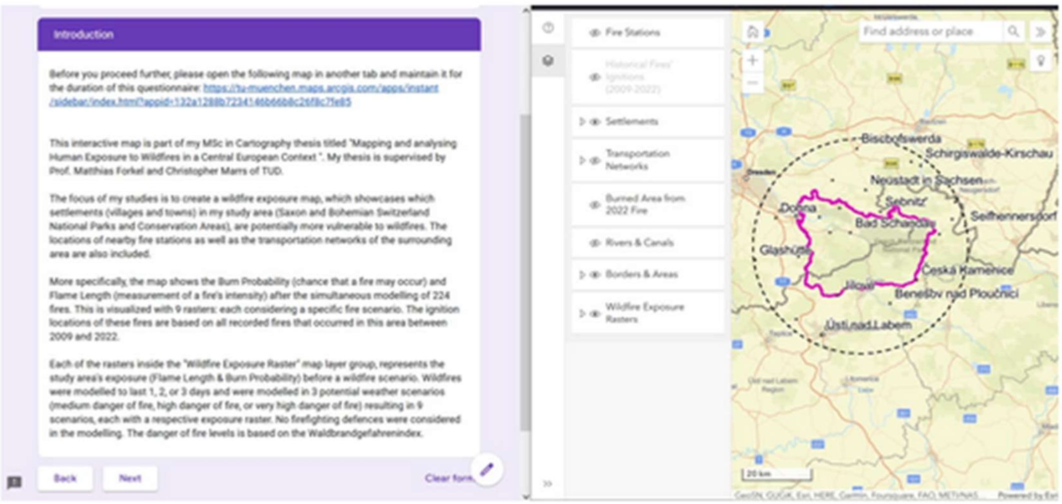
Vyberte prosím jazyk, který nejlépe ovládáte.

- English
- Deutsch
- Čeština (úvod v češtině, otázky v angličtině)

Back Next Clear form

Preliminary Step

Before you proceed further, please open the following map in another tab and maintain it next to the questionnaire while answering the following questions: https://tu-muenchen.maps.arcgis.com/apps/instant/sidebar/index.html?appid=132a1288b7234146b66b8c26f8c7fe85



Back   Next   Clear form

Introduction

This interactive map is part of my MSc in Cartography thesis titled "Mapping and analysing Human Exposure to Wildfires in a Central European Context ". My thesis is supervised by Prof. Matthias Forkel and Christopher Marrs of TU Dresden.

The focus of my study is to create a wildfire exposure map, which showcases which settlements (villages and towns) in my study area (Saxon and Bohemian Switzerland National Parks and Conservation Areas), are potentially more vulnerable to wildfires. The locations of nearby fire stations as well as the transportation networks of the surrounding area are also included.

More specifically, the map shows the Burn Probability (chance that a fire may occur) and Flame Length (measurement of a fire's intensity) after the simultaneous modelling of 224 fires. This is visualized with 9 rasters: each considering a specific fire scenario. The ignition locations of these fires are based on all recorded fires that occurred in this area between 2009 and 2022.

Each of the rasters inside the "Wildfire Exposure Raster" map layer group, represents the study area's exposure (Flame Length & Burn Probability) before a wildfire scenario. Wildfires were modelled to last 1, 2, or 3 days and were modelled in 3 potential weather scenarios (medium danger of fire, high danger of fire, or very high danger of fire) resulting in 9 scenarios, each with a respective exposure raster. No firefighting defences were considered in the modelling. The danger of fire levels is based on the Waldbrandgefahr

Back Next Clear form

Participant Profile

What is your name? *

Your answer

What is your job title? *

Your answer

How is your job related to the National Parks of Saxon or Bohemian Switzerland, or to firefighting/emergency response? *

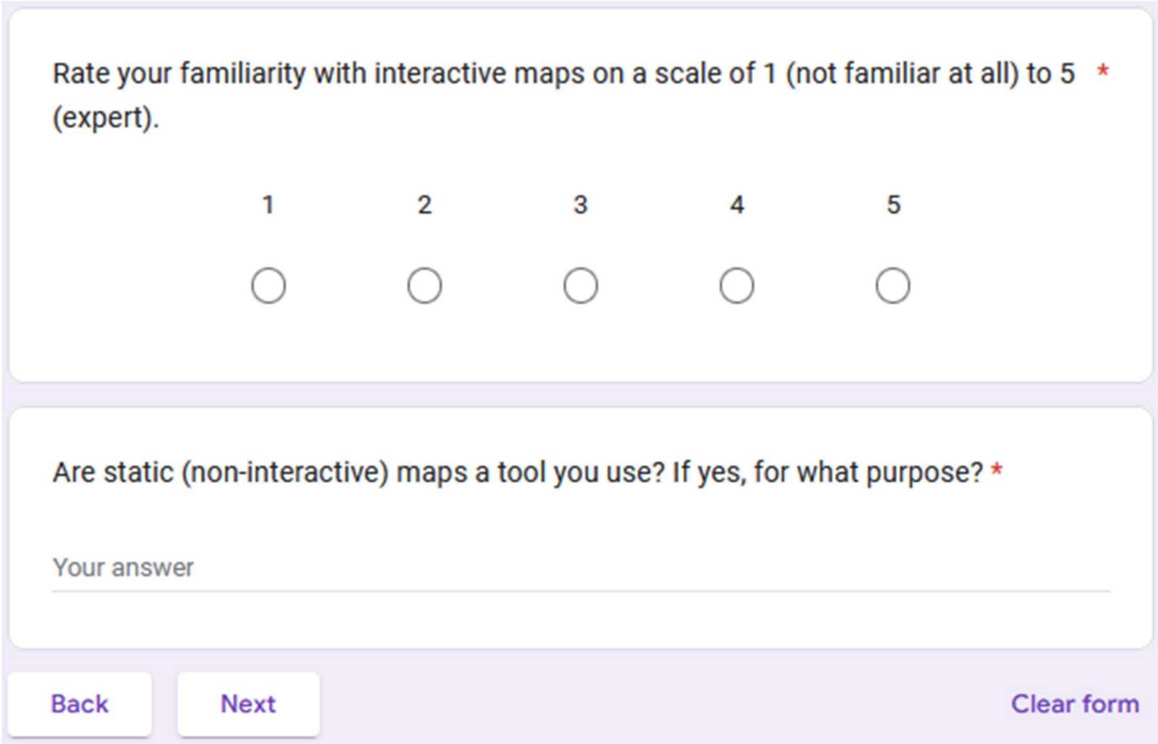
Your answer

Do you use any geographic information system software in your work? If yes, what is it? *

Your answer

Are interactive maps a tool you use in your job? If yes, for what purpose? *

Your answer



Rate your familiarity with interactive maps on a scale of 1 (not familiar at all) to 5 (expert). *

1 2 3 4 5

Are static (non-interactive) maps a tool you use? If yes, for what purpose? *

Your answer

Back Next Clear form

Activity

Please take a few minutes to interact with the map, try to do the following tasks:

1. Make sure that the only Wildfire Exposure Raster visible, is the scenario of Fire Danger = medium and duration = 3 days. Also make sure the "Fire Stations" layer is on.

2. Using the search bar, search for the village of Mezna.

3. What values of Flame Length and what values of Burn Probability can you observe around the buildings of this village for this specific scenario (Fire Danger = medium, duration = 3 days)? The legend of the map can be opened on the top left, indicated with a "?" button. On mobile devices, the button is at the bottom left of the screen. To make the buildings layer visible, you need to zoom in to the location.

4. Can you locate the closest fire station to Mezna?

5. Can you trace a path from the nearest fire station to Mezna?

Where you able to fulfil these tasks? Which ones could you not, and why? *

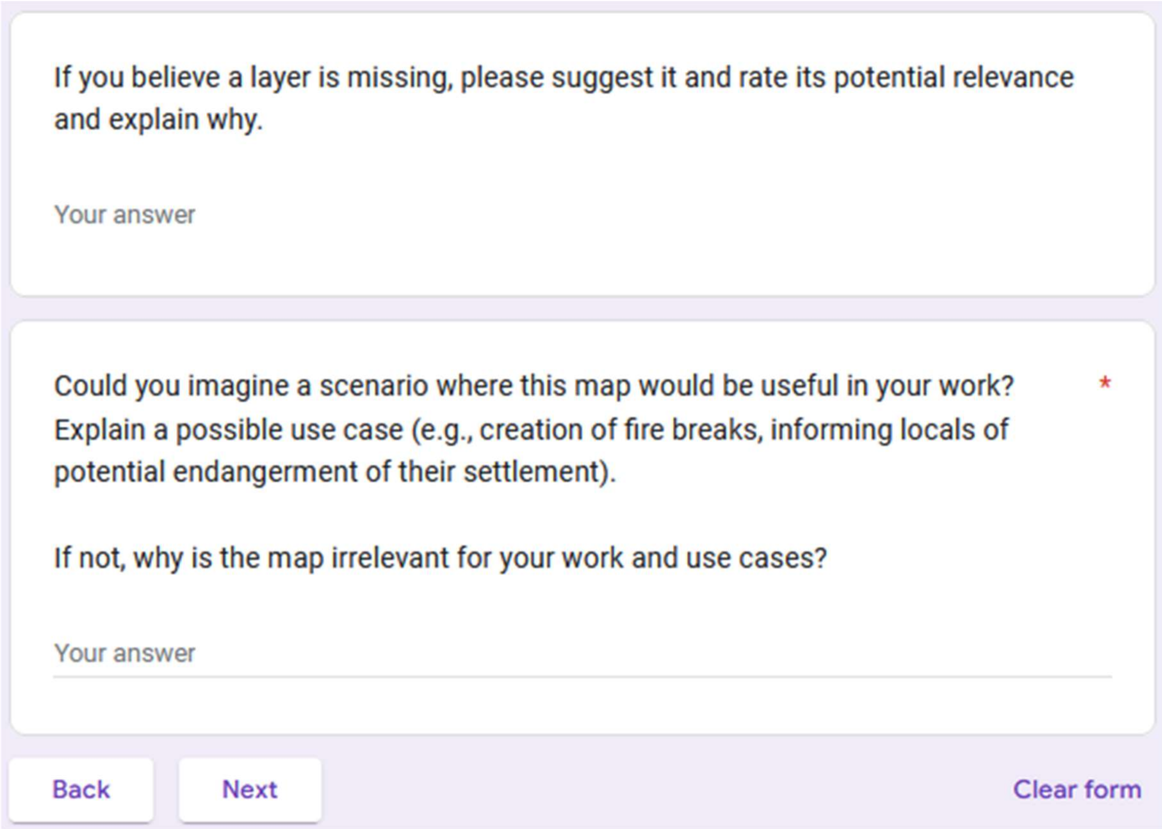
Your answer

Back Next Clear form

Content Questions

Please rank the following information layers in terms of their relevance to your work or use cases of the map. Use a scale from 1 to 5, with 1 being 'Not Relevant' and 5 being 'Highly Relevant.' You can assign the same rating to multiple layers if you find them equally relevant or irrelevant. *

	1 (Not relvant)	2	3	4	5 (Highly relevant)
Fire Stations	○	○	○	○	○
Historical Fires' Ignitions (2009-2022)	○	○	○	○	○
Settlements – Villages, Towns and Cities [2 layers]	○	○	○	○	○
Settlements – Buildings	○	○	○	○	○
Transportation Networks	○	○	○	○	○
Burned Area from 2022 Fire	○	○	○	○	○
Rivers & Canals	○	○	○	○	○
Borders & Areas	○	○	○	○	○
Wildfire Exposure Rasters	○	○	○	○	○



If you believe a layer is missing, please suggest it and rate its potential relevance and explain why.

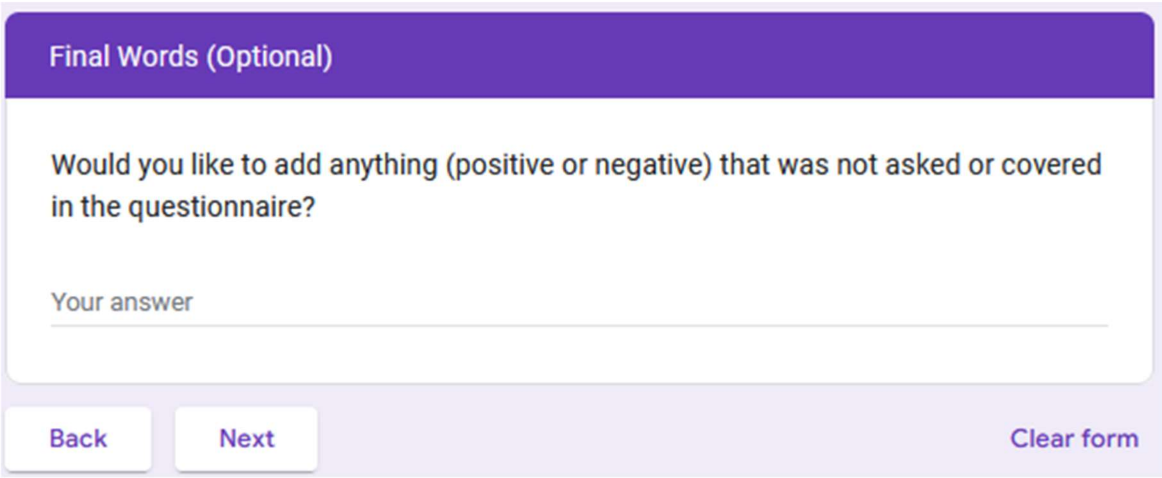
Your answer

Could you imagine a scenario where this map would be useful in your work? *
Explain a possible use case (e.g., creation of fire breaks, informing locals of potential endangerment of their settlement).

If not, why is the map irrelevant for your work and use cases?

Your answer

Back Next Clear form



Final Words (Optional)

Would you like to add anything (positive or negative) that was not asked or covered in the questionnaire?

Your answer

Back Next Clear form