Forest fires in Tyrol, Austria. Current hazard assessment and future outlook.

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a.s.l	Above sea level
AFFRI	Austrian Forest Fire Research Initiative
AFFRI2	Austrian Forest Fire Research Initiative II
ALDIS	Austrian Lightning Detection and Information System
BFW	Bundesforschungszentrum für Wald
Cal. Yr. BP	Calibrated year before the present
CFFDRS	Canadian Forest Fire Danger Rating System
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
E	East
EEA	European Environmental Agency
Eq.	Equation
ESA	European Space Agency
FWI	Fire Weather Index
GIS	Geographic Information System
IR	Infrared
LF	Lightning Flashes
LIDAR	Light Detection and Ranging System
N	North
NDVI	Normalized Difference Vegetation Index
NE	North – East
NIR	Near Infrared
NW	North – West
PTZ	Pan Tilt Zoom
S	South
SE	South – East
SPP	Species pluarlis
SW	South – West
USD	US – Dollar
Var.	Variant
VPD	Vapour Pressure Deficit
W	West
WSN	Wireless Sensor Network
WUI	Wildland Urban Interface
ZAMG	Zentralanstalt für Meteorologie und Geodynamik

1. Introduction

Global change and especially climate change are topics of significant importance and are highly discussed in today's society. At the last, with the rise of Fridays for Future, this topic is now more present than ever before. People want to see a change in the system regarding environmental protection, which includes more than just the reduction of emission of greenhouse gases. It is also the protection of the natural habitats all around the globe which are under constant anthropogenic pressure. With the rate of today's exploitation of these ecosystems, it is a necessary step to take action in trying to preserve them.

A concern of global dimension are wildfires that destroy millions of hectares of forested area every year and put the lives hundreds of thousands of people at risk. The news of the summer of 2023 were covered with headlines regarding wildfires and forest fires that were unprecedented and out of control. It was a year of record-breaking forest fires in the northern hemisphere, with especially intense fires in boreal forests. The fires ravaged through the United States of America, Canada, and many European countries. 2023 has been the worst forest fire season in Canada based on total area burned and on carbon emission. The season has seen 42 million acres burned and an approximate amount of 410 megatons of carbon emitted. This amount counts for more than a quarter of the global wildfire carbon emission of 2023 (Jacobo and Peck 2023; Stillman 2023). But also many European countries were effected. Greece has been devastated by large fires, and declared the largest wildfire ever recorded in the European union. The fires have burned more than 800 square kilometres (km^2) and have killed 20 people. Over 400 firefighter and 28 aircrafts have been deployed to tackle the out-of-control fires. Greece called the wildfire trend unfavourable and demanded more firefighting capacities (France-Presse 2023).

In contrast to this, the fire season in Austria has seen very few forest fires. If the trend of the 2023 fire season continues, it has the potential to be the one with the lowest amount of documented forest fires since 2005 (Müller 2023). Although this fire season has been comparably low in the amount of forest fires, these fires must not be underestimated. They can have devastating effects in regions where forest fires have not been the norm and the environment is not prone to fires. As climate change worsens, with rates of change that far exceed the targeted values and seem to follow the predictions of worst-case outcomes, the uncertainty of future forest fire occurrence in the Alps and Austria grows. The concern regarding these mountainous landscapes arises, prompting apprehensions that the future might entail a fate similar to that currently faced by the Canadian boreal forest.

1.1 Context and research motivation

Austria is largely covered by mountainous and non-mountainous forest of different species composition and structural arrangement. These forested areas serve a multitude of ecosystem functions from which human live is a definite beneficiary. That means that the conservation of a sustainable and healthy forest must be a priority considering the dependency of the local population on it.

Compared to other hazards that endanger the integrity of a healthy forest, such as bark beetle outbreaks or storms that cause windthrow, forest fires currently cause only a fraction of the overall damage. Although currently a minor factor, forest fires are predicted to increase in frequency, size, and severity. This creates yet another problem, which need to be addressed, analysed and solved using tailored and ahead thinking strategies, to keep the damage and the potential risk for the local population as minimal as possible.

During the research for the bachelor thesis of the author, which was about the topics of ecosystem health and forest fires in two mountainous regions in East-Africa, many unsolved research topics regarding forest fire occurrence, behaviour and the resulting impacts of severe fires emerged and led to a heighten interest and awareness regarding the effects of forest fires. Coupled with the topic of natural hazard mitigation and the risk analysis during the time of the master's degree the idea of an in-depth analysis of the forest fire hazard around Innsbruck was created.

In the initial stages of research on the topic of forest fires in the Alps and Austria, it became apparent where research gaps exist and where efforts should be directed to establish a more comprehensive knowledge based upon which future research can be built.

1.2 Objective of the master's thesis

This master's thesis has multiple objectives. The main one is the development of a comprehensive forest fire hazard and risk model utilizing a multi-parameter geographic information system (GIS) approach. It will provide detailed spatial information about the local forest fire hazard and risk situation in the study area. A second, minor goal is the assessment of a customized forest fuel and deadwood mapping approach. At last, the integration and compilation of valuable forest fire related knowledge is a superordinated goal, which is necessary to provide the needed information regarding the forest fire hazard and risk modelling approach. It also aims to offer collected knowledge about possible future outcomes regarding the forest fire danger in the alps and suitable forest and forest fire management options toward a healthy and sustainable forest.

1.3 Research inquiries

The topic of forest fires is a very diverse research field, and a multitude of unanswered question are still around waiting to be resolved. This master's thesis will try to answer the following research questions. The main question is more of an exploration of a new and more detailed forest fire hazard and risk modelling approach. It focuses on what parameters should be included in such a modelling approach and how much influence each of the parameters should have to create a reasonable accurate representation of the current forest fire hazard and risk situation.

Another query revolves around the creation of forest fuel maps. The specific question is if an in situ mapping approach is more effective and suitable to create forest fuel maps and deadwood maps than other approaches, such as remote sensing. A third, more subordinate question examines how the local fire department sees the threat of forest fires and how prepared they are if potentially larger fires would occur in the future.

1.4 Methodology and research approach

The research is predominantly of quantitative design, employing a mixed-method approach to interconnect the findings. The modelling and mapping approaches are done using computer supported quantitative research methods, while a semi-structured expert interview integrated the qualitative aspect of forest fire research into this master's thesis.

The necessary data for the modelling will be interpreted using a GIS software, and data analysis and visualization tools such as R and Excel. These provide the abilities for simplified and comprehensive, yet insightful forest fire hazard and risk modelling.

1.5 Structure of the master's thesis

The master's thesis is divided into three main parts. The first one focuses on important forest fire related knowledge. It provides the necessary information about forest fire occurrence, its behaviour, the most influential factors, the implications for the environment and currently used prevention measures.

The second part is about the study area and the methods and findings of the here conducted research. It starts with a brief description of the study area, including the landcover, the forested areas and the climatic conditions. Afterwards the current state of the Austrian forest and the current Austrian fire regime is addressed. Then the research methods and findings follow. Each of the three methods (expert interview, fuel mapping, forest fire hazard and risk modelling) has its own short discussion at the end of each chapter of the method.

The third part focusses on an outlook into the future. Here predicted future climate scenarios and the implications for the future fire regime and the Austrian forest are examined. Afterwards a short part about the annotations for future forest and fire management is followed by the main discussion where the results are compiled, the advantages and limitations are presented and implications for future forest fire research is showcased.

2. Definition and introduction of the topic forest fires

The term forest fire describes unwanted fires burning in forested areas which in some literatures are referred to as wildfires (Faivre et al. 2018, p.10). Forest fires are a natural part of the ecosystem forest and play an integral role in vegetation dynamics and the global biochemical cycles (Venevsky et al. 2002, p.984; Kaltenbrunner 2009, p.464). A forest fire can be characterized as a process of rapid reaction between oxygen and other elements, which in this case are natural forest fuels (Yananto et al. 2017, p.76).

The appearance of fires depends on local conditions such as location, elevation, wind velocity, precipitation, temperature, air humidity, topography, litter type, and levels of suppression amongst other explanatories (Brillinger et al. 2003, p.178). A very important factor is the overall vegetation type with parameters including fuel type, forest structure, coupled with socioeconomic factors which play into the creation of forest fires (Müller et al. 2012, p. 1). As numerous studies show, some factors are more determining than others. Arapaci et al. 2014 found that climate and anthropogenic factors are the most important factors for fire ignition (Arpaci et al. 2014, p.265), while Müller et al. (2020a) found that the ignition of a fire is mostly determined by the ignition source and the moisture content of the fuel (Müller et al. 2020a, p. 3). Afterall, the occurrence of forest fires boils down to two main components. It needs the right weather conditions in areas that are susceptible to forest fires. If these variables meet, a forest fire will ignite given the chance (Faivre et al. 2018, p. 11).

Forest fires that get out of control are of concern globally (Freudenschuß et al. 2021, p.48). Since the 1950s the annual number of fires and area burned has increased in countries like Canada, Sweden and the United States. However, these trends may partly reflect the increasing ability to monitor fires (Baker 2003, p.120). These open regions experience on average about 1300 fires per year burning around 7000 hectares annually (Wastl et al. 2012, p.2).

Forest fires are also a serious and increasing threat throughout Europe – with particular severity in southern European countries such as Greece, Spain, France, Italy and Portugal. If out of control, these fires can produce large environmental and economic losses and even harm human life. The most destruction from forest fires happened due to the largest and most intense fires that only represents 2% of all fires recorded (Faivre et al. 2018, pp. 6).

In Austria a forest fire is defined as an uncontrolled fire in wooden areas which were defined as forest by the Austrian forest law. This definition also includes clear cuts, blowdowns, small groves, and dwarf mountain pine (*Pinus mugo*) (Müller et al. 2012, p. 2). In this master’s thesis the term forest fire will use the definition from Müller et al. (2020a) saying forest fires are uncontrolled fires in forested areas that are independent of the fire type, the size or the cause (Müller et al. 2020a, p. 12).

Currently the Alps are not a region that is commonly associated with forest fires, when compared to the Canadian tundra or the western United States (Wastl et al. 2012, p.2). Each year around 250 fires occur in Austria, with most fires being recorded in spring and summer. Most of the Austrian fires are being recorded in Lower Austria, Tyrol, Styria, and Carinthia (Freudenschuß et al. 2021, p.48).

Forest fire related terminology

To understand the occurrence of forest fires and the impacts that result from them some definitions, terminology and fire mechanics must be explained.

First, the overall **fire regime**. The fire regime includes the return period, the seasonality, the size and intensity, as well as the outcome of the forest fires in a certain area (Weibel et al. 2016, p.433). It is the results of the complex interaction between the weather, the fuel, the topography and the ignition source. Changes in those variables are mainly connected to climate change as well as the human influence on them (Pezzatti et al. 2016, p.224). The fire regime can vary largely in terms of the **fire frequency**, meaning how often fires occur, the **fire season**, meaning when it occurs and the **fire intensity**, regarding how fiercely it burns (Bond and Van Wilgen 1996, p.16).

The **intensity** of a fire describes the physical combustion process of energy release from organic matter. It is correlated closely with the **fire severity**, which refers to the loss or decomposition of organic matter above ground and/or below ground (Keeley 2009, pp.116). Tree mortality is consistent with the definition of fire severity as a loss of organic matter. Because of that, the fire severity is often estimated as the proportion of overstory trees killed by fire (Stephens et al. 2013, p.41; Keeley 2009, p.119)

To ignite a fire some conditions must be met. First, a source of ignition must be present for a fire to consume the present fuel and secondly the weather condition must be sufficient to ensure that the fuel is dry enough for ignition and combustion (Bond and Van Wilgen 1996, p.17). Here the term **fuel** refers to the living and dead biomass that is burnable under certain moisture conditions (Jenkins et al. 2008, p.19). Bond and Van Wilgen 1996 referred to fuel as "the food of fire" (Bond and Van Wilgen 1996, p.6). The fuel that forest fires need to sustain themselves, consisting of leaves, litter, small and larger branches, and deadwood, depends on the forest type and what management measures have been taken (Weibel et al. 2016, p.434).

This so-called **fuel load** is an important factor influencing the fire severity, intensity, and the likelihood of transition from surface to crown fires (Neumann et al. 2022, p. 693; Zumbrunnen et al. 2010, p.2189) as the insufficient fuel buildup may limit the potential for larger forest fires even in suitable weather conditions (Baker 2003, p.134). Salvage logging for example can leave behind a lot of woody debris which can dry out and make of good fuel and fire spread condition. Also, the suppression of every minor fire may lead to a buildup of fuel that can lead to larger and more intense fires (Gossow et al. 2007, p.4).

Understanding the fuel load and its structure in the temperate European coniferous forest is a crucial part in understanding the fire regimes in these areas (Neumann et al. 2022, p. 693). Fire models showed the fuel dependency of forest fires as they would be much more likely in areas with sufficient fuel than in others (Bond and Van Wilgen 1996, p.6). To estimate the amount of surface fuels a ground observation is needed (Neumann et al. 2022, p.693).

Fuels can be divided into **fuel categories** according to the classification used in the United States. They are separated into time lag classes (1, 10, 100, 1000 hours) which correlates to the diameter (0-6, 6-25, 25-75, <75 mm). This time lag refers to the time in which the fuel will reach 2/3 of the difference between its initial moisture content and the moisture content of the current surrounding environment. This property is related to the moisture holding ability as well as the diameter of the fuel (Neumann et al. 2022, p.694).

The **flammability** of the fuel includes four components. The ignitability, the combustibility and the sustainability. The **ignitability** refers to the time a material needs to ignite when sufficient heat is added. The **combustibility** describes the way the material burns. The **sustainability** just refers to the capacity of the material to stay ignited and burn over time. The **consumability**, describes the proportion of material that is consumed during combustion (Popovic et al. 2021, p.2; Xanthopoulos et al. 2012, p.80).

These flammability components of the fuel can be influenced in different ways, including the structural composition, the moisture content and the chemical components of the fuel. Thinner fuel components are more easily ignited, due to a higher surface area to volume ratio. The density of the fuel will affect the total amount of heat the fuel can absorb before ignition (Xanthopoulos et al. 2012, p.80).

The **fuel moisture content**, which just describes the moisture contained by the fuel is another important factor influencing flammability (Xanthopoulos et al. 2012, p.81) since low fuel moisture act as a key trigger of forest fires in central Europe (Neumann et al. 2022, p. 694). The fuel moisture content regulates the ignition delay and the energy amount that is available for combustion (Chuvieco et al. 2014, p.609), as high fuel moisture may limit flammability and therefore the occurrence of forest fires (Guyette and Dey 2000, p.28). Fires usually start in areas with fine dead fuel with low moisture content because compared to live fuels less heat input is needed to ignite the fuel. Fuel moisture also influences the fire rate spread and the flame length (Xanthopoulos et al. 2012, p.81). The moisture content, the arrangement and mass of fuels are the most important drivers of the fire spread in intensity of a forest fire (Blauw et al. 2017, p.475).

The accumulation, distribution, and flammability of the fuel can all affect the risk of ignition and spread forest fires (Carcaillet et al. 2001, p.940). Forest fires begin and end with fuels. Any factor that affects the quality and or quantity of fuels in time and space has the potential to alter fire behavior (Jenkins et al. 2008, p.25).

The **behavior** of a fire can be described in terms of its rate of spread, flame length, and intensity (Jenkins et al. 2008, p.23). The **rate of spread** of fire is dictated by the fuel characteristics and the wind direction and wind speed. The more energy the flame front can build up the faster the fire can spread (Venevsky et al. 2002, p.989).

A forest fire can be separated into three **types of fires** as follows. Firstly, the **ground fire** or **smoldering fire** which usually only burns the humus and peat. Secondly the **surface fire** which propagates along the forest floor and consumes the shrub vegetation. Lastly if the fire propagates higher into the vegetation it is called a **canopy -** or **crown fire**. This type of fire propagates from canopy to canopy (Yananto et al. 2017, p.76).

Smoldering is a flameless type of combustion that can last for prolonged periods of time. During prolonged periods of drought, the soil may dry out enough to be suitable for smoldering combustion in organic soils. The smoldering will spread laterally and far underground resulting in extensive burning of the soil below the surface with little or no indication of that extent above the location of smoldering. These fires are difficult to control and extinguish due to the tendency for those combustions to occur deep within the soil. The heat that is transported from the combustion into the organic soil and the plants can result in significant damage and mortality of trees (Watts and Kobziar 2013, pp.124).

3. Influential parameters for forest fires

3.1 Human activity

A forest fire does not just ignite at random. An ignition source is always needed (BML 2022, p.5). The occurrence of forest fires is significantly determined by human presence (Badeck et al. 2003, p.2), as most of the forest fired worldwide are directly or indirectly ignited due to human activity (BML 2022, p.5; Martinez et al. 2008, p.1241).

In the alpine region the question behind the fire cause is also quite clear: 90% of all fires are ignited due to direct or indirect human action (Müller et al. 2020a, p. 22). Similarly in Austria 85% of all forest fires are ignited due to direct or indirect human action (Müller and Vacik 2019, p.7; Arpaci et al. 2014, p.259; Freudenschuß et al. 2021, p.48).

Human activity plays a crucial role in both igniting and controlling forest fires. Carelessness and inappropriate behavior can lead to ignition (Müller et al. 2020a, p. 31). Some of the most common ignition sources are cigarette butts, uncontrolled fires, hot ashes, and arson (Freudenschuß et al. 2021, p.48). Humans can also directly and indirectly influence fire occurrence through various means. This includes altering the landscape, changing forest composition, and affecting fuel amounts (Zumbrunnen et al. 2010, p.2189). Additionally, human interactions with fire management, policies, and regulations can have significant impacts on the fire regime (Pezzatti et al. 2016, p.224).

Forest fires that are caused due to human activity are usually ignited very close to human infrastructure (Weibel et al. 2016, p.440). The area where human infrastructure and settlements meet forested areas is called the **Wildland-Urban-Interface** (WUI).

The Wildland-Urban-Interface is commonly characterized as the area where urban development presses against private and public wildlands (Theobald and Romme 2007, p.340; Conedera et al. 2015, p.10). With a population increase it saw a gain in significance in terms of forest fire risk management in the last couple of decades (Freudenschuß et al. 2021, p.48), as forest fires are an ongoing threat in areas with a WUI (Castillo Soto 2012, p.199). In these areas, the number of anthropogenic ignition sources and amount flammable fuels increase. This makes protecting human infrastructure inside this area very challenging (Conedera et al. 2015, p.10) due to the high ignition probability that comes together with a high risk of loss (Freudenschuß et al. 2021, p.48; Faivre et al. 2018, p. 16).

An increased trend of constructing housing near or in forested areas will lead to an increasing issue of the WUI, which could potentially put human lives in direct danger (Müller et al. 2020a, p. 10).

The Wildland-Urban-Interface will also become more important in the future because forested areas in close vicinity to human settlement, that used to be quite unaffected by forest fires, might increase in forest fire danger (Müller et al. 2020a, p. 43). Some studies have tried to establish the major influences on forest fire occurrence in these areas.

Pezzatti et al. (2016) found that buildings have the most influence on the occurrence of human caused forest fires, followed by roads (excluding highways). In the canton of Wallis 75% of forest fires are ignited within 160 meters around relevant human infrastructure (Pezzatti et al. 2016, pp.238). Arapaci et al. (2014) on the other hand suggested a 300-meter radius around buildings and a 100-meter radius around railroads as the possible maximum ignition range (Arpaci et al. 2014, p.260). Sparking from breaking trains can cause surrounding fuel to ignite. This is happening especially on steeper slopes downhill, where trains have to break more frequently.

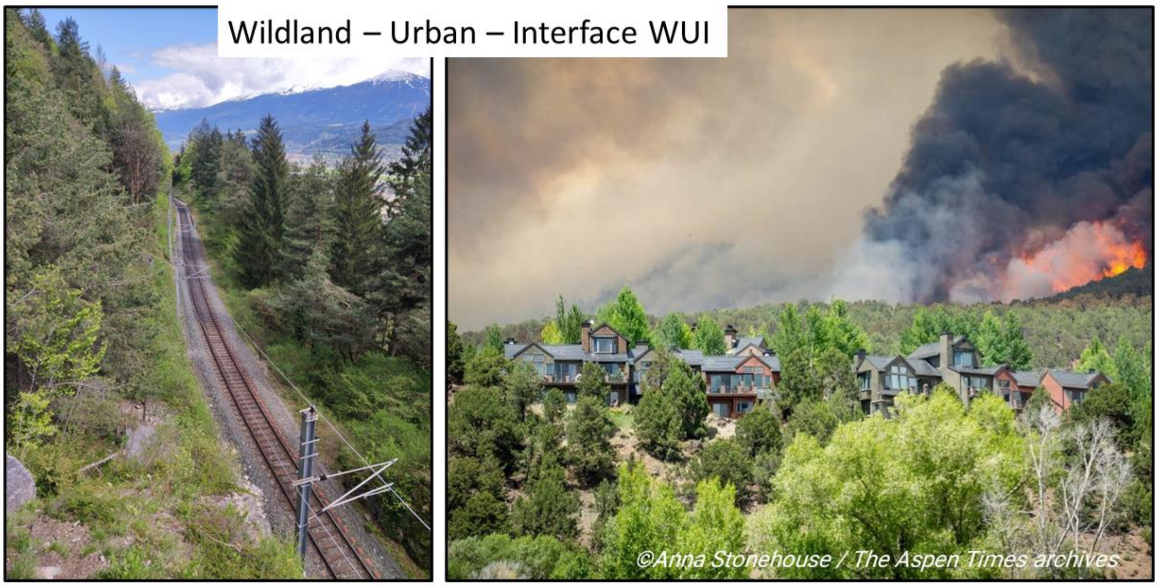

Figure 1: The Wildland - Urban - Interface. Depicting the interconnectivity between forested areas and human infrastructure and settlement (Source: left photo Nils Scheffler. Right Photo: Anna Stonehouse, The Aspen Times archives).

Arndt et al. (2013) describes that the density for railroad, forest roads and hiking trails are all significant factors influencing forest fire ignition. Arndt et al. (2013) also found in the study that the population density only plays a minor role for forest fires as they were found not to be significantly related to fire danger (Arndt et al. 2013, pp. 315).

The extensive recreational use by nature-based tourism can also influence fire occurrence, due to the negative impacts they exert on these forest ecosystems, which are very sensitive to environmental changes (Arndt et al. 2013, p. 315). Müller et al. (2020a) found that tourism and recreational activities count as the most important social factor that influences the occurrence of forest fires (Müller et al. 2020a, p. 43). An increase in recreational use of the forests might lead to an increase in ignition in that particular area (Arndt et al. 2013, p. 322).

Zumbrunnen et al. (2009) found that a higher ignition potential at lower elevations is created due to denser human settlement, implementing that temperature and precipitation have lost their relevance as influencing factors at low elevations (Zumbrunnen et al. 2009, p. 82-83).

While the ignition probability is higher, Arndt et al. (2013) argues that in areas with a higher railroad and road density the likelihood of a fire being reported in that area would increase both due to a higher number of residents and visitors (Arndt et al. 2013, p. 322).

All these findings suggest that forested areas, which are near human settlement, roads, and pathways are statistically more prone to forest fires than remote areas due to humans as the main ignition source for forest fires (Müller et al. 2020a, p. 13). This indicates that the appearance of human activity, which is made possible by infrastructure, is the biggest factor for human caused forest fires (Pezzatti et al. 2016, p.238).

3.2 Climate and weather

The climate and weather impacts fire activity, creating suitable forest fire conditions due to high temperatures and low precipitation, coupled with wind and lightning activity (Zumbrunnen et al. 2010, p.2189). On one hand it can have direct metrological influences such as lightning strike. On the other hand periods of drought and heat waves can be an indirect influence as they lead to more suitable forest fire conditions (Pezzatti et al. 2016, p.224).

After the ignition of a fire, it needs certain weather conditions that promotes sufficient fire spread such as low precipitation amounts, high average temperatures, and strong winds. If these parameters are not met, the spread of the fire will not be significant. Suitable weather conditions alone are considered insufficient in sustaining the spread of fire certain minimum fuel conditions need to be met (Baker 2003, pp.122).

The overall fire behavior is largely affected by air temperature and wind speed. With the latter having a stronger influence on the fire risk than temperature. With wind speed the flame height will increase (Cseresnyes et al. 2011, p. 162-163). Weather phenomenons like foehn can play a major role in fire ignition and propagation in the alps (Arpaci et al. 2014, p.259). During strong foehn events the wind speed and wind direction will influence intensity and the speed of the fire spread (Müller et al. 2020a, p. 13).

Also, locally in connection with strong foehn events in the northern or southern Alps, winter fires can occur especially during times of temperature inversion that cause very sunny conditions above the fog line making the environment and fuel moisture condition suitable for forest fires (Müller et al. 2020a, p. 16).

At higher altitudes the usually wet and cold conditions make vegetation much less prone to fire than at lower altitudes and ignition sources are much more abundant in the valleys (Zumbrunnen et al. 2010, p.2196). In lower altitudes, low snowpacks during winter and early snow melt in late winter and early spring can contribute to the occurrence of fires during the early spring and summer months (Baker 2003, p.123).

As climate is the main limitation for vegetation growth it influences the distribution of vegetation (Zhang et al. 2016, p. 1) and the biomass production and is therefore influencing the fuel load which has an impact on the forest fire regime in certain areas (Zumbrunnen et al. 2010, p.2189). There is also a hypothesis called the "Weather Hypothesis" that suggests that large, severe fires are driven by extreme weather events and burn intensely through forests regardless of the condition of the fuels (Gumming 2001, p.98)

Lightning strike

In Austria 85% of all fires are ignited due to human action while, the other 15% are triggered due to natural cause, usually lightning, as it is the only relevant natural cause in Austrian forest as well as most other forest ecosystems worldwide (Müller et al. 2020a, p. 22; Müller and Vacik 2019, p.7; Conedera et al. 2006, p.1). In the summer months, fire ignition due to lightning strike take up to 50% of all ignition sources in Austria, playing a major role in the Austrian fire regime (Müller et al. 2012, p. 2; Müller et al. 2020a, p. 22).

The yearly occurrence of lightning induced forest fires in Austria is variable. More lighting induces forest fires usually occur in years with a higher overall number of forest fires. It also seems to correlate with years of larger summer droughts, in which the number of lightning fires was also higher (Müller et al. 2012, p. 6). As thunderstorms are usually accompanied by rainfall not lightning strike not always ignites a forest fire (Guyette and Dey 2000, p.28). Most of the lightning caused forest fires were recorded in Lower Austria and Carinthia (Müller et al. 2012, p. 6).

Lightning usually causes forest fires and coniferous forests at high elevation in the Alps (Conedera et al. 2006, p.6). The relative number of lightning induced forest fires increases with elevation while the relative number of human-caused fires decreases and vice versa. Lightning induced forest fires are also more prone to start underground and smoldering fires (Müller et al. 2012, pp. 9).

For detection of lightning strikes, the Austrian Lightning Detection and System (ALDIS) is in use. It locates the lightning strikes and takes record of thunderstorm activity in Austria (Müller et al. 2012, p. 2).

3.3 Vegetation

Vegetation plays a major role in the occurrence of forest fire. Without the vegetation, that acts as the fuel, combustion would not be possible, even under the right fire weather conditions. The structural component and the type of vegetation, as well as the moisture content are significant influences on forest fires.

The structural composition of the forest and the overall continuity of it can impact the fire behavior (Müller et al. 2020a, p. 13). This includes litter and deadwood that accumulates in the forest. Large accumulation of deadwood and close tree stands can also elevate the danger of a fast-spreading forest fire (Wohlgemuth et al. 2008, p.338). Another example of the fuel composition effecting forest fires is when litter is composed of large, long, or curled leaves, it provides a suitable structure for high oxygen flow rates that can, while ignite, enhance flammability (Popovic et al. 2021, p.12).

The overall composition and distribution of tree species in forested areas may change the fire regime due to species specific differences in flammability. This can affect the ecosystems response to forest fires (Blauw et al. 2017, p.475). Different tree species can also affect the fire regime in terms of return period. While certain species have a faster recovery as others due to sprouters that can regenerate from buds, even after the canopy of the tree was damaged or destroyed by the fire, vegetation might recover quicker and lead to a faster build-up of new fuel to be consumed by fires (Bond and Van Wilgen 1996, p.7).

3.3.1 Coniferous forest

The fire regimes in coniferous forests are usually expected to be more severe than in broad leaved forest with the fire intensity and fire spread rate being higher than in deciduous forest stands (Blauw et al. 2017, pp.475). A reason for this is that in forest stands which are dominated by conifers, the available fuel is more flammable, and the fire can spread much faster than in broad leaved forests (Carcaillet et al. 2001, p.940). The evergreen coniferous trees burn from 5 to 10 times faster than other species of deciduous trees (ESRD 2012, p.1).

Another reason is the chemical composition of those trees. Coniferous trees have a lot of sap in their branches which burns very quickly and creates fast moving forest fires. The fumes that are released from ethereal oil, which is stored in them, can combust explosively given the circumstances and ignite trees in the vicinity (Wohlgemuth et al. 2008, p.338). Conifers also tend to grow much closer together, which raises the probability of a crown fire and makes it easy for a fire to burn effortlessly through large areas of forests (ESRD 2012, p.1; Baker 2003, p.132).

These forests also contain a lot of ladder fuels, which usually consist of branches that reach near the ground and can help a fire to rise from a ground to a crown fire, therefore acting as a fire ladder (Baker 2003, p.131; Müller et al. 2020a, p. 13). Areas that contain large amounts of these ladder fuels and shown an abundance of dead fuels may be hotspots for future fires (Baker 2003, p.145)

Due these physical and chemical differences coniferous forests in the northern alps burn more frequent and with higher intensity than broadleaf forests. Especially those that appear on southern slopes of limestone are at higher risk. These forests, however, usually play an important role in the protection against natural hazards (Müller et al. 2020a, pp. 10).

Although the susceptibility to forest fires is higher in coniferous forest, there are differences within coniferous species, that are investigated by studies: For example, Neumann et al. (2022) suggests that the forest type is the most important driver of fuel structure in all coniferous forests. They found that Norway spruce (*Picea abies*) forests have higher loads of litter and deadwood material compared with Scots pine (*Pinus sylvestris*) (Neumann et al. 2022, p. 702).

The findings coincide with Müller et al. (2020a). Here it also show that the amount of fuel, that is available for fires, is much higher in *Picea abies* stands than compared to pine forest. *Picea* *abies* stands have the potential to facilitate forest fires that can reach higher intensities. This is again due to the phenomenon of the fire ladder, because of which it could lead to a more rapid development of crown fires from ground fires (Müller et al. 2020a, p. 45).

Other studies have looked into how the snow retention effects of *Pinus mugo* can change the fire regime. A concept called the "Moist Canopy Hypothesis" plays with the idea that under the *Pinus mugo* canopies snow can be retained far longer into the year whereby that creates wet conditions leading to the canopies acting as a natural fire break (Leys et al. 2014, p.61).

In contrast to this concept stands the "Fuel hypothesis" that refers to the dense and connected structure of *Pinus mugo*, which leads to higher fuel connectivity that, in turn, could lead to suitable high intensity fire conditions (Leys et al. 2014, p.61).

Leys et al. (2014) found that the moisture holding ability which refers to the "Moist Canopy Hypothesis" does in fact not prevent the spread of fire at all, as fires were very frequent between 8200 and 2200 cal. Yr. BP. Leys et al. (2014) concluded that *Pinus mugo* favors the spread of fire due to the layering effect which would connect to the "Fuel Hypothesis" (Leys et al. 2014, p.66).

3.3.2 Deciduous forest

The fire regime in deciduous forest differs from that in coniferous forest. A general rule implies that deciduous trees don't burn as fast or as intense as coniferous trees. A reason for that is the frequent absence of ladder fuels in deciduous forests. Therefore, fires cannot convert from ground fires to crown fires as easily as they do in coniferous forests (ESRD 2012, p.1).

Although the rule is mostly correct, deciduous trees can be extremely flammable in early spring, right before the new leaves emerge (ESRD 2012, p.1). For example, the European beech (*Fagus sylvatica*) forests also had their difficulties with particularly dry years in the last decades, resulting in forests that could potentially be affected by large fires as well, which used to be less fire prone. Also, in the southern and maritime Alps, forest fires are frequent in broad leaf forests, which are usually dominated by European beech or Chestnut (*Castanea sativa*) (Müller et al. 2020a, pp. 10).

Dimitrkopoulos et al. (2011) suggest that the overall flammability is more influenced by the fuel bed properties rather than individual forest fuel characteristics, implementing that the tree species might not be the decisive parameter (Dimitrakopoulos et al. 2011, p.136).

3.3.3 Vegetation flammability

The probability that a fire develops depends largely on the flammability of plant tissues (Lillis et al. 2009, p.203). The different plant traits that are the main determining factors are the moisture content, the overall morphological features as well as the chemical composition (Popovic et al. 2021, p.4; Xanthopoulos et al. 2012, p.82). As mentioned earlier volatile isoprenoids may be the first parts of the plant that ignites. While igniting abruptly, these can sometimes create larger fireballs that may ignite trees in the vicinity (Lillis et al. 2009, p.203; Xanthopoulos et al. 2012, p.81). Indicating that isoprenoids increase the flammability of plant tissue. The structural components such as the wood density and the lignin content of the wood can have negative effects on the flammability resulting in a lower burning rate (Osvaldova and Castellanos 2019, p. 95).

The primary restrictor of flammability though is the moisture content of the plant tissue (Lillis et al. 2009, p.203). Studies show that the positive correlation between the moisture content of leaves and the time to ignite is highly significant (Dimitrakopoulos et al. 2001, p. 149).

Popvic et al. 2021 found that the moisture content is directly related to flammability as the moisture content of leaves, twigs, litter, wood, and bark decreases the overall biomass's ability to ignite (Popovic et al. 2021, p.5).

Figure 2: Clear cuts in forested areas in the study area. Both pictures were taken near Innsbruck. (Source: Nils Scheffler).

In forest stands with low canopy cover the ground might experience increased input of solar radiation which could result in higher ground temperatures and decreased relative humidity which lowers fuel moisture content (Jenkins et al. 2008, p.18). There is also a clear increase in probability of ignition after forest areas experienced clear cuts, due to the same effect resulting in overall lower fuel moisture and usually dry grass dominated fine fuel environment (Müller et al. 2020a, p. 16).

Although high fuel moisture might not always hinder forest fires, studies show that some tree species for example Aleppo pine (*Pinus halpensis*) can ignite even at high water content levels of around 70% (Lillis et al. 2009, p.208).

In terms of foliage structure and morphology Popovic et al. (2021) suggests that the overall surface leaf area to volume ratio had the most impact for flammability, as the surface leave area to volume ratio is associated with a high exchange rate of energy resulting in shorter ignition time (Popovic et al. 2021, p.12).

3.3.4 Bark properties

The resistance of tree trunks to forest fires depends on the flammability and the response of tree bark to fire. The tree bark is composed of the inner and the outer bark. It functions as a protective layer and transports vital products of photosynthesis through the tree (Eberhardt et al. 2015, p. 604). A thick bark can protect the cambium of the tree from reaching lethal temperatures due to fire as the heat takes longer to reach the cambium due to thermal insulation of the thick bark (Hengst and Dawson 1994, pp.694). Numerous studies have shown that bark thickness is a major factor affecting the resistance of trees to fire.

Bär and Mayr 2020 found that the thickness of the bark is the most important factor when looking at the insulation capabilities (Bär and Mayr 2020, p.5). The study indicates that tree species with a thick bark have a lower maximum cambial temperature, longer times to reach peak temperature and shorter time until bark-surface ignition (Hengst and Dawson 1994, p.688). The temperature at which the damage to the tissue might result in the death of the tree is considered to be about 60 ° C. The study analyzed the insulation capabilities of ten alpine tree species and found that European larch (*Larix decidua*), Swiss stone pine (*Pinus cembra*) and *Pinus sylvestris* have the highest insulation capability (Bär and Mayr 2020, pp.1) as seen in figure 3 below.

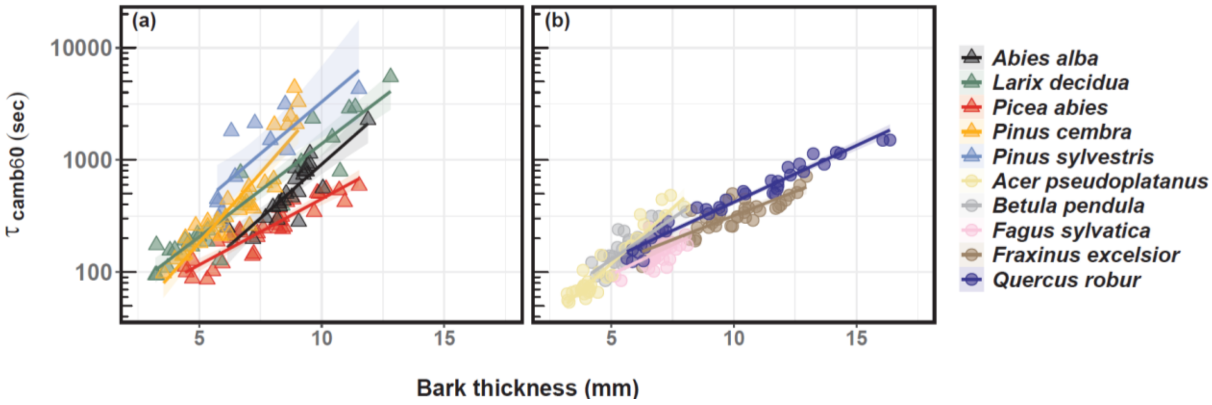

Figure 3: Correlation between bark thickness and the insulation capabilities for different alpine tree species (Bär and Mayr 2020, p.4).

Pinus cembra, compared to *Pinus sylvestris*, has a slightly higher bark flammability and is, due to the low crown height, much more susceptible to crown ignition. Silver fir (*Abies alba*) is considered to be a relative fire-intolerant species with lower bark insulating capabilities compared to other species, due to the fact that it does not form a thick layer of bark to protect the internal tissue. Bär and Mayr (2020) found *Picea abies* to perform the worst of all coniferous species and provide the lowest bark insulation (Bär and Mayr 2020, p.7).

Sycamore maple (*Acer pseudoplatanus*), Silver birch (*Betula pendula*) and *Fagus sylvatica* all show limited insulation performance due to lower bark thickness. Only English oak (*Quercus robur*) with its thicker bark performed better. Especially in fire-prone environments, a thick and therefore insulating bark can increase the survival rate of a certain tree species in case of a forest fire (Bär and Mayr 2020, pp.1). Next to overall thickness, the density of the bark can also come into play, as lower density of the bark itself can provide extra insulation due to the enclosed air. This can explain differences in insulation capabilities of barks with the same thickness (Bär and Mayr 2020, p.6).

Figure 4 shows a selection of barks from different Austrian tree species. The difference in bark thickness is clearly visible in the pictures below.

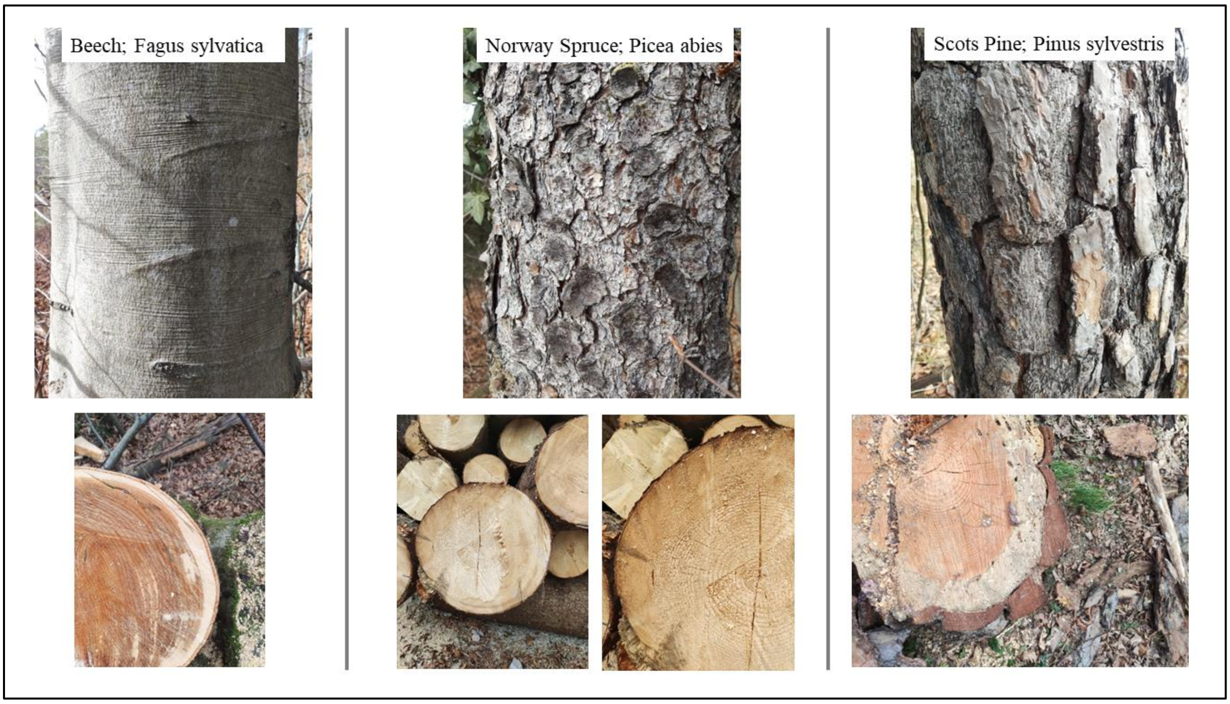

Figure 4: Differences in bark types from different tree species (Source: Nils Scheffler).

Bark thickness is a key adaptive factor in many plants growing in fire prone ecosystems and is usually the main factor determining tree survival in intense fires (Dehane et al. 2014, p.203). The knowledge about fire resilience in tree species can help to understand vegetation dynamics in fire prone ecosystems and improve forest management and fire risk analysis (Bär and Mayr 2020, p.2).

3.3.5 Selected tree species and their fire resistance

As forest fires have significant impact on the forest ecosystem, it is important to understand why vegetation ignites and sustains combustion. The previous chapter has focused on overall vegetation traits in connection with forest fires. This chapter explores the fire resilience and characteristics of selected tree species, including *Quercus spp.*, *Larix decidua*, *Pinus sylvestris*, and *Fagus sylvatica*. The analysis is based on various studies, investigating the attributes that enable these tree species to endure and recover from different fire intensities.

Oak (*Quercus pubescence*)

Wohlgemuth et al. (2008) found that *Castanea sativa*, Robinia (*Robinia pseudoacacia*) and *Quercus spp.* have great characteristics making them resistant to forest fires. It's their thick bark and the ability to quickly sprout again after a fire as all oak trees are resprouters (Wohlgemuth et al. 2008, p.338; Valleijo et al. 2012, p. 95). Another plant trait of *Quercus pubescence* is a high leaf water content that can be held even in the dry seasons, which reduces the overall flammability of that species (Lillis et al. 2009, p.208). This coincides with another study where Oak showed on of the highest resistance to ignition and burning. The study focused on comparing the burning rate of selected hardwood tree species (Black locust, European white birch, European beech, Sessile oak and Norway maple) (Osvaldova and Castellanos 2019, p. 91).

European beech (*Fagus sylvatica*)

According to Maringer et al. (2016), *Fagus sylvatica* is one of the most ecologically and economically important tree species in Europe. Beech lacks obvious fire resistance or fire adaptation traits such as thick bark or quick resprouting ability. That led to numerous and large beech forest fires in the Southern Alps, especially in the summer of 2003 (Maringer et al. 2016, p.699).

Although the resprouting ability of the European beech is not adapted to fire prone ecosystems, it can potentially regenerate naturally soon after fire event. The presence of other tree species does not hinder beech from regenerating after forest fires. The shade tolerant beech regeneration enables tall growth under the canopy of fast-growing pioneer trees. After a 20-year period, beech even shows a dominant presence. Maringer et al. (2016) found that beech forests that were disturbed by a single surface fire appeared to recover to pre disturbance species composition levels within a short period of only 40 years (Maringer et al. 2016, pp.700).

Larch (*Larix decidua*)

Moris et al. (2017) showed that the European larch forests are resilient to fire across a range of severity (Moris et al. 2017, p.673). The bark of the *Larix decidua* provides an adequate protection against heat from fires. Müller et al. (2020a) presented that tree species such as *Larix decidua*, *Pinus cembra,* and black pine (Pinus nigra) show high resilience to ground fires due to the thick and protecting bark (Müller et al. 2020a, p. 39). This thick bark might have evolved under a fire regime that can be characterized by frequent but low intensity fires (Moris et al. 2017, p.677).

The European Larch is resilient to fire because it recovers the same type of forest after a forest fire and shows rapid initial growth followed by a potentially long live, if undisturbed (Moris et al. 2017, pp.676). Due to factors such as an insulating bark, overall low bark flammability and the ability of a capable post fire regeneration, *Larix decidua* can be considered to be a fire-resistant tree species in fire regimes with low to moderate intensity (Bär and Mayr 2020, p.7).

Although adapted to fire prone environments, changes in the current fire regime towards higher severity fires may limit the regeneration of *Larix decidua* as this tree species also has a low tolerance to drought, which could weaken the tree making it susceptible to fire (Moris et al. 2017, pp.676).

Scots pine (*Pinus sylvestris*)

Scots pine shows high survival rates even when more than half of the crown has been torched. Studies at the burn site in Absams (Tyrol, Austria) showed that the trunks of *Picea abies* were more damaged that those of the Scots pine (Müller et al. 2020a, pp. 39).

Under low severity fire, pines possess traits that make them somewhat fire resistant. For instance, the thick bark that can insulate the tissue from reaching lethal internal temperature during a fire, but also the overall structure with relatively thick needles, a deep rooting habit and a tree crown that lets heat dissipate faster and can therefore avoid a lot of the crown scorch (Fernandes et al. 2008, p. 247). The thick bark of *Pinus sylvestris* reflects the evolutionary adaptation to a long history in fire prone environments (Bär and Mayr 2020, p.7)

Another fire adapted trait of the pine is that in high severity fires, which usually stand replacing, the pinecone, which endures the heat of the fire, will help the recovery process by fast sprouting after a fire (Fernandes et al. 2008, p. 247).

With age *Pinus sylvestris* will become more tolerant to fires due to an increased crown height (Fernandes et al. 2008, p. 251). The crown of older *Pinus sylvestris* trees is usually further up the stem, which indicates another adaptation to avoid canopy ignition.

Bär and Mayr 2020 consider it the most fire-tolerant species in their study, where ten European forest species were selected (*Abies alba* Mill., *Larix decidua* Mill., *Picea abies* (L.) Karst., *Pinus cembra L.*, *Pinus sylvestris L.*, & *Acer* pseudoplatanus L., *Betula* pendula Roth, *Fagus sylvatica L.*, Fraxinus excelsior *L.*, *Quercus robur L.*) (Bär and Mayr 2020, p.7). Meanwhile in Fernandes et al. (2008) *Pinus sylvestris* is categorized as a tree species that is moderately resistant to fires and will most likely endure fires with low intensity (Fernandes et al. 2008, p. 249).

3.4 Bark beetle

Bark beetle infestation can have serious consequences on the ecosystem forest. The infestation of bark beetles fluctuates depending on the availability of suitable host materials, with their numbers rising during bark beetle epidemics. These beetle outbreaks have far-reaching effects, not only affecting the trees but also influencing the dynamics of forest fires (Jenkins et al. 2008, p.17).

These insects have, unlike vegetation, indirect effects on the forest fire occurrence. Bark beetles typically infest trees that are damaged due to blow down trees weakened by fire, diseases, and drought. During larger infestation, these insects will also attack healthy trees and cause an increase in forest fire probability (Jenkins et al. 2008, p.17).

This increase is not all due to changes in fuel loadings but also due to the lack of overstory trees in post epidemic stance which decreases the sheltering effect of vegetation, allowing more wind to reach the forest floors, which increases flame speeds. The greater surface wind speeds increase the ability of the fire to transfer heat through convection and radiation, therefore increasing rates of fire spread (Jenkins et al. 2008, p.24).

3.5 Deadwood

3.5.1 Definition

Deadwood consists of dead trees or part of the trees of different dimensions and quality, including the remains from wood harvest such as tree stumps, crown branches, and low-grade trunk parts. These different deadwood types create important structures that are considered an important habitat space for many different animal species. The accumulation and decomposition of deadwood is a part of the natural cycle in forests and the basis of life for numerous animal species. In most managed forest deadwood was of high demand as material for building and burning. That is the reason why it was very uncommon in central European forests for a very long time (Lachat et al. 2019, pp.1).

As soon as a tree has died the process of decomposition has already begun. Insects, fungi, and other organisms are involved in the process, that happens at different rates for different tree species. As a rule of thumb, the wood that is located at warmer or wetter locations will usually decompose faster and the contact with the ground also increases the rate of decomposition. That's why standing deadwood can take a long time to decompose fully. There are also a differences in the composition time between tree species. For example, the wood from beeches has reached a state of decomposition of 95% in about 25 years, while wood from Norway spruce and silver fir takes around 80 years to achieve the same state of decomposition (Lachat et al. 2019, p.3).

3.5.2 Ecological purpose

Deadwood is an important part of the natural cycle in forest ecosystems. The insects that live in deadwood are an important source of food for other animal species like the woodpecker and after the woodpecker has moved out of its wooden cave, which is commonly in deadwood, other animals can move into that. Also, amphibious species and reptiles use deadwood as a place to stay during winter months or to protect themselves from the sun. Some demanding insect species depend on very large amounts of deadwood of certain quality, which is fairly uncommon in managed forests, (Lachat et al. 2019, pp.1).

Following a rule of thumb, the more deadwood a forest has, the more diverse the species inhabiting the deadwood are. Not only the amount, but also the age diversity plays an important factor. Deadwood with larger diameters can create multiple suitable habitat zones because of the different decomposition states it offers. Most species that rely on deadwood need at least 20 to 50 cubic meters per hectare, with some demanding species need at least 100 m^3 per hectare. Modern forest management practices should include reserved zones that seem suitable for the accumulation of deadwood. The promotion of deadwood organisms is a contribution to sustainable forest management in the sense of an equal fulfillment of all forest functions and services (Lachat et al. 2019, pp.4).

These large amounts of deadwood do not instantly appear. It is a process that takes a long time if happening naturally. Due to forest management or natural events such as windthrow can this process be sped up. Although currently in managed forests the tree mortality is far lower, and a large amount of deadwood is being transported out of the forest, the residue of the wood harvest can lead to an accumulation of deadwood with smaller parts of trees, that are of no real economic value, being left behind in the forest (Lachat et al. 2019, p.2).

Deadwood accumulation can also have a protective function against natural hazards. Intact tree stumps and larger deadwood that lies on the ground can help to stabilize the soil and the snowpack. They can also help to reduce the risk of soil erosion due to heavy rainfall and the risk of avalanches which is important in an Alpine environment (Lachat et al. 2019, p.2; Freudenschuß et al. 2021, p.35).

Deadwood acts as a natural carbon sink and retains a lot of water which can help during periods of drought (Lachat et al. 2019, p.2). An estimated 8% of the current global terrestrial carbon stock is stored in deadwood (Grootemaat et al. 2015, p.1486).

Although seen from an ecological function, deadwood seems to be essential, forest fire research found deadwood to present more of a danger to the forest, as the accumulation of it can increase the severity and duration of a forest fire (Müller et al. 2020a, p. 13). A not yet fully decomposed litter bed, that emerges uncovered during snow melt at the end of winter, can become very dry especially in deciduous tree stands. That happens due to lack of canopy cover, which could be an explanation for the many forest fire occurrences in the early spring season (Zumbrunnen et al. 2009, p. 83). Deadwood can also become a danger when it falls from trees to the ground risking the health and lives of visitors in the forest and forest workers (Lachat et al. 2019, p.2).

3.6 Topography

Topography plays a crucial role in the science of forest fires because it has a direct impact on fire behavior parameters such as flame length, fire line width, the direction and speed of the spread. The height above sea level, the steepness of the slope, and the exposition all have an influence on the amount of precipitation, the temperature, the solar radiation, wind speed and direction, and the type of tree species and forest stand (Weibel et al. 2016, p.434; Zumbrunnen et al. 2010, p.2189; Linn et al. 2007, p. 183).

In the Alps, south facing slopes are drier than north facing slopes because of stronger solar radiation and higher temperatures, leading to a lower fine fuel moisture content and therefore a higher ignition probability (Müller et al. 2020b, p.4). They also have a higher surface temperature, which leads to south facing slopes usually containing vegetation that is drier, posing the potential of a higher spread rate of a forest fire (Müller et al. 2020a, p. 13; Holden and Jolly 2011, p.2133). The increase in solar radiation also leads to much earlier snow ablation on south facing slopes than on north facing slopes at upper elevations (Holden and Jolly 2011, p.2133).

Holden and Jolly 2011 studied thermal effects in the Canadian Rocky Mountains and found that the driest conditions were observed 100 – 200 meters above the valley floor where mid slope thermal belts frequently develop above areas of cool air pooling (Holden and Jolly 2011, p.2133).

Due to the fact that the hot air from forest fires rises up slope and therefore preheats the fuel particles, the spread of fire is more rapid uphill, playing a role in the intensity and the spreading potential of forest fires (Müller et al. 2020a, p. 13). Fires on an uphill slope will see the fastest increase in speed compared to other topography, with all other factors being equal (Linn et al. 2007, p. 183).

Experiments have proven that the speed of the fire front on an upslope hill is much greater than on horizontal terrain. Cseresnyes et al. (2011) found that on an uphill slope of 30 degrees, the speed can be four to six times higher than on flat ground (Cseresnyes et al. 2011, p. 162-163). Coinciding with this, Santoni and Balbi 1998 found that a substantial spread rate increase can be seen with increasing slope. They found a substantial increase of rate of spread when slopes are already greater than 10 to 15 degrees. The study also found that fire travels a distance of 1 meter 10 to 20 times faster at values of 30 degrees than at 0 degrees (Santoni and Balbi 1998, p.215).

Topography does not only affect the fire behavior it also effects the firefighting ability due to steep, dangerous, and inaccessible terrain. While a forest fire burns on a steep enough slope, pieces of burning wood and tree stumps can roll down the hill, igniting new fires on their way down and being a potential hazard of firefighters working down slope (Müller et al. 2020a, p. 13).

4. Forest fire implications

4. 1 Implications for human lives and infrastructure

Forest fires can have a number of effects not only on the vegetation in the forested area itself but on the environment surrounding it as well as human infrastructure and settlements (Müller et al. 2020a, p. 24). Even though these fires are a part of the natural ecosystem, by playing a vital role for the vegetation dynamics, if they get out of control they can lead to serious ecological loss and economic damage.

Intense and out of control fires can be dangerous to human lives and infrastructure (BML 2022, p.8). Between the year 2000 and 2017 an estimated 8.5 million hectares of forest burnt down in Europe due to fires with 611 human lives have been lost. That accounts for nearly 34 people per year. The economic loss accumulated to over 54 billion euros over that time span (Faivre et al. 2018, p. 10). The total cost that is associated with forest fires in the Alps due to firefighting and post fire management is estimated to be around 75 million euros per year (Müller et al. 2020a, p. 3). While this sum seems large, the cost of fire suppression is increasing and unsustainable in the US with an estimated spending of over 2 billion USD per year (Stephens et al. 2013, p.42).

The current yearly cost for forest fires in Austria lies at around 2.2 million euros (Müller and Vacik 2019, p.28). Although when comparing the cost (ecological and financial) of natural hazards and other natural disturbances such as storms and bark beetle, the effects that forest fires create are marginal. Nevertheless, these effects are expected to increase due to factors such as climate change, as well as socioeconomical- and global changes (Müller et al. 2015, p. 903).

Wildfires can also have far reached human health implications. Incomplete combustion and smoldering fires lead to higher levels of CO and CH_4 emissions. These are associated with an increase in health hazards for the surrounding population (Benscoter et al. 2011, p. 427).

Currently most human infrastructure in the Austria is only indirectly threatened by fires due to the effects of fires on forest areas. The forest areas in the mountainous Alps provide several ecosystem services including a protective function against natural hazards. Currently a large percentage of the forest can be classified as a protective forest against natural hazards such as erosion, rockfall, mud floods, and avalanches. Due to severe fires, these protective functions could be impaired (Müller et al. 2020a, pp. 3).

After severe fires the change in the hydrological soil characteristics can lead to increased erosion that comes with heavy rainfall (Pezzatti et al. 2016, p.223). Severe fires have the ability to destroy the current vegetation on the soil layer as well as the organic material in the soil below it, making it far more unstable (Sass et al. 2012, p. 118). In some areas of the Alps only a thin layer of soil has been developed, which could be largely impacted by erosion. When vegetation has been cleared due to fires, and open areas result from that, it can lead to new avalanche prone slopes (Müller et al. 2020b, p.1).

An example of this process can be found at the Arnspitze in Tyrol, where large forest fires have destroyed vegetation and soil. This led to intensified geomorphic processes that are still ongoing even more than 60 years after the fire. In the following years after the fire, an evident intensification of fluvial processes and avalanche activity has been noted in that area (Sass et al. 2012, p. 118).

Climate change and a potential change in the fire regime will likely have a major effect on mountain forests in the European Alps, affecting their ability to protect against natural hazards (Generies et al. 2009, p.476). If the protective function of the vegetation is at all to be damaged by forest fires it could lead to severe consequences regarding the appearance of gravitational natural hazards (Müller et al. 2020a, p. 50; Conedera et al. 2015, p.11; Müller et al. 2020a, p. 3; BML 2022, p.5; Müller et al. 2020a, p. 24; Sass et al. 2012, p. 117). Also, if forest fires become larger and potentially reach important infrastructure, for example the energy supply system of a hospital, it could have severe implications for the local population (BML 2022, p.8).

Even though most infrastructure is currently not directly at risk, the cost due to more fire suppression and post fire measurements is rising. For instance, when the protective function of the forest is impaired, costly artificial protective measure must be implemented (BML 2022, pp.8).

4.2 Implications for the vegetation and ecosystem

Forest fires have profound implications on vegetation, shaping the dynamics and composition of plant communities. While some tree species have evolved in fire-prone areas to be adapted to reoccurring fires, others may face challenges in recovery and survival. The influences on the ecosystem as a whole can be widespread. Forest fires can impact landscape transformations, vegetation succession, soil degradation, and air quality (Chuvieco et al. 2009, p.46; Blauw et al. 2017, p.475). Fires also influence the carbon stock in forested areas and have an important share in the greenhouse gas emission (Benscoter et al. 2011, p. 427; Chuvieco et al. 2009, p.46).

They are the key driver of long-term plant dynamics and Bebi et al. (2003) considered fires the most important form of disturbance in the Rocky Mountain landscapes (Generies et al. 2009, p.476; Bebi et al. 2003, p.362). Forest fires will have direct and indirect impacts on the vegetation and on itself due to the changes that they cause.

Direct effects of forest fires are severe ecological consequences considering a decline in forest health and protective function against other natural hazards (Arpaci et al. 2014, p.258). As different vegetation types will respond differently to the effects of fires some forests might even change into non forest vegetation after fire (Stephens et al. 2013, p.42). If, for example, a crown fires kills most of the trees in a forest, the recovery could take decades depending on the tree species, while the effect of fires in grassy areas may not be visible after a few months (Bond and Van Wilgen 1996, p.6). The ecosystem services that are provided by the forest such as water supply, carbon sink, recreational and protective purposes can be negatively impacted by forest fires as the previous chapter mentioned (Arndt et al. 2013, p. 315).

In fires with high severity, critical soil heating, which is approximately 500 degrees Celsius for 15 minutes, will lead to a significant loss of mineral and nitrogen substance, as well as the combustion of organic matter. This critical heating of the soil has a direct impact on plants and the ground below due to the heat that affects the biota and site fertility (Kreye et al. 2020, pp. 300). Soil heating due to fires can hinder the natural rejuvenation process in forests, due to unsuitable soil conditions (BML 2022, p.7).

Forest fires can also have positive implications on the ecosystem. They can have a direct impact on the structure of vegetation and ecosystems as a whole. While changing species composition and the spatial pattern of vegetation cover, they potentially create a mosaic of a very heterogenic landscape. By killing the current vegetation, it can create openings in otherwise close canopies and therefore facilitate seed germination of certain species influencing the composition of vegetation in certain areas (Venevsky et al. 2002, p.984; Zumbrunnen et al. 2010, p.2188). This process can provide many habitats for different plant and animal species (BML 2022, p.8), which leads to an increase of the landscape heterogeneity that will likely results in a more resilient forest stand (Müller et al. 2020a, p. 24).

After a fire that has created some sort of open patch, pioneer tree species like *Larix decidua*, the silver birch (*Betula pendula*) can take advantage of that as these species need open environments to grow and if suitable will likely replace the burnt down tree composition (Müller et al. 2020a, p. 26).

5. Current forest fire prevention measures

The previous chapters have focused on "why" a forest fire ignites and what influences the fire behavior as well as what implications might follow forest fires. As large and severe forest fires have a large destructive potential, forest fire prevention is a critical aspect of managing and safeguarding the forest ecosystems. This chapter focuses on the various methods and approaches that are currently involved in forest fire prevention.

Principles that fire prevention should follow is firstly the targeted reduction of fire ignition as well as the management of fuels. Secondly, fire prevention must integrate the long-term adaptation of forests to climate change. Thirdly, it should actively engage citizens fire services, forest management and stakeholders into fire prevention, and therefore increase public information on forest fire risk that is easily accessible (Faivre et al. 2018, p. 35).

5.1 Silvicultural fire prevention measure

Previous chapters have explained how the current state of the vegetation can influence forest fire. A tool to reduce forest fire can be silvicultural measures (ESRD 2012, p.2). As tree species impact the ignitability and overall fire behavior, a change in tree species composition can be implemented. In some areas in Germany large forest areas that are dominated by coniferous tree species have been separated into smaller sections and are divided by strips of broadleaf trees. These separations also happen around roads and railway lines and can act as a buffer to counter the high ignition potential that these infrastructures bring into a coniferous dominated forest (Müller et al. 2020a, p. 28).

However, the forested areas in the Austrian alps are vastly divided into small sections of land ownership. As the selection of tree species is often decided by the landowner, adequate changes in tree species composition can be quite difficult to achieve (Müller et al. 2020a, p. 28).

This small-scale subdivision of larger forested areas can also be a problem for the next measure: fuel reduction. Fuel reduction in forested areas will lead to a reduction in easily ignitable material, a reduction in fire intensity and overall positive change in fire behavior. A method to reduce the fuel load in forests is the manual or mechanical removal of it or prescribed burning, as the time after the last fire is an important factor for the occurrence of forest fires (Neumann et al. 2022, p. 703). Additionally harvesting dead or bug infected trees will reduce the potential intensity of a forest fire (ESRD 2012, p.2). Although prescribed burning, as it's used all around the world, is usually not applied or even forbidden in most of the Alps with some regional exceptions in Austria and Slovenia (Müller et al. 2020a, p. 29).

Thinning that is applied to the current vegetation, grazing, or changing the tree species composition to a less flammable composition could also lead to a reduction of fuel (Neumann et al. 2022, p. 703; Müller et al. 2020a, p. 28).

If not all of the forested area can be cleared from excess fuel, the integration fuel breaks will act as a cut between otherwise continuous expanse of forest, creating openings in the forest canopy which can limit the potential for crown fire spreading (ESRD 2012, p.2; Müller et al. 2020a, p. 28).

Before any fuel clearing can be applied, areas that need to be treated have to be identified. This is done in creating and using fuel maps. Fuel maps can help to compute fire hazard, risk, behavior, and effects (Arroyo et al. 2008, p.1249). They classify the landscape into different fuel types that come with certain fuel characteristics, having different influences on forest fires.

There have been many fuel classification systems developed. Each one is specifically developed for a certain task and a certain region and is therefore only applicable under certain conditions. These classifications are only applicable for similar geographic locations and the adaptation in other environments or of foreign classification systems are difficult and results have been poor (Arroyo et al. 2008, pp.1244).

Fuel maps can be created by physically mapping a specific area. While creating fuel maps, doing field surveys has the advantage that the researcher is in physical contact with the fuel and these fuels are mapped from actual conditions that were observed in the field. This method, although very accurate, can be very time and cost intensive. Using remote sensed data can be a way to quickly cover larger areas. If fuel maps are created from remotely sensed data, they should be validated using field reference datasets (Arroyo et al. 2008, p.1245).

The knowledge over the spatial distribution of forest fuels is essential to developing management strategies. Although helpful these fuels are difficult to describe and map due to the high complexity and variability (Arroyo et al. 2008, pp.1240).

5.2 Forest fire danger estimation

The estimation of forest fire danger levels and the prediction of forest fire occurrence is another essential tool of forest fire prevention. Using models to determine potential fire hotspots involves current and precise data about environmental factors such as weather conditions, fuel characteristics, topography and socioeconomic factors that affect the occurrence of forest fires (Arndt et al. 2013, p. 315; Anderson 1982, p. 1). Preferably, these models can indicate the current forest fire hazard level for different regions, create fire risk maps and give out daily fire danger indices.

Here the term fire hazard refers to the potential fire behavior associated with the static properties of the fuel, regardless of the moisture condition on a given day (Chuvieco et al. 2014, p.607). The estimation of the forest fire hazard to identify hotspots that have a high fire danger potential. In these areas targeted and specific forest fire prevention measurements must be implemented, as the fire hazard is directly related to fuel flammability (Freudenschuß et al. 2021, p.49; Xanthopoulos et al. 2012, p.79). Knowledge about the flammability of the material is very important in calculating the fire hazard (Xanthopoulos et al. 2012, p.80). A map that shows the fire hazard evaluation is an important part of fire prevention (Chuvieco et al. 2009, p.46).

A fire hazard map identifies and evaluates the potential for fire ignition and spread in a given area. It focuses on the factors that contribute to the development of fires, such as the presence of combustible material, fuel load, climatic conditions of the area, topography and ignition sources. The map classifies areas according to their susceptibility to fire ignition and spread.

A fire risk map, on the other hand, evaluates the potential consequences of a fire in a given area. It considers the values that are at risk, such as the human infrastructure and lives, natural resources, and the ecological values. The risk map integrates fire hazard information with data on the potential impact of a fire on the environment, property, and human life. If the fire risk is to be mapped it must include fire vulnerability (Chuvieco et al. 2014, p.607). Important for understanding the concept of risk is the connection between risk and hazard. A hazard is defined as the potential of an event, technology or undertaking to negatively affect human life. A hazard becomes a risk when there is a high probability that this circumstance will occur (Habegger, 2010; Renn, 2008, S. 52).

The term vulnerability originates from the Latin verb "vulnerare," which means "to wound" (Bergler-Hellein, 2019, pp. 14). The term generally describes "the conditions in the affected societies [...] which often determine the social effects and consequences of physical events and decide whether natural events and hazards become disasters or not." (Bohle & Glade, 2007, S. 99).

Currently the daily fire danger, calculated using the Fire Weather Index (FWI), is communicated via the webpage of the ZAMG (Zentralanstanlt für Meteorologie und

Geodynamik) (now GeoSphere) and through a website of the Austrian Forest Fire Research Initiative (Müller et al. 2020a, p. 35). The FWI, a subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS), rates relative mid-afternoon fire danger from noontime weather data. In the calculation it is using one single forest type and three fuel layers. Each of those layers has a different time lag in which it loses about 2/3 of the free moisture at equilibrium. It does not include any differences in forest cover types and relies on interpolated point source weather data (Leblon et al. 2001, p. 2840).

The estimation of forest fire danger from the ZAMG as well as the European model EFFIS (European Forest Fire Information System) only use metrological components to estimate the ignition and spread danger. Factors such as the human influence, the vegetation, the topography, and a realistic estimation of danger of fire spread is not included (Müller and Vacik 2019, p.18).

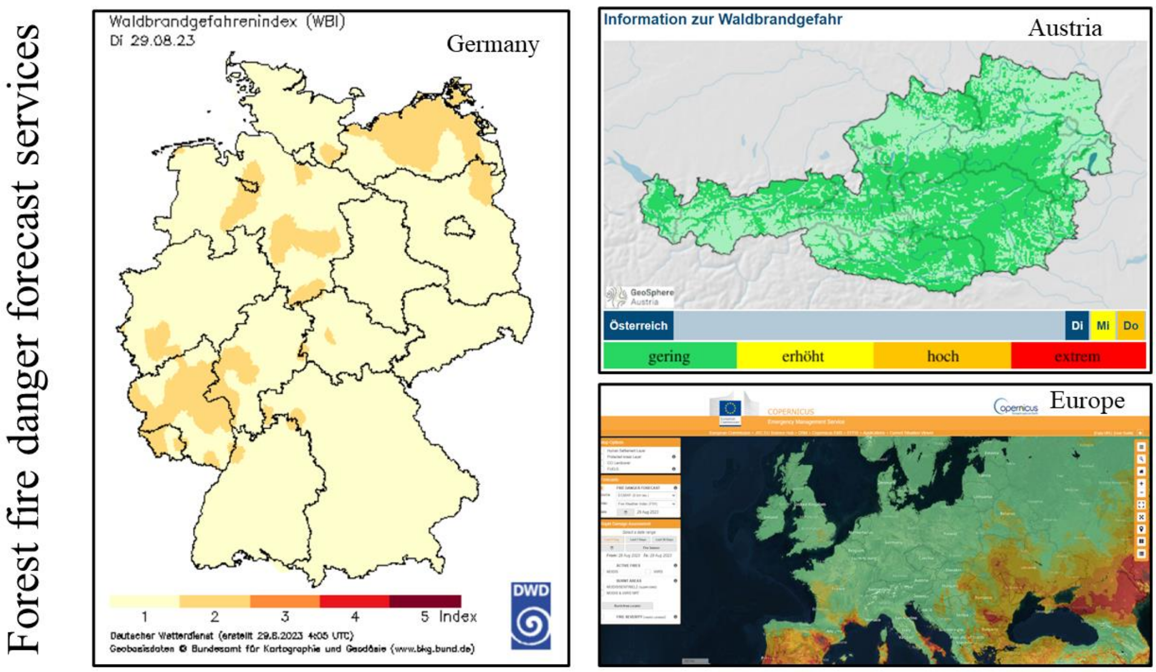

Figure 5: Examples of forest fire danger forecast services in Europe (Screenshots from: https://www.dwd.de/DE/leistungen/waldbrandgef/waldbrandgef.html, https://effis.jrc.ec.europa.eu/apps/effis_current_situation/, https://www.zamg.ac.at/cms/de/wetter/wetter-oesterreich/waldbrand)

5.3 Forest fire detection in the Alps

If preventive measure had no effect and a forest fire has ignited, the early detection of fires is crucial, as only then effective firefighting can occur (Müller et al. 2020a, p. 27). With increasing fire hazard, the monitoring of potential risk areas, and the ability to react quickly, can reduce the potential damage as well as the cost of firefighting. Given the right fire weather conditions small fires can rapidly develop into large and intense fires that could lead to catastrophic consequences. In the initial stages of a fire or shortly after ignition, surface fires are much more manageable. If it catches on to the adjoining trees and the flames become higher, the overall fire intensity increases, seemingly all methods of fire suppression can become irrelevant, and stopping the fire seems even impossible at times. A *burn time - water rule* applies here: 1 minute-1 cup of water, 2 minutes-100 litres of water, 10 minutes-1,000 litres of water (Alkhatib 2014). The fast and accurate detection of those fires are of fundamental importance to mitigate the potential risk that could follow those larger fires (Faivre et al. 2018, p. 17).

The detection of forest fires has long relied on human observers. Over time and due to the innovation of new technologies, new systems for an automatic detection of fires have already been used in many fire-prone areas of the world (Müller et al. 2020a, p. 27).

An example are unmanned fire detection systems. These can be setup either with camera surveillance or using Wireless Sensor Networks (WSN). The systems for optical automated early recognition and fire warning were developed when sensors and image procession advanced. There are three main types of optical fire detection available (Alkhatib 2014):

- Video-camera, sensitive to the visible spectrum of smoke recognizable during the day and a fire recognizable at night
- Infrared (IR), thermal imaging cameras based on the detection of heat flow of the fire
- IR spectrometers to identify the spectral characteristics of smoke
- Light detection and ranging systems — LIDAR (detection of light and range) that measure laser rays reflected from the smoke particles

The other fire detection technique is the WSN. These systems can solve the problems with optical detection systems and can be applied almost anywhere in the world. The WSN consists of a self-organized system and follows an efficient algorithm. In Spain, for example, a mesh network of sensors was deployed provided with internet protocol cameras. If the sensors would detect a fire, they would send an alarm signal to a sink, which would activate the cameras in that area to make sure that it is not a false alarm (Alkhatib 2014).

Another WSN is the FIRESENSE project that aims to develop and implement an automatic early warning system to remotely monitor areas of special interest. It consists of multi-sensors, optical, IR, and PTZ (Pan-Tilt-Zoom) cameras, temperature sensors, and weather stations. Each of the sensors collects data and processes them with different techniques and algorithms. The whole project is built on complicated scientific models and algorithms, concepts, and comparisons (Alkhatib 2014).

The system was taught that the atmospheric conditions, the absorption and scattering of radiation, changes with the influence of fire. It constantly compares subsequent images of the scene and if the differences surpass a certain point, an alarm is generated (Alkhatib 2014).

Currently, the best solution for fire detection is using sensor networks (Alkhatib 2014). If it is setup correctly, it is the most efficient way to detect fires. The WSN technology deploys a large number of small, low-cost sensors, that can observe the physical world by constantly gathering information. These are being send to a sink to analyse them and then to make a decision that is of critical importance to the firefighters. It's a real-time monitoring system that can provide information at ignition instances with very small delays (Alkhatib 2014).

Forest fires can also be detected via remote sensing using satellite images. Unfortunately, due to image resolution, smaller fires that are below 30 hectares cannot be detected (Müller et al. 2020a, p. 14).

Although forest fire detection measures have already been successfully deployed, the Innsbruck fire Chief Mr. Riedl stated that the Innsbruck fire department does not and will not be using a forest fire detection system. They rely on their knowledge of the surrounding area and the help of the local population to report forest fires immediately.

5.4 Fire fighter equipment and training

When a fire has been detected, the deployment of fire-fighters has to be as quick as possible. In Austria, the response time of fire fighter is very quick, due to a well-developed network of fire brigades and infrastructure, that allows quick access to the fire effected areas (Müller et al. 2020a, p. 37).

The training and type of equipment of fire-fighters is essential as it can assure the protection of the fire fighters against the heat, flames, and smoke from fires. The firefighting equipment also effects the supressing ability during active duty. It must meet the highest international standards and has to be adequate to combat forest fire in difficult alpine terrain (Müller et al. 2020a, p. 37). An indirect tool during the firefight are forest roads that allow for quick access to the affected areas. In Italy, forest roads were constructed to gain better access into high danger forest areas. Also, water tanks were strategically placed where the access to water was limited (Müller et al. 2020a, p. 37).

Due to the forest road network, the forest accessibility far better than compared to other countries. Some regions can not be reached by a fire truck. In these situations, helicopters are an essential tool to transport water into remote areas and to gain overview of the current fire situation. Helicopters can be of great help to the firefighters on ground. They can be efficiently used for combating and containing already existing fire or as a method of reconnaissance, giving the ground troops an update on the overall situation. These helicopter operations are of great importance in the fight against forest fires because in the Alpine landscape with narrow valleys and steep slopes, the deployment of other aircraft such as planes is mostly not suitable. Due to the high machine and personal cost that comes with those helicopter operations they are not always covered by federal or state governments, which could lead to that helicopters will not be used in the case of a forest fire (Müller et al. 2020a, pp. 38).

During the conducted interview with the fire department Innsbruck, the fire chief explained, there would be only slight chances to control forest fires without the help of helicopter. This again states the importance of these aircrafts in the fight against forest fires.

5.5 Public forest fire danger awareness

As human influence is the main driver of forest fire ignition, the public awareness about forest fires must be raised. This is a great indirect forest fire prevention tool, as it can decrease the ignition probability. Currently the public awareness about forest fires and the current hazard situation is still quite low and only a few measures are taken to improve that situation. For instance, voluntary fire brigades will go into public schools and teach the basics about forest fire awareness and prevention. Even though the overall awareness is comparably low, the willingness to report forest fires is quite high. With most areas of the alps being somewhat populated, most fire are quickly reported and within minutes the suppression of that fire can begin (Müller et al. 2020a, pp. 30).

Not only the spread of awareness can act as a suppression method. Statewide rules and regulations in regard to forest fires can be applied. The Austrian regulations allow for a ban of legal fires in forested areas and smoking during days of high forest fire danger. Even a restriction of access to certain high danger areas can be issued (Müller et al. 2020a, p. 31).

5.6 Current difficulties in forest fire prevention

There are many difficulties regarding the prevention, prediction, and fight of forest fire. Therefore, the management of forest fires comes with complex challenges. Despite all the advances in technology, equipment, and preventive strategies, many obstacles still persist the effective prevention, prediction and fighting of these potentially destructive fires.

The complex terrain in a mountainous environment such as the Alps makes rapid deployment and firefighting very difficult (Cane et al. 2013 pp.734). Most of the lightning induces forest fires occur in steep and inaccessible terrain which puts the firefighters at higher risk of injury. Steep terrain coupled with strong winds and a sudden change of direction can also put firefighters into a life-threatening situation if they can't leave or be extracted from the area. Also, if a sudden change in the vegetation composition occurs, it could lead to a dangerous situation for fire-fighters when the new vegetation suddenly allows the already occurring ground fire to intensify and become a crown fire. Forest fires of a few hectares in size can takes several days to be extinguished, due to these complex challenges (Müller et al. 2020a, pp. 12).

Even though the prediction of daily forest fire danger occurs on a daily basis and is always improving, there are still lots of impediments that hinder accurate prediction. For instance, the current spatial resolution of one square kilometer is state-of-the-art for regional weather models. This is the best resolution that is offered but is just not fine enough for a heterogenic environment such as the Alps (Müller et al. 2020b, p.2; Müller et al. 2020a, p. 36). Maps with a spatial resolution of one by one kilometer are insufficient considering some of the narrow valleys in the Alps (Müller et al. 2020a, p. 46; Linn et al. 2007, p. 183).

Most of the forest fire danger assessments that are given out for Austria use fire weather indices. These fire danger rating systems do not include important parameters such as vegetation, including different species, the deadwood content and the overall ground cover, anthropogenic influence, topographic factors, with slope inclination and exposure, or the potential triggers of forest fires which are lightning and human activity. As all of these factors influence the fire regime, they should be included in an integrated forest fire danger assessment system (Müller et al. 2020a, pp. 35).

The currently employed fire danger models also have a limited temporal coverage, as they are not entirely suitable for the winter and early spring season where south facing slopes can be snow free a lot earlier than north facing ones. That can result in drying out fine fuels, leading to earlier and higher risk of forest fire ignition in those areas (Müller et al. 2020a, p. 47; Müller et al. 2020b, p.2).

Currently forest fires cause damages of around two million euros per year in Austria. This amount, compared to the financial damages that windthrow or pest infection cause, is still considered low (Müller and Vacik 2019, p.28). That's why measures against forest fires from a forest management standpoint have not been implemented and are currently not considered (Müller and Vacik 2019, p.28; Freudenschuß et al. 2021, p.49; Müller et al. 2020a, p. 41).

6. The Austrian forest

As earlier chapters have mentioned, the physical arrangement and composition of a forest, including elements such as tree density, height, age, and the spatial distribution of tree species can influence the appearance and behavior of forest fires. An overview of the current Austrian forest structure can help to understand the current fire regime in Austria, which will be discussed in the next chapter.

The European Alps are tremendously inhomogeneous in terms of fauna due to many biogeographic subregions, fast changing topography, and climatic conditions. That's why each region has its own characterization of the local vegetation structure. A similarity that almost all the forest areas in the Alps share is the human influence. Most parts of natural forest stands have been replaced due to human activity. Therefore, the current vegetation might not represent the natural range of original vegetation distribution (EEA 2007, pp.45). Also, since the 19th century the reduction of land use in the Alps has led to an increase in forest connectivity by closing open areas which led to the accumulation of standing fuel loads (Leys et al. 2014, p.60).

Currently, the forest cover in the European Alps in dominated by coniferous tree species (Müller et al. 2012, p. 1). The dominant forest types in most of the Austrian mountain forests are being spruce, spruce-larch, spruce-fir, spruce-fir-beech, and beech forests (Freudenschuß et al. 2021, p.28).

The lowest part of the mountain forest is the **submontane zone**. Here oak- and beech forest are intermixed with each other. Altitudes of this zone varies depending on location ranging from 400 up to 850 meters above sea level (a.s.l.) (Kilian et al. 1994, p.12). The different altitude zones are shown in table 1.

Above that follows the **montane zone**. The large range in altitude of more than 1000 meters in this zone allows for a further differentiation into low-, middle-, and high-montane zone. Dominant tree species are beech, spruce, and fir. The montane zone also entails the upper vegetation limit for Beech and Fir (Kilian et al. 1994, p.12). Mountainous beech forests have their upper height limit at around 1200 meters of elevation in the northern parts of the Alps and 1500 meters in Tyrol (EEA 2007, p.62).

Mountainous beech forests have gone through less intensive anthropogenic exploitation. Although they have experienced significant push back as spruce and silver fir was largely anthropogenically spread in areas where natural beech forest occurred (EEA 2007, p.62). Natural stances of silver fir today are restricted to areas between 1000 and 1700 meters a.s.l. (Wick and Möhl 2006, p.435). The occurrence of silver fir is decreasing steadily as in forest stands dominated by mountainous mixed spruce-silver fir forest, human activity has increased the proportion of spruce as a result of silviculture. Also, due to the negative effects of browsing deer, the silver fir lost their competitiveness in these environments (EEA 2007, p.47; Wick and Möhl 2006, p.435). The difference in altitudinal boundaries can be seen in table 1.

The last altitudinal zone is the **sub-alpine zone**, also split into the low- and high sub-alpine zone. This area is mostly covered by coniferous tree species, with Norway spruce being the dominant tree species. It is the most common tree species in Austria and does occupy areas outside its natural habitat (Büchsenmeister 2013, p.3). Even in mixed spruce-fir and spruce-fir-beech forests, the Norway spruce is the dominant tree species (Leitgeb et al. 2013, p.7). In the sub-alpine forest, they can also be found mixed with *Pinus cembra* and *Larix decidua* (Arpaci et al. 2014, p.259; Leitgeb et al. 2013, p.7; Kilian et al. 1994, p.11).

Norway spruce has relatively low demands on the soil properties and can cope with extreme soil conditions. Only precipitation of under 800 millimeters per year combined with a high mean annual temperature could cause problems (Leitgeb et al. 2013, p.7).

In today's periods of drought, the evaporation and transpiration combined is higher than the precipitation which leads to a decreased water supply that is available for trees resulting in decreased growth rates (Schüler et al. 2013, p.11). Due to the root system of the Norway spruce, it is not able to efficiently use water reserves that are deeper within the soil which can lead to dry stress and tree mortality (Leitgeb et al. 2013, p.8).

The abundance of Norway spruce can be attributed to human activity, driven by a monetary motive (Leitgeb et al. 2013, p.7). Due to the economic performance of the Norway spruce, it is being referred to as the bread tree of the Austrian forest industry (Fritz 2013, p.30). Wood from Norway spruce is in large parts the general basis of the Austrian wood and paper industry, as deciduous wood for example is not suitable to be used in constructive woodwork (Pickenpack 2013, p.24).

Although vulnerable to future climate change, (Freudenschuß et al. 2021, p.28) from an economic standpoint Norway spruce will remain the main tree species in Austria (Büchsenmeister 2013, p.6).

Higher up in the high sub-alpine zone, Swiss stone pine and larch replace spruce as the dominant species. *Pinus mugo* also inhabits this altitudinal zone and forms large densely vegetated shrublands (Leys et al. 2014, p.61). This zone has been strongly influenced and shaped by human activity, such as high mountain pastures that have replaced larch and Swiss stone pine forests. Overall, the sub-alpine zone ranges from altitudes of 1650 to 2200 meters a.s.l. and reaches the upper limits of the tree line in the Alps (Kilian et al. 1994, p.11).

Table 1: Altitudinal subdivision of forest vegetation zones for each growth region (4.1, 2.1 and 1.2) (Kilian et al. 1994, pp. 15 ff.).

Altitudianl zones (m)			
Vegetation zone	4.1	2.1	1.2
Sub-montane	400 - 600	500 - 750	--- - 850
Low-montane	600 - 800	750 - 1000	850 - 1100
Middle-montane	800 - 1200	1000 - 1300	1100 - 1400
High-montane	1200 - 1450	1300 - 1600	1400 - 1700
Low sub-alpine	1450 - 1650	1600 - 1800	1700 - 1950
High sub-alpine	1650 - 1950	1800 - 2050	1950 - 2200

The forest in Austria plays an important role as habitat for animals and plants as well as a recreational space for humans and is of high economic importance supplying the means for thousands of workers in the country (BML 2022, p.5). Mountain landscapes are heavily shaped by natural and anthropogenic disturbances. The alpine ecosystems, particularly forests provide a number of crucial goods and services to the human population (Schumacher and Bugmann 2006, p.1435). One of those is the protective function of the Austrian forest against natural gravitational hazards such as rockfall, avalanches and mudslides.

In the protective forest in the Montafon area Norway spruce stands are indispensable. The avalanche protection function is excellent, and together with the silver fir it prevents against avalanches very well. Although spruce does not have a good healing capacity against rockfall injuries compared to other deciduous trees, it still has a very good protective function. For the optimal fulfillment against the combination of avalanche and rockfall protection spruce is an indispensable tree species under the currently prevailing climatic conditions (Malin 2013, p.29).

Although being a crucial component, the overall health of the forest is in a declining shape. Studies showed that the Austrian forests that serve a protective function have a major rejuvenation deficit and that 2/3 of the forested area, that are classified as protective forest, need rejuvenation measures. Currently large areas of forest stands are old and lose their stability over time. While in reforesting projects in the past, not all factors were integrated into the selective progress that has decided over the tree species. In some cases, tree species are not suitable for the location where they have been placed (Freudenschuß et al. 2021, pp.28).

Another problem regarding dangers to the Austrian forest is climate change and the potential forest fire hazard. As of now, the Austrian forests are not a particularly endangered area considering forest fire, and they have never been a great danger to human lives and infrastructure. Higher temperatures and prolonged periods of drought can put stress onto forested areas, leading to a further decline in forest health (BML 2022, p.6). This, coupled with higher temperatures, prolonged periods of drought and a high percentage share of coniferous forests in the Austrian Alps, could make them particularly prone to summer forest fires (Conedera et al. 2018, p.95).

7. Current forest fire regime in Austria

In the forest environments of the European alps, which includes a large part of the Austrian country, forest fires have only played a minor role for the last few decades (Müller et al. 2012, p. 1). These forest fires do not constitute a significant hazard in central and northern parts of the Alps. Although the fires on the southern side of the Alps are more common, comparing that to the Mediterranean area it is still considered low (Cane et al. 2013 pp.734).

Austrian forest fire recordings from before 1900 show very large-scale fires in the range of up to 3000 hectares, nearly 30 times the size of the largest fires in the past 100 years (Müller et al. 2015, p. 904). That clearly states that the fire regime has drastically changed since then. Since 2008 the documented forest fires in Austria are collected into a larger database. Analysing this database can give a clear understanding of the Austrian forest fire regime. In July of 2023, more than 6000 fires were documented and added to the database.

Compared to the overall forest area of Tyrol, the state has a relatively low number of forest fires. The fire years of 1993, 2003 and 2007 stand out to be years of high fire activity in Austria (Vacik et al. 2011, pp.10).

Most fires that were documented only burn the size of one hectare. Large fires with a size above 20 hectares make up only a very small portion of the recorded fires in Austria. As for duration of the fires, the majority of all fires, about 80%, only last about one day (Vacik et al. 2011, p.11).

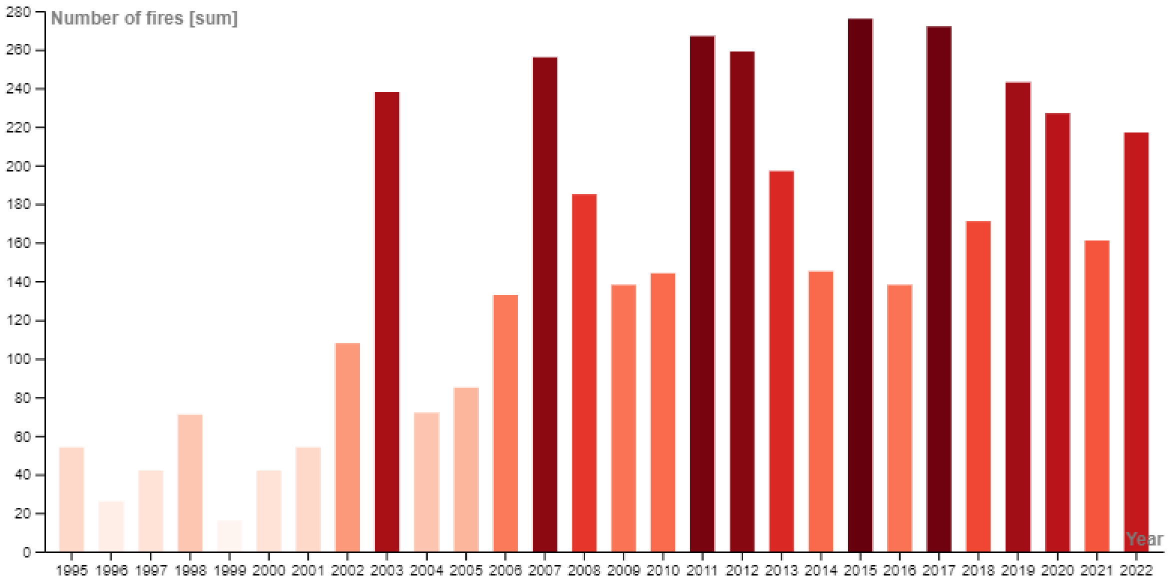

Figure 6: Number of yearly fires for the time span between the years 1995 and 2022 in Austria (Waldbrand-Datenbank Österreich 2023).

The cause of the forest fire in Austria is quite clear. Human activity is the major cause of forest fire as only about 15% of those were due to natural ignition causes. Most ignitions, that could be labelled as human cause, were due to prescribed burning that got out of control, and railway related ignition cause, such as sparks from breaking trains. Forest fires that have been categorized as natural cause were mainly ignited by lightning strike (Vacik et al. 2011, pp.3).

These lightning caused fires can be complex to manage as they sometimes happen at night, during which they might not be spotted instantly and make fighting them even harder for the emergency services. Also, forest fires that are ignited by lightning usually result in fires that are located in remote and hard to access areas, where fire-fighters have a hard time to gain control over the fire. Most fires found in the study by Vacik and Müller 2017 that were ignited by lightning, happened at an elevation of about 1100 meters (Vacik and Müller 2017, pp.26).

Looking at the seasonal distribution of documented fires shows a clear picture. The two main fire seasons in the Alpine region are early spring around March or April and a second one in July and August. The first fire season is linked to spring dryness and stable weather conditions and the second one occurs because of prolonged dry-periods, during hot summer months and increased lightning activity (Müller et al. 2020a, p. 16; Arpaci et al. 2014, p.259).

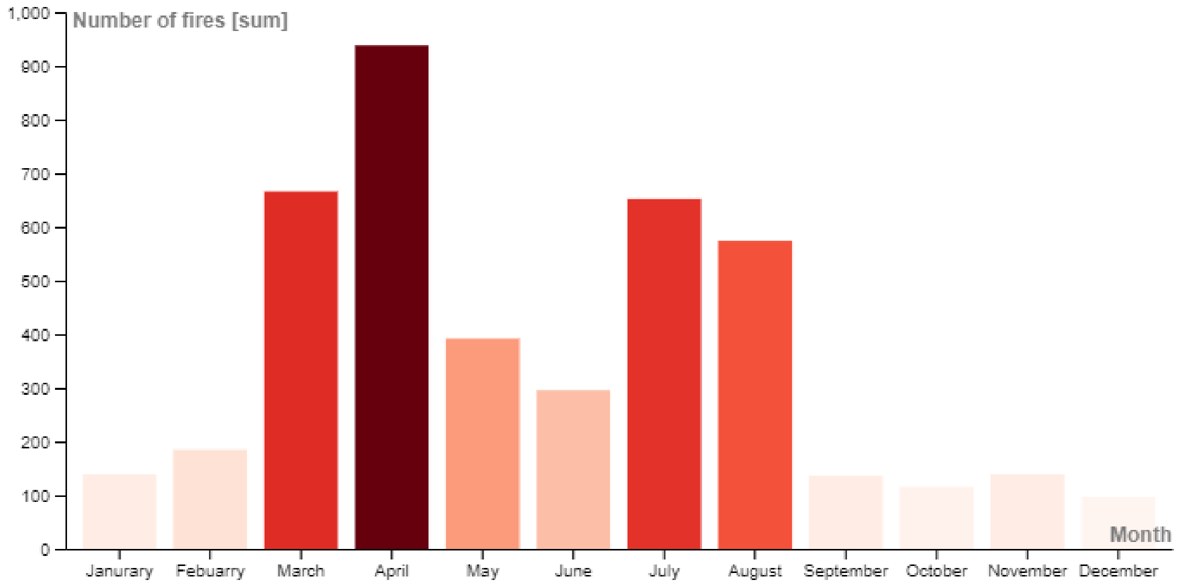

Figure 7: Distribution of forest fires throughout the year in Austria (Waldbrand-Datenbank Österreich 2023).

Notably, most fires were detected between the hours of 11 am to 7 pm. Vacik and Müller 2017 showed that forest fires, which ignite at daytime, tend to be larger than those ignited at night, due to the fact that windier and dryer conditions outweigh the difficulties of fire suppression that present them self during the night (Vacik and Müller 2017, pp. 3).

As the Austrian mountains are highly homogeneous in terms of topography, it influences the fire regime substantially. Conedera et al. (2018) found a clear difference between high fire density on the southern slopes of the Alps and the substantially lower proportion of burned area on the northern slopes (Conedera et al. 2018, p.95). Coinciding with this, Vacik et al. (2011) found that almost half of the recorded fires had a south facing exposure (Vacik et al. 2011, p.17). As for regional differences, Müller et al. (2020a) found that most fires in the alpine region occur in the southern parts and the dry inner Alpine valleys (Müller et al. 2020a, p. 16).

In terms of damage and cost due to destruction, forest fires in Austria don't play a major role yet when compared to other natural hazards. That might very well change if certain climatic and socioeconomic scenarios come in place in the future (Vacik and Müller 2017, p. 32), as it certainly will influence the future fire regimes (Generies et al. 2009, p.476). But not only the climate will influence the fire regime. With human activity being the major cause for forest fires in Austria, it plays a major role in the overall fire activity of the country (Vacik et al. 2011, p.21). Because as stated in a previous chapter, forest fires always need a source of ignition to even start, and this ignition risk can be influenced by human activity (Zumbrunnen et al. 2010, p.2189).

8. Geographic and climatic allocation of the study area

8.1 Location

Austria lies in the middle of the European Alps, one of the most iconic mountain belts on earth. The unique shape, that has been formed due to complex tectonic movements and climatic factors has been long aspired by adventurers and researchers alike. The regions unique geography, climatic conditions, and rich biodiversity make it a significant area of interest for various scientific disciplines. Among the numerous environmental challenges faced in this region, forest fires have the potential to develop into a crucial issue with potentially severe consequences for the delicate Alpine ecosystem (Schuster and Stüwe 2022, p.3).

This master's thesis focuses on the study area of Innsbruck-Stadt and Innsbruck-Land, which is located towards the western parts of the Austrian Alps as seen in figure 8. It borders Germany to the north and South-Tyrol (Italy) to the south. The study area is known for its high and steep mountain ranges and peaks, deep valleys, abundant forest areas, and the typical Austrian mountain pasture landscape. The study area entails two districts, Innsbruck-Stadt and Innsbruck-Land covering 105 km² and 1990 km² respectively. Innsbruck itself lies in the district Innsbruck-Stadt and is the state capital, as well as the most populated city in Tyrol.

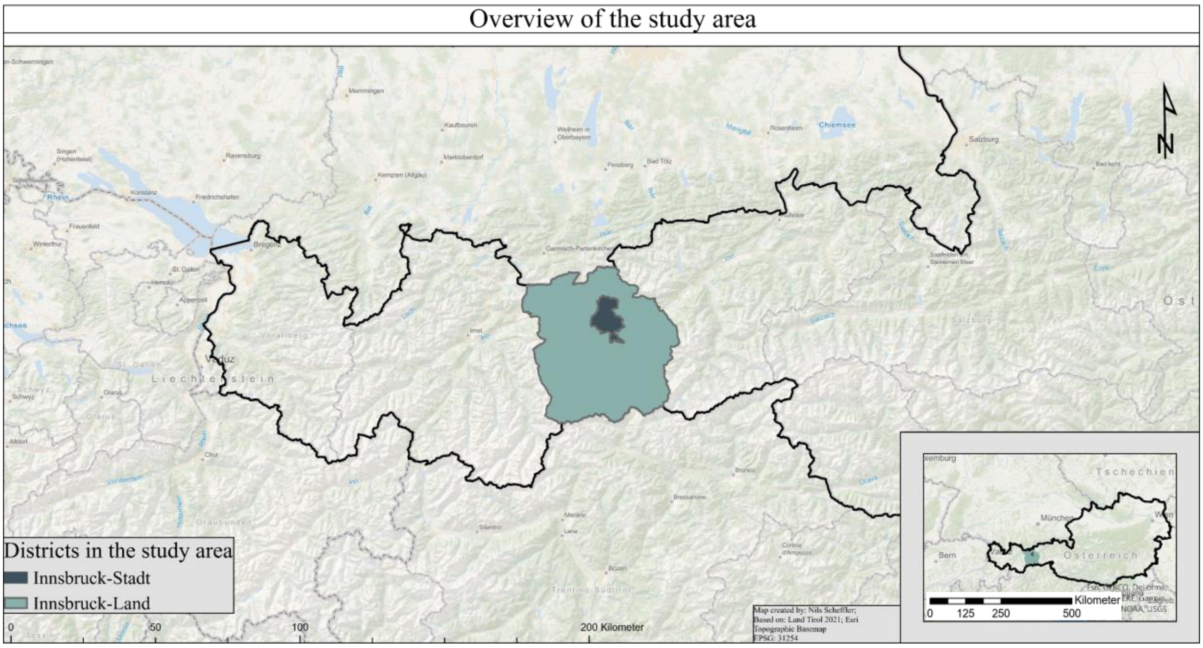

Figure 8: Overview of the study area of Innsbruck-Stadt and Innsbruck-Land.

8.2 Landcover, forest types, and climatic conditions

The whole region is characterized by the mountainous and alpine environment. Figure 9 shows the land cover classification of the study area based on the land cover classification from the European Environmental Agency (EEA 2018) and figure 10 the corresponding percentage share of the landcover types.

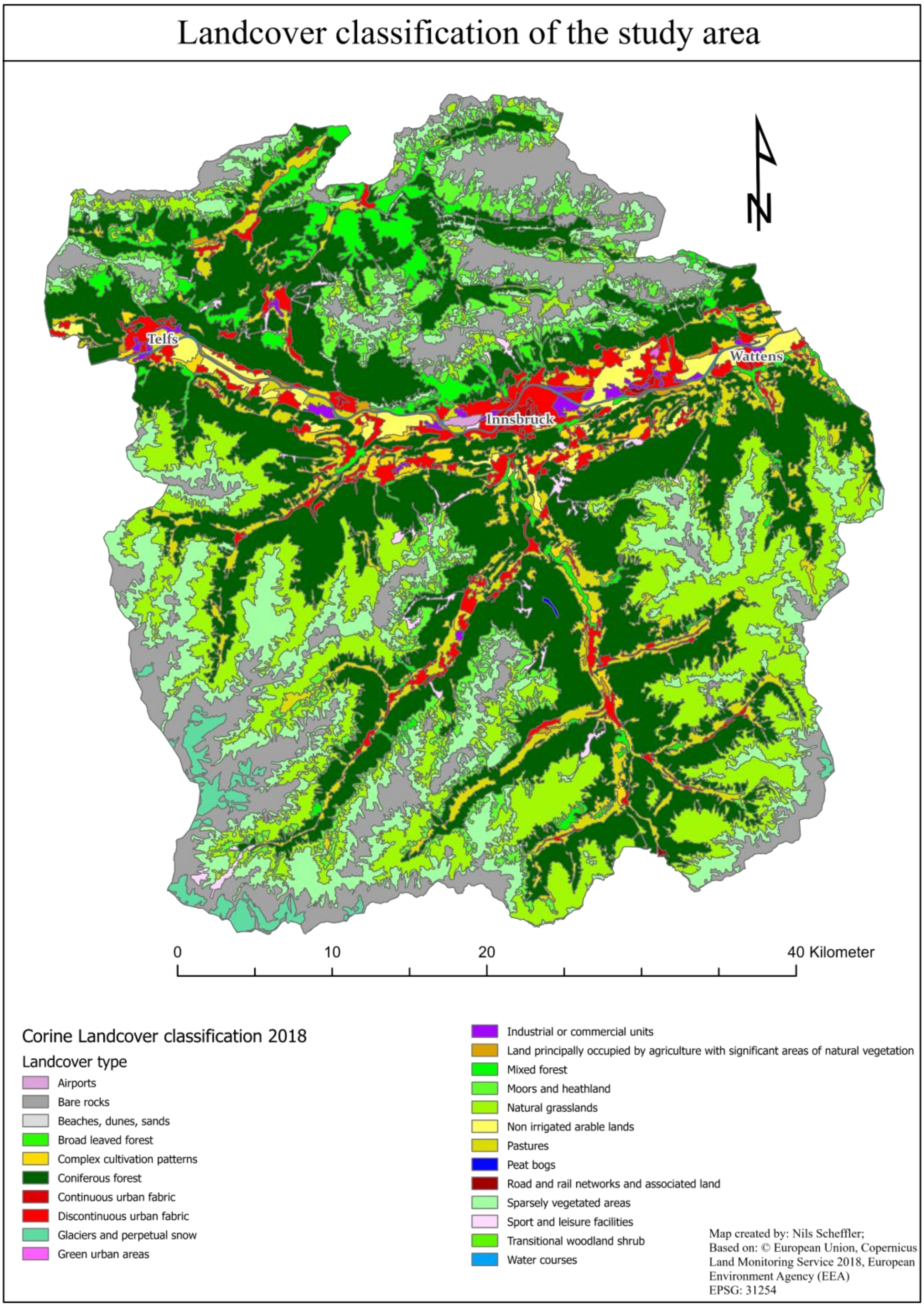

Figure 9: Map of landcover classification of the study area.

Most of the study area can be classified as *Coniferous forest* (29.3%), *Natural grasslands* (18.7%), *Sparsely vegetated areas* (15%) and *Bare rocks* (14.1%). These categories already cover more than ¾ of the whole study area. Urban areas account for less than 5%. This describes the study area very well, as it is mostly forested or otherwise vegetated land and bare rock, with low amounts of populated areas. This distribution is shown in figure 10.

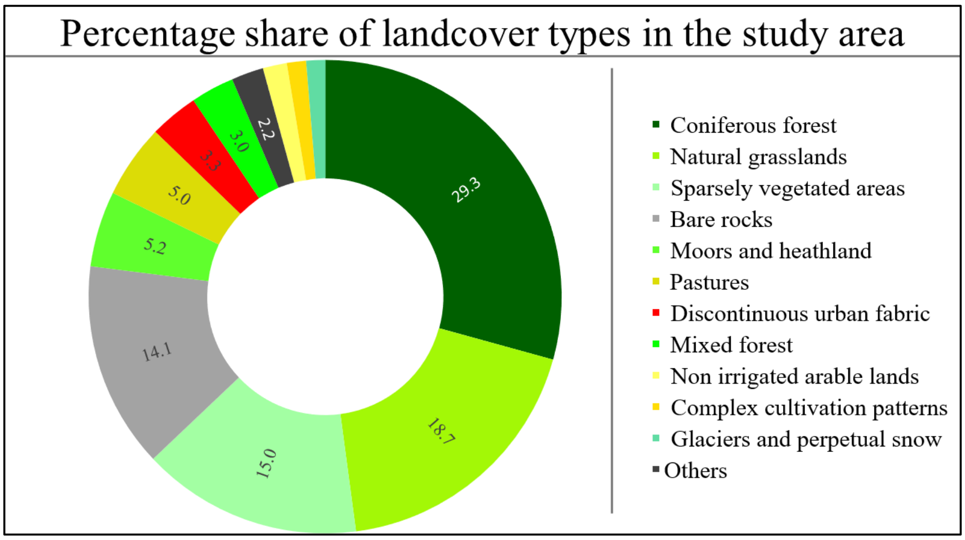

Figure 10: Percentage share of landcover types in the study area.

The forested areas fall into the growth area description of 4.1, northern alpine boundary zone – east (Nördliche Randalpen – Ostteil), 2.1, northern interalpine zone – west (Nördliche Zwischenalpen – West), and 1.2, subcontinental inner alps – west (Subkontinentale Innenalpen – West) according to Kilian et al. (1994) and the classification from the office of the Tyrolean provincial government (Amt der Tiroler Landesregierung, Abteilung Forstplanung 2019a,b,c, p.2; Kilian et al. 1994, p.13).

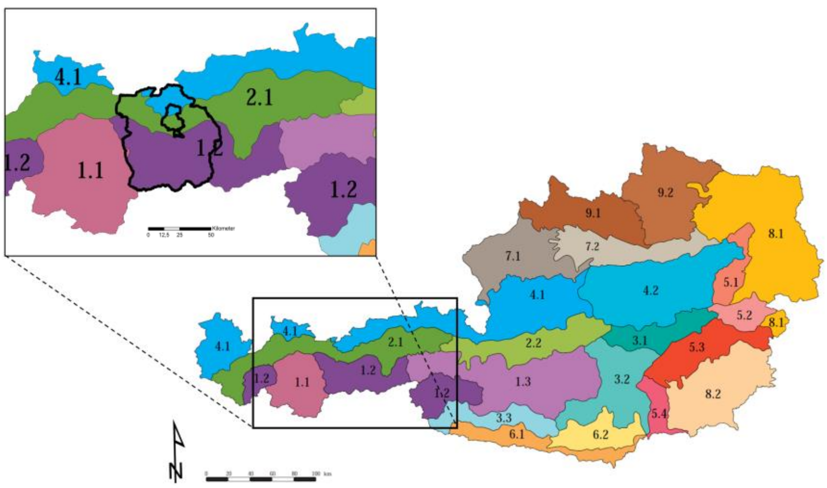

Figure 11: Location of the study area regarding growth areas (Kilian et al. 1994, p.13).

Typical characteristic of the growth area 4.1 is the cool-humid Central European climate with frequent, long-lasting precipitation periods, although their intensity is lower than in the Southern Alps. The forested areas in zone 4.1 can be characterized by spruce-fir-beech forest areas and it entails the beech optimum of the North Alps. (Kilian et al. 1994, p.30)

The colder and humid climate of the northern boundary of the Alps is defined by the high yearly precipitation amounts, ranging from 1100mm to 2200mm and in the subalpine up to 2500mm. Yearly mean temperatures range from merely above 0 °C in the high alpine zone up to 8°C down in the valleys (Kilian et al. 1994, p.30; Amt der Tiroler Landesregierung, Abteilung Forstplanung 2019a,b,c, p.6). Figure 13 shows the climate of Seefeld and Kufstein.

The forested areas in zone 1.2 are dominated by coniferous trees with a clear lack of beech forest in that area. Spruce-larch forest are dominant in the submontane and zone, sometimes in combination with fir. In sunny areas Scots pine is fairly common from the submontane to the high montane zone. Entering the subalpine zone, spruce-larch, larch and Swiss stone pine forest dominate. In the high subalpine zone, these forest stands are typically replaced by mountain pine and Alpenrose (Rhododendron ferrugineum) (Kilian et al. 1994, p.17; Amt der Tiroler Landesregierung, Abteilung Forstplanung 2019b, p.12).

The climate can be characterized as continental mountain climate. Annual mean temperature is between 0°C at the forest line up to 7.5°C down in the valley. Yearly amount of precipitation lies around 800mm in the valley, up to 2000mm on the mountain tops. Figure 13 shows the climate for Neustift im Stubaital and Gries am Brenner (Kilian et al. 1994, p.17; Amt der Tiroler Landesregierung, Abteilung Forstplanung 2019b, p.5).

Between the continentally influenced spruce forest of the inner alpine zone (1.2), and the mixed deciduous forest in the northern alpine boundary zone (4.1), which is influenced by high mean precipitation, a transitional spruce-fir zone is placed, zone 2.1.

The forested areas in zone 2.1 can be characterized due the fir-optimum in the montane altitudinal zone. In this area the mild climate is reflected by the sub- and low-montane beech forests. An exception is the area between Schwaz and Stams. On the northern facing, shadow dominated slopes, beech forest only dominates restricted zonal forest types, usually in the submontane. Furthermore, on the Mieminger plateau, with its dry climate, the submontane Beech forests are practically non-existent, and are also missing in the low-montane zone (Kilian et al. 1994, p.20; Amt der Tiroler Landesregierung, Abteilung Forstplanung 2019c, p.32).

Here the climate is characterized by a subcontinental-suboceanic transitional climate with moderate yearly precipitation ranging from 800 to 1500 mm. Yearly mean temperature lies around 3°C in the subalpine and 8.5°C in the valleys (Kilian et al. 1994, p.20; Amt der Tiroler Landesregierung, Abteilung Forstplanung 2019c, p.8). Figure 13 shows the climate for Innsbruck and Telfs.

Figure 12 below shows the long-term temperature and precipitation patterns in the area. Clearly the Inn valley has the highest mean temperature, and it gradually decreases with increasing altitude. The precipitation patterns are a little bit different. There is a clear separation between the northern parts, including the Karwendel, Seefeld-plateau and Wetterstein-massif, which show high precipitation levels and the southern parts, all the way down to the border. This area, starting from the Inn-valley southward, is particularly dry and shows a clear east-west precipitation shift, with the eastern parts having higher overall precipitation.

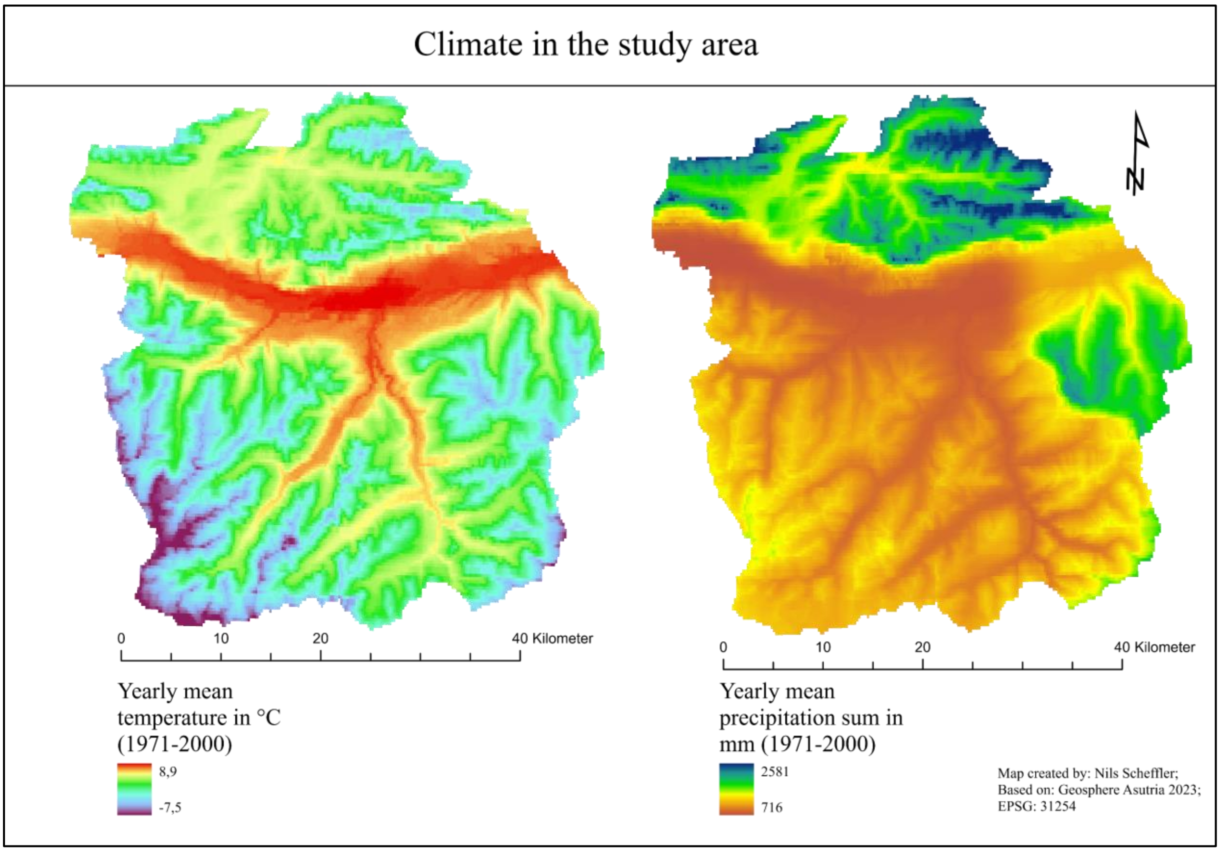

Figure 12: Climatic conditions between 1971 and 2000 in the study area.

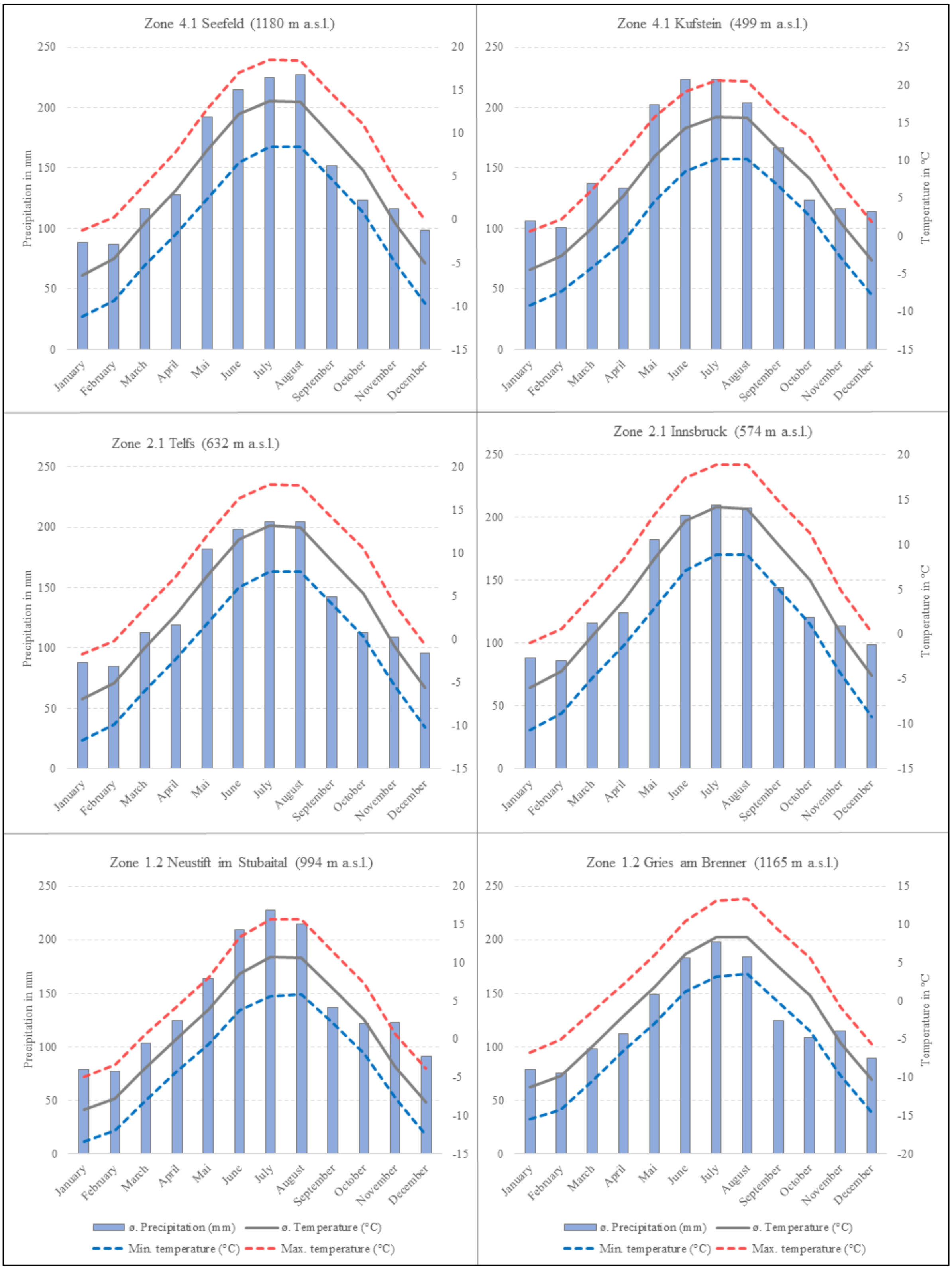

Figure 13: Climates for selected cities in and around the study area (Climate data.org 2023).

9. Methodological framework, analysis and discussion

The following chapters will entail the applied methods with subchapters about the methodological approach, the results, and a short discussion of the used methods. The previous chapters will now come into play as much of the needed knowledge has already been provided and won't be further explained in such detailed form.

9.1 Expert interview

For this master thesis an expert interview with two firefighters from the Innsbruck fire department was conducted.

9.1.1 Methodology

The expert interview is an important social science method, that allows non-experts to gain in-depth insights into complex topics and issues. In this method, specifically selected experts of a certain field are interviewed. Although the requirements to be an expert are not clearly specified, some research should be done beforehand to select someone who would qualify to be an adequate interviewee. He or she should possess extensive expertise and insights that are relevant for the interviewing researcher (Wassermann 2015, pp. 51).

The interview is typically conducted as follows. The researcher should ask the expert open-ended questions, enabling the expert to elaborate on their knowledge. Here, a structured and focused interview guide is recommended to ensure competence and encourage detailed responses. This guided structure should not be too stiff, as a certain degree of flexibility in the interview process allows for the exploration of unknown aspects and interactive exchanges between the interviewer and the expert. After the interview, a transcription of the recorded audio is recommended depending on the research design (Wassermann 2015, pp. 55).

9.1.2 The conducted interview

The here conducted type of interview is often called a joint- or group interview and can be beneficial in situations where it is advantageous to have multiple individuals providing expertise for complex topics.

The reason for the expert interview was the authors lack of knowledge regarding the relationship of forest fires, firefighting, the Innsbruck fire department and current scientific knowledge. During the in-depth research of literature regarding forest fires worldwide and specifically in Austria, the fire departments where often mentioned to be a crucial factor in the so complex topic of forest fires. They are the first responders if a fire breaks out and carry a huge burden as they are seen to be responsible for the fast and safe extinction of forest fires.

Although a considerable amount of scientific literature talks about the role of the fire departments in forest fire prevention, an in depth look into the firefighter's perspective was still lacking. One great example of an in-depth investigation was the forest fire workshops that were held in Wien and Graz in 2018, during the Austrian Forest Fire Research Initiative II (AFFRI2) project (Müller and Vacik 2019). Here many experts form different fields (fire department, forestry, civil protection) came together to discuss the topic of forest fires.

The interview was conducted with Chief Fire Officer Andreas Friedl and Fire Chief Stefan Löffler, both from the Innsbruck fire department. The interview was held in the german language so that the content can be communicated correctly and limitations due to language barriers can be avoided. The goal was to gain insights into the work of the fire department regarding forest fires and how they currently assess the hazard situation. Further, questions that could potentially help in the later investigation and modelling of the fire hazard- and risk category were included. A structured interview guideline was prepared which in included 19, mostly open-ended questions and the interview was conducted on December 2nd, 2022. The transcription of the interview can be found further below in the appendix.

9.2 Fuel and deadwood data collection, and mapping

As stated earlier, fuel is considered the food of the fire. It is crucial regarding forest fires as the amount, the structural composition, the moisture content, and type of fuel can influence forest fire occurrence and behaviour. Current measures to increase the biodiversity in forests such as the accumulation of deadwood could lead to potentially larger and more intense forest fires (Pezzatti et al. 2016, p.240). The type and structural composition of fuel will have a major effect on forest fires, that's why fuel maps are needed to cope with this increasing hazard (Wohlgemuth et al. 2008, p.338).

Fuel maps can help researchers to better estimated fire danger levels due to the influence of fuel on forest fires. Fuel maps are currently very sparsely available as they are very difficult to create. Neumann et al. (2022) tried to assess fuel structure and fuel loads in Austrian coniferous forest using 93 sample plots across Austria. They found a dependency on region and forest type. The study also showed that the highest fuel loads were found in spruce forest. Due to the large variations in fuel load that were found, further studies are needed to gain more insights into the fuel load distribution (Neumann et al. 2022, p.693).

As the fuel load, type, and structure is of such high variability, fuel maps that are created by interpolation of data points from different regions in Austria will have a certain degree of incorrect predictions.

9.2.1 Fuel mapping objectives

The goal of the fuel mapping is to gain insights into the type, amount, and distribution in the mapping area. As other studies have shown that the variability of fuel distribution is very high, the data for the fuel map had to be collected in situ to minimize the inaccuracy that would follow other mapping procedures. The collected data is then analysed to create a fuel hazard map, which could be used to refine the forest fire hazard maps that will be explained and discussed later on. Another objective was to find out if in-situ fuel mapping can even be considered to the potential time and cost inefficiency.

9.2.2 The mapping area

The Nordkette was chosen as the mapping area. It is a mountain range that lies north of Innsbruck, just behind the city itself. The boundaries of the mapping area consist of the mountain tops to the north and the begin of the built-up area of Innsbruck to the south. Both northern and southern boundaries also represent the natural boundaries for closed forested vegetation. The eastern and western boundaries were chosen at the Mühlau gorge and the Hintere Brandjochspitze respectively. An overview of this area can be seen in figure 14. The mapping area was chosen because of the close proximity to a populated area and the easy accessibility via the Nordkette cable car, which is located at the centre of it. Overall, the perimeter has an area of more than 2300ha. It consists mostly of forest and alpine landscapes and has a high touristic utilization (Steixner 2017, p. 15).

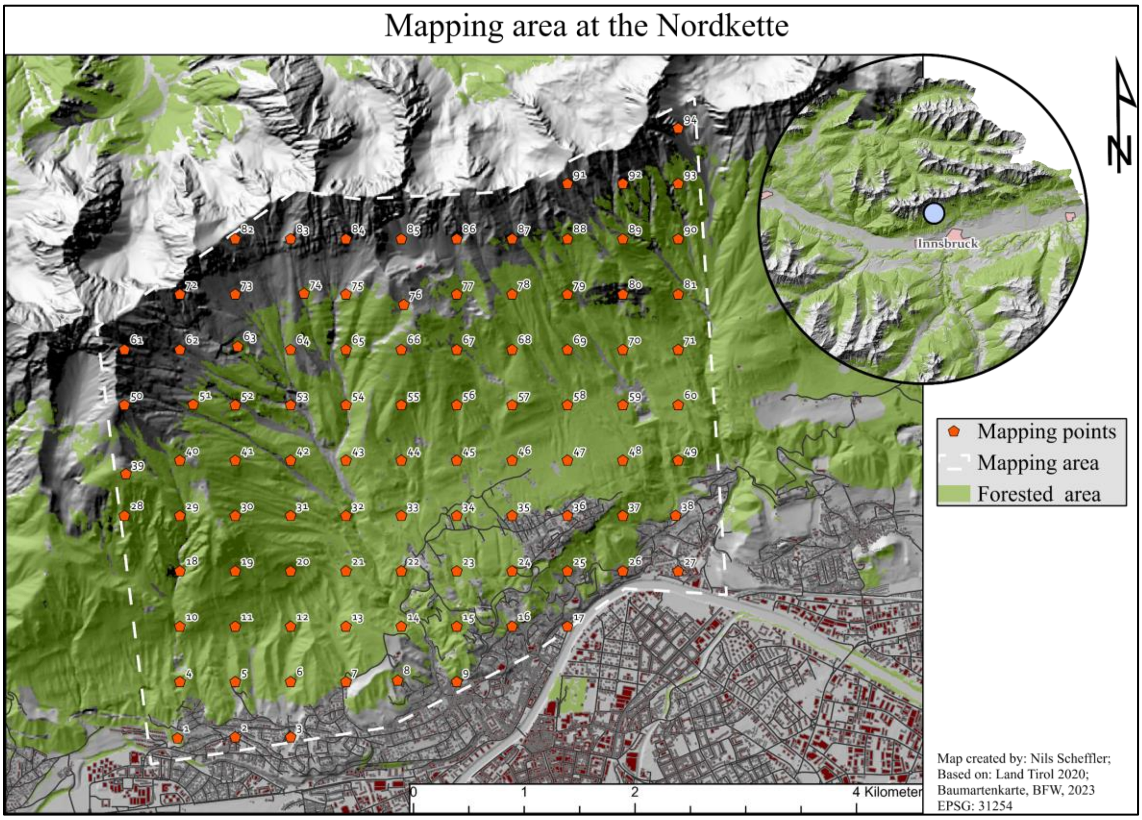

Figure 14: Location of the mapping area at the Nordkette, Tyrol, Austria.

Most of the forest in the mapping area consist of *Spruce-Deciduous* -, *Mountain pine* -, and *Pine* forest, which take up about 50% of the area. Figure 15 shows the different tree species in the area and figure 16 shows the percentage share of tree species.

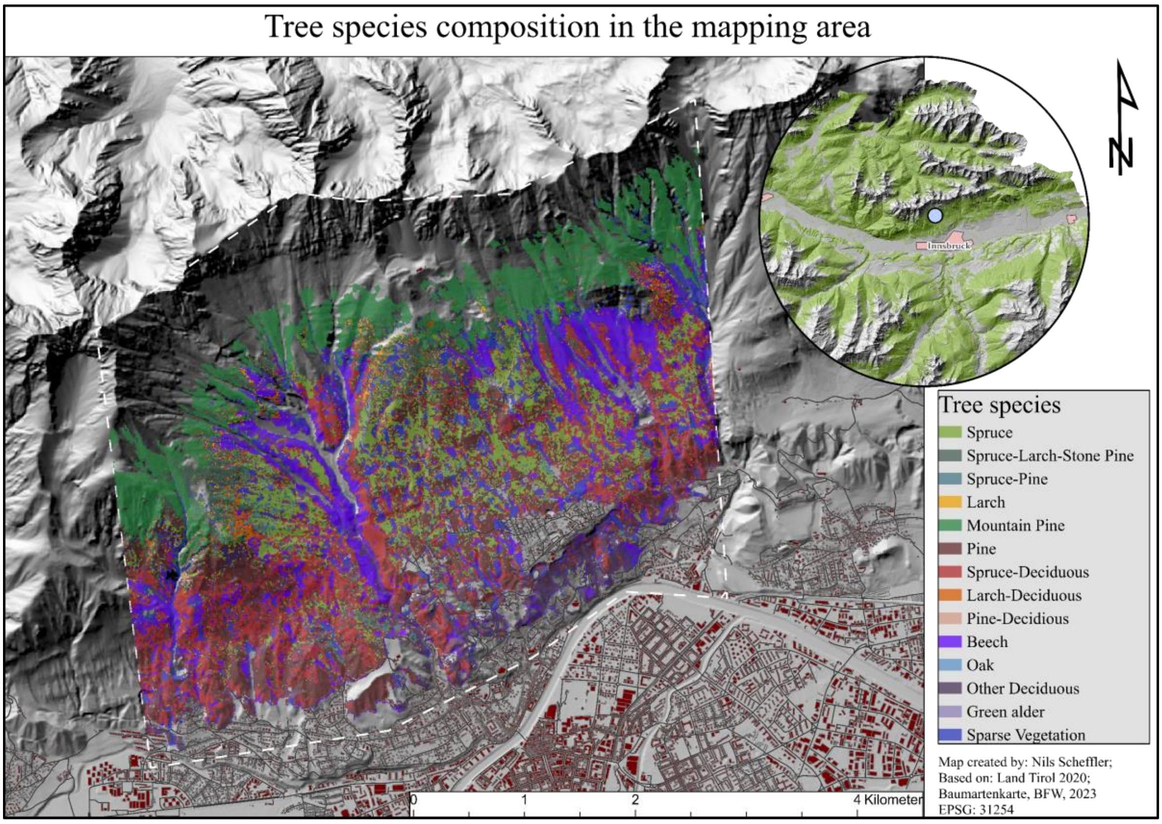

Figure 15: Map of the tree species composition according to the federal research center for forest (BFW 2023).

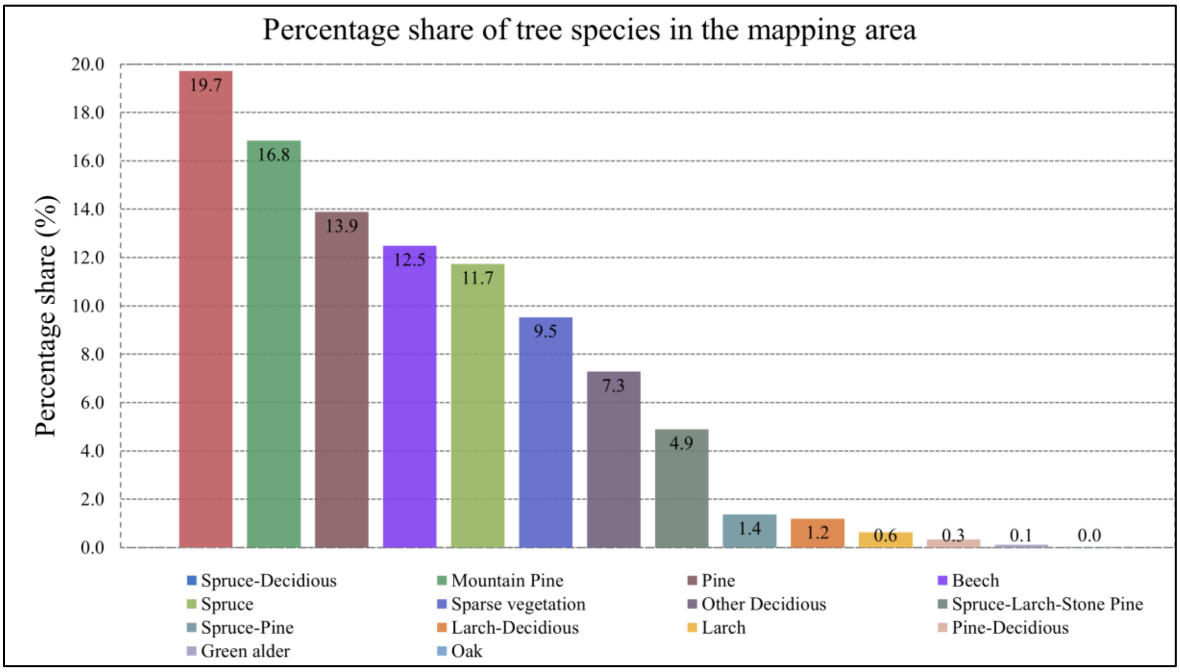

Figure 16: Percentage share of tree species in the mapping area (based on BFW 2023).

The percentage share above is calculated by analysing the pixel count for each tree species in ArcGIS Pro and dividing it by the total number of pixels of the forested area.

9.2.3 Methodical mapping approach

The goal of this mapping was clear: A fuel map that could be included into the fire hazard- and risk approach could be of great advantage. As the mapping area was already set, research into what parameters would be useful for the data collection was done next. To elaborate the, in this chapter used, term “fuel” as it differs from other definitions of this master’s thesis. This fuel map would only represent the burnable material that is either already dead, regardless of size, or the living biomass, which does not exceed two meters of height, or could be classified as shrub vegetation rather than a tree.

Past research in fuel mapping usually collected data on size and structural composition of the fuel, the height of understory- or shrub vegetation (living or dead), the state of decomposition of deadwood, and the density of the current tree stand.

The here used approach collected data on the diameter of lying deadwood, the height of the standing understory- or shrub vegetation (living and dead), the number of dead- and unhealthy standing trees, the state of decomposition of deadwood, and the density of the current tree stand.

With such as large mapping area, mapping points had to be created that were equally spread out inside the mapping perimeter. These points were set 500 meters in each celestial direction apart from each other. The resulting 94 locations of the points can be seen in figure 14. Data from points was not collected when they were out of the forested areas, either above the tree line or already in the city boundaries.

At each of those points thorough data collection was conducted always using the same approach for each of the points. As there was 500 meters to the next point, a 200-meter radius was set around each point to include as much area as possible without having to examine each square meter of the mapping area. Figure 17 below displays a schematic visualization of this approach.

Each point had been entered into a mobile GPS device and therefore could be reached with a high spatial accuracy. With the centre point marked by an object, the 200 meters in each direction could be measured. For this measurement steps were counted in each direction. The authors normal step length is 82 cm, a rough estimation of 250 steps was assumed to be accurate enough. This marked area was then used to collect the needed data. The area in between was later interpolated in ArcGIS Pro.

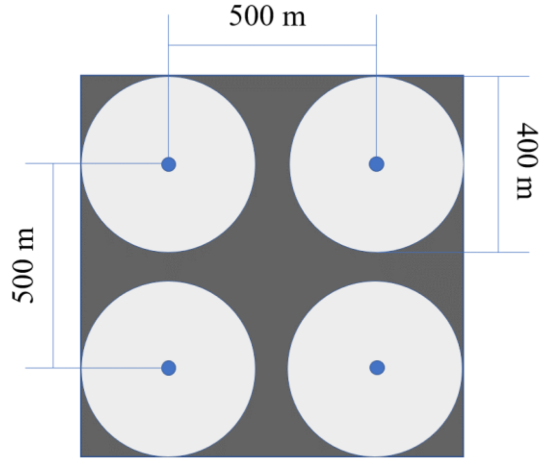

Figure 17: Schematic illustration of the distancing between each data point.

The task of the data collection needed a clear and structured intake form, which had to be prepared to make the collection as easy and correct as possible. An intake form was created in Excel and used during data collection.

To collect data on the diameter of the ground fuels, four classes were used (0 – 6, 7 – 25, 26 – 75, <75 mm), derived from past research and fuel classifications (Neumann et al. 2022, p. 694). As mentioned in an earlier chapter, the diameter of the fuel correlates with time lag classes (1, 10, 100, 1000 h). This time lag refers to the time in which the fuel will reach 2/3 of the difference between its initial moisture content and the moisture content of the current surrounding environment. This property is related to the moisture holding ability which influences ignitability (Neumann et al. 2022, p. 694). The diameter classes of the fuel were collected as an estimated overall percentage share of the data collection area for each point. An example of different fuel accumulations considering of lying deadwood is shown in figure 18.

Figure 18: Examples of different deadwood accumulation types (photos: Nils Scheffler).

The height of the standing understory- or shrub vegetation was collected by measuring it with a regular measuring tape. Here the height classes were also divided into four classes (0-50, 51-150, 151-200, < 200cm). As shrubs grow larger the potential for better ladder fuel conditions increases. Therefore, taller shrubs would be classified as potentially more hazardous during forest fires. As before the height of shrubs was collected as an estimated overall percentage share of the data collection area for each point. Figure 19 represents an example of two height classes.

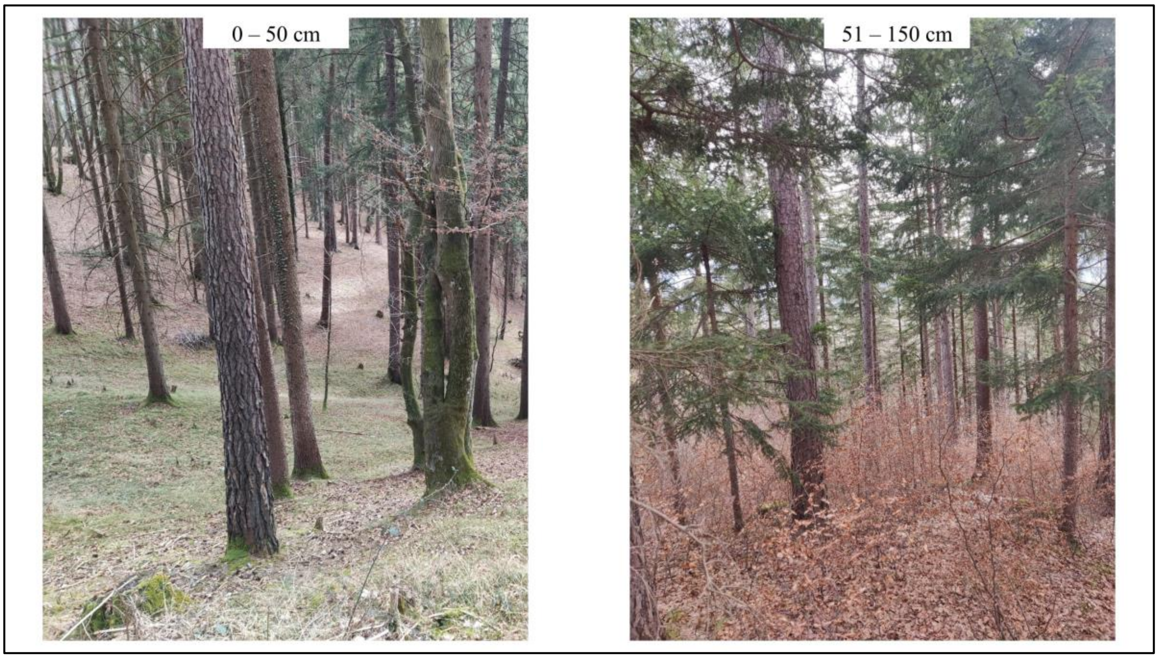

Figure 19: Example of different shrub heights (photos: Nils Scheffler).

The number of dead and clearly unhealthy standing trees in the forest stand for each collection point that was acquired simply by counting them. Dead trees can be easily spotted due to a number of signs that indicate the vegetation state. Some of the most frequent signs and indications were largely missing bark, complete lack of the tree crow, decomposition signs at the trunk, unusual small amounts of foliage cover in the tree crown, and discoloration of leaves, needles and bark. As dead and unhealthy trees do not have the fire resistance of healthy vegetation, they are more prone to ignition and can increase the overall fire hazard level The classes were divided as 0-3, 4-6, 7-10, <10 dead or unhealthy trees per collection point. The class division was made by the author and not derived from other research, as none was found. The following figure 20 shows examples of dead and unhealthy trees found during the mapping exercise.

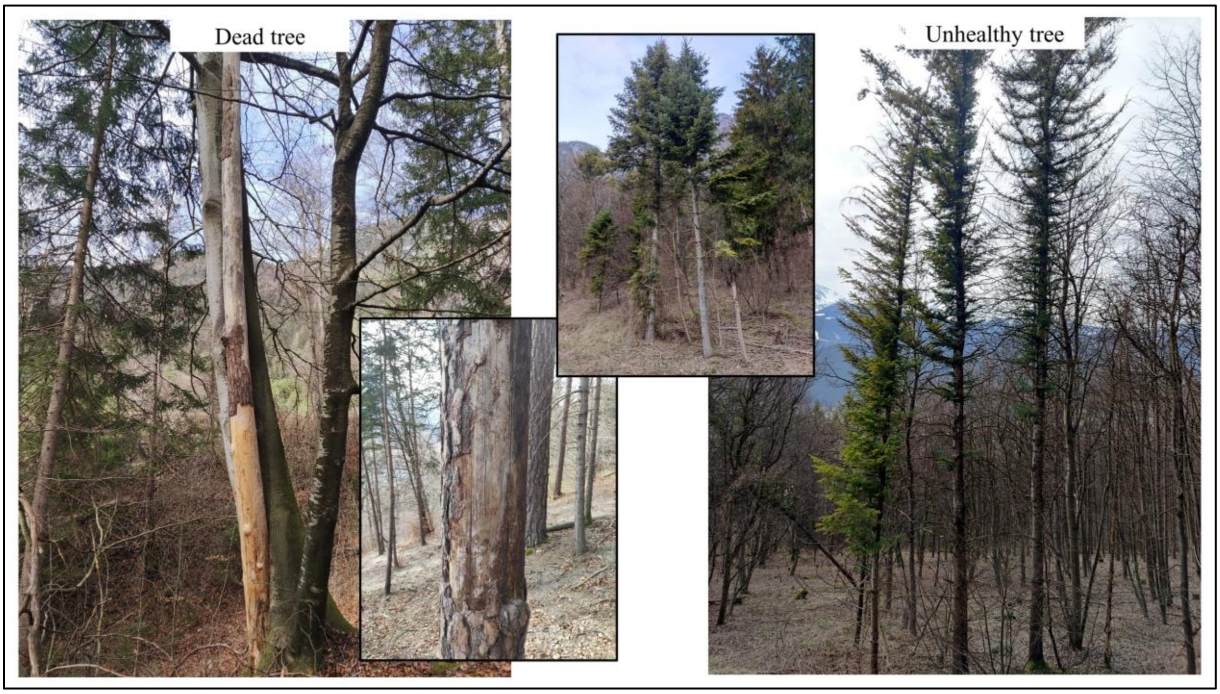

Figure 20: Examples of dead and unhealthy trees (photos: Nils Scheffler).

The decomposition state of the lying deadwood was measured and categorized following the Swiss-knife approach (Lachat et al. 2019, p.4). The four classes are moder wood (Moderholz), sap bearing wood (Saftführendes Holz), decayed wood (Morschholz) and hard wood (Hartholz). The decomposition state can give information about how it will combust if ignited. Wood that is too decomposed or too fresh will both not burn very well due to chemical composition and moisture content of it. Wood that has been lying around for some time and had the chance to dry out will have the best combustion and flammability traits. Below in figure 21, hard wood and moder wood are shown.

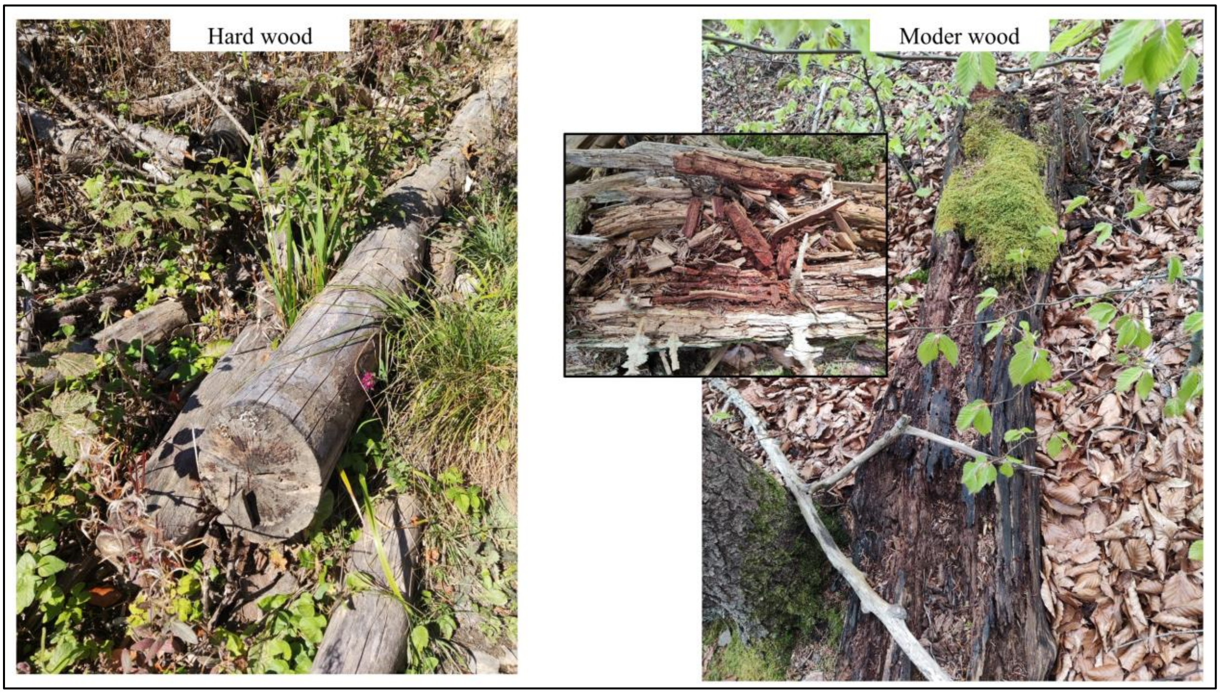

Figure 21: Examples of different decomposition types (photos: Nils Scheffler).

Lastly, the data on the density of the tree stands was collected. The four classes were separated in light stock, patchy stock, closed stock, and dense stock. The density of trees can lead to more intense fires, as the fire has more fuel available for combustion and the close distance between trees helps the fire to spread faster as it does not have to overcome larger distances. This data has been collected as an estimation of average tree density for each data collection point.

Below in table 2, all the collected data categories, divided into the four classes, is shown.

Table 2: Division of the data categories into four classes.

Class	Fuel diameter (mm)	Shrub height (cm)	Dead and unhealthy trees	Decomposition state	Tree density
1	0 – 6	0 – 50	0 – 3	Moder wood	Light stock
2	7 – 25	51 – 150	4 – 6	Sap bearing wood	Patchy stock
3	26 - 75	151 - 200	7 - 10	Decayed wood	Closed stock
4	< 75	< 200	< 10	Hard wood	Dense stock

After all the data was collected, the Excel sheet gave out points for each data category. In the case of the diameter of the deadwood, and the height of the shrub vegetation the percentage share was multiplied with the number of points for each class. In every data category, each class has a certain "danger value" which is represented by an increasing number. As there are four classes the categories are given the value 1 through 4, with 4 representing the highest "danger value". The multiplication of the percentage share with the class value will give a partial points rating. This is then added up into the total points section. This process is shown in figure 22. Each data category has a maximum value of 4 points.

Points	Diamater of lying deadwood	Percentage share	Partial points	Total Points
1	0-6 mm	0.70	0.7	1.7
2	7 - 25 mm	0.05	0.1	
3	26 - 75 mm	0.1	0.3	
4	> 75 mm	0.15	0.6	

Figure 22: Exemplary illustration of the data processing, using the percentage share method.

As the other three data categories were not represented by percentage share values, each class already represents a certain "danger value" as mentioned before. This was then adopted as the final point value. This can be seen in figure 23.

Class / Points	Decomposition state	Local decomposition state	Points
1	Moder wood		3
2	Sap bearing wood		
3	Decayed wood	x	
4	Hard wood		

Figure 23: Exemplary illustration of the data processing, using the single value method.

After calculating the points for each data category, they were added up to form the final "danger value". Each data category was weighted equal, as there was not a sufficient number of previous studies and weighting information found to make reasonable claims as to how the values should be weighted. As each category had a value of at least one, the lowest number of overall points was 5, ranging up to the highest number with 20. This value was separated into 5 "danger classes" as table 3 shows.

Table 3: Division of value ranges into danger categories.

Number of points	Danger category
5 – 8	Very low
9 – 11	Low
12 – 14	Moderate
15 – 17	High
17 - 20	Very high

Now each data point had an overall value representing a certain danger category. This data was imported into ArcGIS Pro and then interpolated using Kriging as interpolation method. This was chosen as the author assumed and later found out that the collected data had some level of spatial autocorrelation, meaning nearby data points are more similar that distant ones.

9.2.4 Mapping results

After the interpolation of the data points, they were classified into the previous mentioned danger classes. The result is shown below in figure 24.

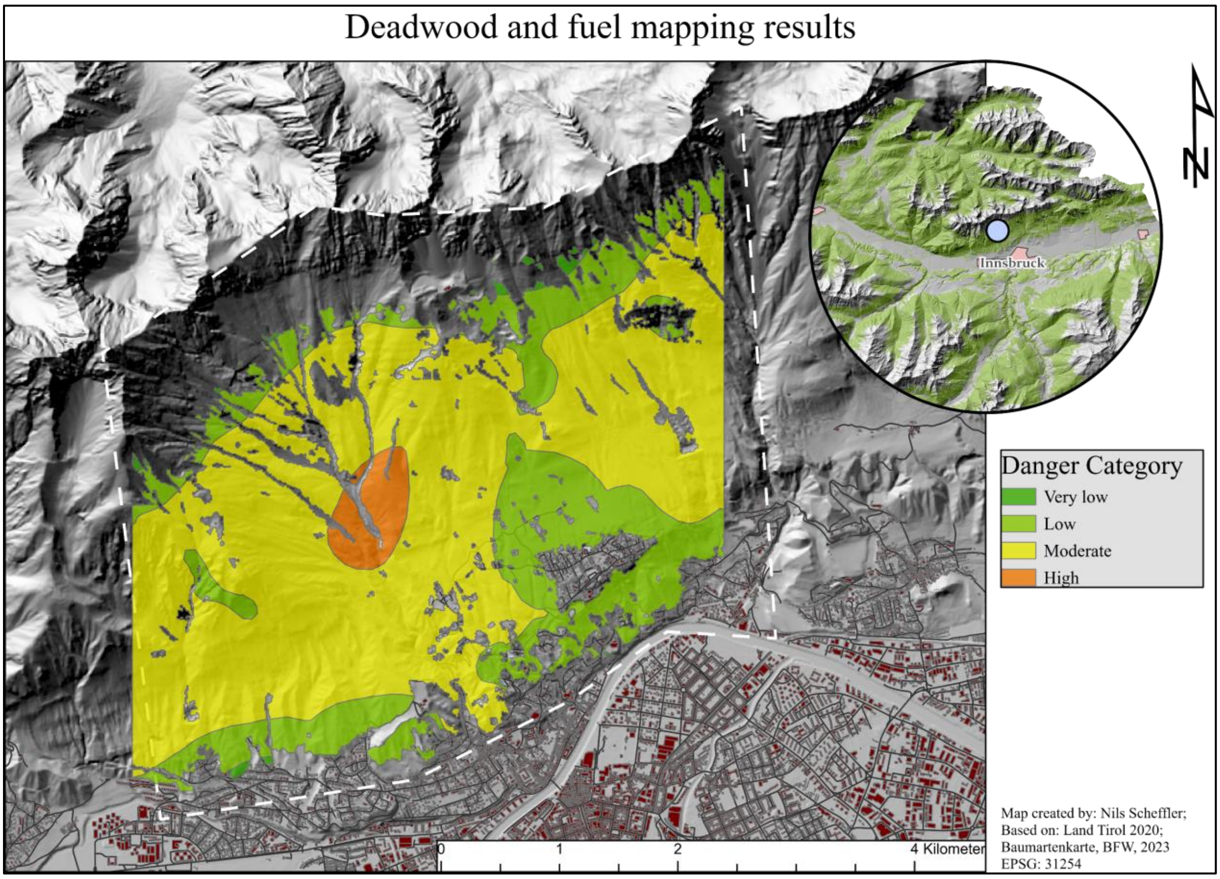

Figure 24: Deadwood and fuel mapping result.

Clearly, a large part of the mapping area resulted in a danger category "moderate". Towards Innsbruck and higher up on the mountain, the area consists mostly of category "Low" to "Very low". Below the Höttinger Alm, almost in the centre of the map, a smaller part falls into the danger category "High".

To gain insights into what causes the spatial pattern of the danger categories, the percentage share of tree species can help to understand the fuel distribution. Figure 25 shows the percentage share of tree species for each danger category.

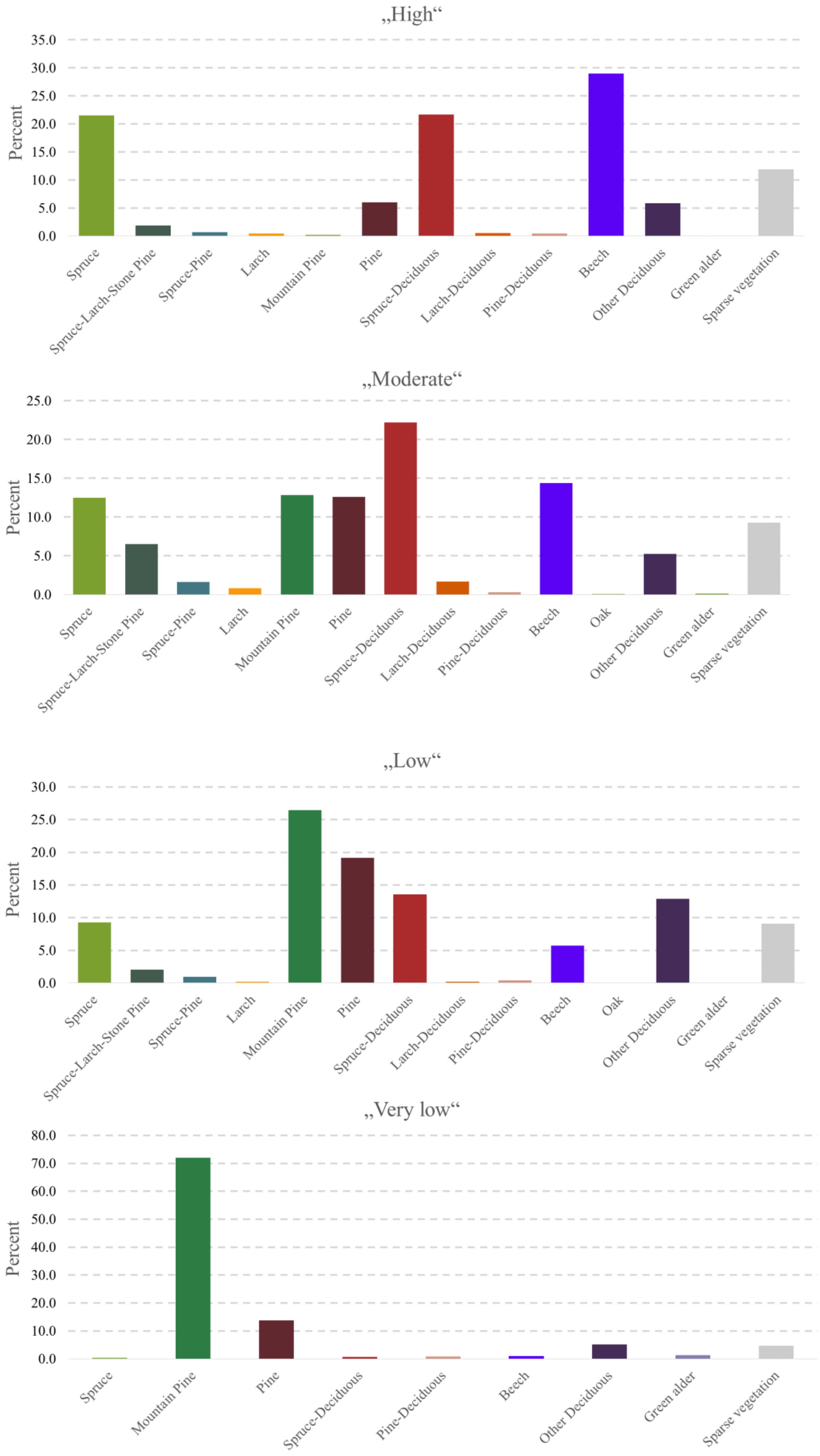

Figure 25: Percentage share of the tree species for each danger category.

The percentage share distribution in category “High” or zone 4 in figure 25 clearly shows, that beech and spruce are dominant, accompanied by smaller amounts of pine and other deciduous species. This can also be seen in category “Moderate”. Here the amount of pine and spruce-deciduous types is much higher with the latter being the dominant tree species. In category “Low” mountain pine, pine and spruce-deciduous are dominant, with the other deciduous types having the highest percentage share compared to all other zones. Lastly in category “Very low” mountain pine is very dominant, with pine only reaching about 15 percent as the second highest type in this zone.

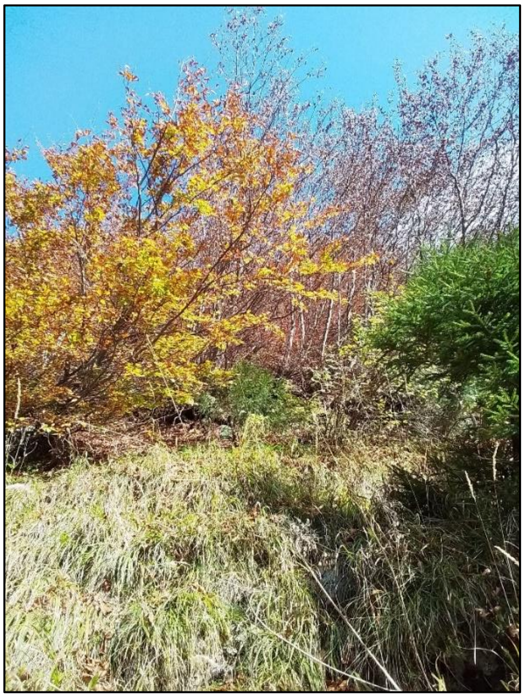

Figure 26: Beech forest in the area that received the highest danger category (Source: Nils Scheffler)

Spruce, beech, and pine tree stands seem to create the highest fuel danger categories. This partly coincides with finding from Neumann et al. (2022) and Müller et al. (2020a). Although typically deciduous forest such as beech does not have such a high fuel load. In this case, the beech forest that was mapped consisted of smaller shrub like trees, although much higher than that. The forest stand was extremely close, and an abundance of deadwood and dead trees was found. These characteristics amounted to a high overall danger rating, resulting in an assignment into the “High” danger category. Figure 26 displays the mapped beech forest, which was categorised so high.

Most of the mapping area falls into the danger category “Moderate”. Here coniferous forest types dominate. The two pictures in figure 27 show two selected mapping points that ended up in this category. In the left picture, the forest stand was overall very close, although some more open spots were visible. The shrub height in the left picture was overall higher, with lower amounts of lying deadwood. The forest stand in the right picture is much more open and the shrub layer much smaller than in the left picture. The abundance of deadwood was the crucial factor which assigned the category to this mapping point.

Figure 27: Examples of the danger category "Moderate (photos: Nils Scheffler)..

Below in figure 28, two mapping points that fell into the category “Low” are shown. The lack of abundant deadwood, of larger shrubs, and of dead or unhealthy trees is notable in both pictures. Although the forest stand might be closer that on other mapping points, the other factors were responsible for the classification into the danger category “Low”.

Figure 28: Examples of the danger category "Low" (photos: Nils Scheffler).

9.2.5 Fuel mapping discussion

The fuel mapping covered an area of 2300 ha on the southern slopes of the Nordkette, just above Innsbruck. Results clearly show highest "danger categories" regarding fuel in coniferous stands, especially spruce dominated stands. Interesting was the high "danger category" in some of the beech dominated forests. This results from the structural components of the beech forest on the Nordkette, as it differs from usual montane beech forest. These consist of much older trees that are spaced further apart.

The results from the presented mapping exercise shows that accurate and high-resolution fuel maps are difficult to achieve. The problems begin during the estimation of how many mapping points will be sufficient to gain as much information as possible without being inefficient time wise. Accurate mapping in situ with such close mapping points is very time consuming. Secondly, the amount of scientific work on this topic is quite slim regarding how a specifically selected number of parameters needs to be measured and documented. During the field work, several unforeseen obstacles regarding data collection occurred. This leads to the next difficulty, especially for beginners: The lack of fieldwork knowledge in regard to the specific task of fuel mapping.

Knowledge about class divisions for all of the collected parameters could not be acquired during research and had to be assumed. One example for an assumption is the class division for the dead and unhealthy trees. Another uncertainty was the weighting of the collected parameters. Here all the parameters were weighted equal. Maybe another weighting distribution will result in "more accurate" results, although this will be difficult to assess, as there is nothing to compare fuel mapping results to.

This mapping exercise as well as other studies found that fuel mapping can be a complicated task with certain levels of inaccuracy or uncertainty. There are also different approaches to fuel mapping. Previously introduced was the method from Neumann et al. (2022), which tried to assess fuel structure and fuel loads in Austrian coniferous forest using 93 sample plots across Austria. Here the spatial uncertainty plays a major role, as fuel structure and fuel load are highly variable.

Another approach can be remote sensing. This can cover large areas in short amount of time, but if the collected data is not being compared to ground data from in situ work, the uncertainties are also considerably high.

The here used fuel mapping method has the advantage of a close grid data collection system. This will ensure high spatial accuracy. Although many favourable factors, the method seems to be too time consuming and therefore inefficient for larger areas. It also requires deep knowledge in planning and executing the fieldwork. This mapping method could be very useful in zones that have a high overall fire danger, or that directly adjoin human infrastructure. Here a close inspection of the forest and the fuel amount can help to make better decisions regarding forest fire management.

9.3 Fire hazard - and fire risk map

The upcoming chapter of this master's thesis focuses on a critical aspect of fire management: the development of fire hazard and risk maps. These maps are of high importance dealing with forest fires and the mitigation measurements. They provide a comprehensive spatial representation of fire hazards and associated risks. They equip policymakers, land managers, and communities with invaluable insights to make informed decisions. These maps not only facilitate understanding but also aid in the identification of vulnerable areas, allowing for proactive planning, resource allocation, and the implementation of targeted fire prevention strategies, such as fuel reduction. In a time when wildfires are becoming an increasing threat in the Alps and in Austria due to changing environmental conditions, the creation of these maps emerges as a pivotal tool in safeguarding both human lives and ecosystems. Many studies have suggested how important these maps are and will be in the future (Arndt et al. 2013, p. 315; Anderson 1982, p. 1; Chuvieco et al. 2009, p.46; BML 2022, p.21; Müller et al. 2020a, p. 45; Faivre et al. 2018, p. 14).

9.3.1 Fire hazard mapping objective

The objective of the later presented hazard map is to identify forest fire hazard hotspots in the in chapter 6 presented study area consisting of the Austrian districts of Innsbruck-Stand and Innsbruck-Land. In terms of forest fire hazard maps creation, the study area made sense in that it lies in Tyrol, which is one of the most fire affected areas in Austria as figure 29 shows.

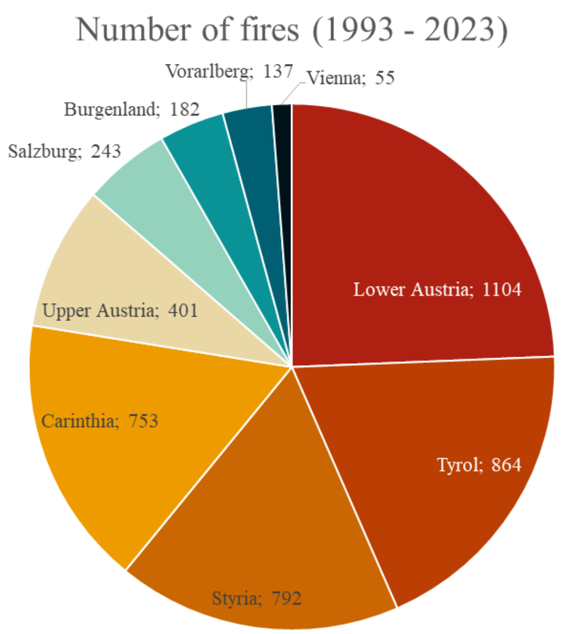

Figure 29: Distribution of documented fire between 1993 and 2023 in Austria, based on state (Waldbrand-Datenbank Österreich 2023).

In the time span between 1993 and 2023, more than 860 forest fires have been recorded in Tyrol. This makes it the second most effected Austrian state, just behind Lower Austria, considering number of fires detected.

Additionally, the study area is the home area of the author of this master's thesis. The advantage of fast access to most of the study area and good knowledge of the peculiarities of the area made it a great choice for the detailed analysis of the current forest fire hazard.

As the current fire hazard maps for Austria rely mostly on the current climatic conditions and result from certain fire risk indices, the presence of static fire risk maps is very sparse. Even if fire hazard maps would be adopted from other countries, they would still lack the required data depth, considering almost all factors that will affect the static forest fires hazard, and spatial resolution that this master's thesis tries to archive.

The goal is to create a forest fire hazard map that includes parameters consisting of the fire ignition probability as well as the fire propagation susceptibility, such as overall climatic factors, topography, vegetation composition and ignition sources. All of this combined into a map with a high spatial resolution of 10 x 10 meters to cope with the heterogeneous terrain complexity.

9.3.2 Methodical modelling approach

The methodical approach to the creation of this fire hazard map is the following. The fire hazard consists of a variety of parameters that either act as a hazard driver or as a suppressant. For example, pure Norway spruce stands on southern facing slopes will act as a fire hazard driver, due to the fire related characteristics in vegetation and aspect. Wet and cold climate on the other hand will be a fire hazard suppressant, as the ignition spread probability is considerably lower.

These hazard drivers or suppressants now need to be compared and analysed, to find out where the hazard driving parameters might add up to create high hazard areas or where they might be supressed, and fires are less likely to occur.

Difficulties can occur when the different parameters have to be weighted, to factor in different parameters with higher magnitude of influence. If previous fires in the area have been documented and mapped it can help to find the correct weighting ratio by comparing the created fire hazard map with the already documented fires. Previous studies, that focused on these maps, have presented weighting ratios and methods, although each study used slightly different parameters to compare. This meant that the weighting ratios could not be implemented completely into this study and had to be modified.

The here used parameters have been selected through the analysis of a large number of articles and research papers, that focus on the main fire hazard drivers and the actual fire hazard modelling. The analysis has shown that the type of vegetation, the topography, and the ignition sources, have all been used previously to create a model output. To define this selection, the following nine parameters were chosen for the creation of the fire hazard map.

1. Type of tree species
2. The Normalized Difference Vegetation Index (NDVI)
3. Slope
4. Aspect
5. Yearly mean temperature
6. Yearly precipitation sum
7. Distance to easily accessible human infrastructure (excl. railroads, hiking paths, forest roads)
8. Distance to railroads
9. Lightning strike occurrence

The type of tree species plays a major role in fire behaviour and indirectly in ignition risk. The flammability of each tree species varies largely as some are more susceptible to ignition than others. Therefore, different tree species pose a higher danger than others which need to be included into these maps.

The NDVI is a crucial part in the creation of a fire hazard map due to its ability to quantify and visualize the health of the assessed vegetation. By assessing the NDVI values, it becomes possible to identify areas with dead, unhealthy or stressed vegetation, which are more susceptible to ignition and rapid fire spread. This index serves as a valuable indicator of the current moisture content in vegetation, aiding in the accurate assessment of fire risk.

The topography, including slope and aspect, has to be also considered, as these parameters are decisive for ignition probability and fire spread rate. The parameter of the slope directly influences the spread rate, as fires spread faster uphill on a slope of 10° or more compared to flat surfaces. The parameter of the aspect on the other hand directly influences the ignition probability. Due to the higher solar radiation intensity on southern facing slopes (in the northern hemisphere), drier surface and fuel conditions occurs, increasing the ignition probability drastically.

The climatic conditions, with yearly mean temperature and yearly precipitation can be an indication for the ignition probability. As stated previously, higher temperatures and lower precipitation conditions will likely lead to an increase in ignition probability. Therefore, including the climatic conditions will help to distinguish between other similar parameters. For example, a coniferous forest, located in dry and warm conditions, will have a higher ignition probability than one in a more cold and wet climate.

The parameters of distance to easily accessible human infrastructure, the distance to railroads and the lightning strike occurrence all influence the ignition probability. Direct and indirect human activity is the main cause of ignition in the Alps, while lightning strike is the only relevant natural cause. Therefore, in regions that are close to human activity (buildings, city roads), and infrastructure such as railroads, and in regions with a high lightning activity the probability of ignition is far higher than elsewhere. This parameter is crucial for the modelling of fire hazard, as without ignition, there will not be a fire.

9.3.3 Acquisition of the required data

The necessary data that was needed to create the fire hazard map, was acquired through different data sources. A part of the data was available online through the open government data – Tirol/Tiris. The parameters slope, aspect, as well all the parameters regarding human activity (building, roads, railroads) were available for download on https://data-tiris.opendata.arcgis.com/.

The tree species composition was provided under the courtesy of the federal research centre for forest (Bundesforschungszentrum für Wald – BFW). This tree species composition is a result from a remote sensing analysis, using Sentinel-2 data to create a high-resolution tree composition map. This map can be viewed online under https://waldinventur.at/.

The NDVI could not be directly downloaded, but the necessary data could be acquired through the Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home). Over a webpage remote sensed data can be downloaded and used for many applications. One of them is the creation of the NDVI from Sentinel – 2 data.

The yearly mean temperature and precipitation sum was available through GeoSphere Austria. They have a vast supply of climate data sets that can be downloaded through their webpage (https://data.hub.geosphere.at/dataset/). The data, that was chosen to represent the climatic parameters was the Austrian climate map, that shows climatic variables like temperature, precipitation, ice days, snow cover duration and many more. The climate map dataset contains raster fields describing the average spatial distribution of important climate variables over Austria for the period 1971 to 2000. Although many variables were available, the two most important were the yearly mean temperature and the precipitation sum, as they are responsible for the creation of suitable fire weather and fuel conditions.

Lastly, the data that represents the probability of lightning strike occurrence was kindly provided by the Austrian Lightning Detection and Information System – ALDIS. The acquired data shows the lightning occurrence (lightning flashes (lf) per m² and year) of Tyrol for the last ten years. ALDIS is a collaborative project between the Austrian Association for Electrical Engineering and Austrian Power Grid AG. The project focuses on lightning detection and documentation in the Central European region.

9.3.4 Data processing

Now that all the data was acquired, it had to be processed to start the finalisation into the fire hazard map. All the raw data came in different data types, with various spatial resolutions. Below in table 4, all the information about the datasets is combined.

Table 4: Information about the here used data sets.

Parameter name	Data type	Spatial resolution (m)	Unit	Data Source
Slope	Raster	5 x 5	degree	Digital elevation model - Open government data – Tirol/Tiris
Aspect	Raster	5 x 5	degree	Digital elevation model - Open government data – Tirol/Tiris
Distance to human infrastructure	Vector	-	-	Open government data – Tirol/Tiris
Distance to railroads	Vector	-	-	Open government data – Tirol/Tiris
Tree species map	Raster	10 x 10	-	Federal research centre for forest
NDVI	Raster	10 x 10	-	Sentinel - 2 (ESA)
Temperature	Raster	200 x 300	C°	GeoSphere Austria
Precipitation	Raster	200 x 300	mm	GeoSphere Austria
Lightning strike occurrence	Raster	1000 x 1000	$lf / km^2 * y^{-1}$	ALDIS

All of the spatial data was processed in ArcGis Pro, a Geographic Information System (GIS) software application developed by ESRI (Environmental Systems Research Institute). The data processing approach was fairly similar for each of the parameters. A first step was the download of the data and the import into ArcGis Pro. Here it could be clipped to the size of the study area and the resolution had to be changed in order to continue the processing of the data. A standard resolution of 10 by 10 meters was chosen to be the opted for raster cell size. As the fire hazard map will later have a "danger category" classification of five classes, each of the parameters needed to be also classified into five "danger categories". Later all the layers can be combined together to create the desired map.

The thought behind this process is to create a "danger category" classification for each map first. That way each map will represent a spatial distribution of lower and higher danger potential with regard to its unique parameter concerning forest fires. The classification for each parameter was different as they all have unique fire related properties that need to be identified. After this process all the parameter maps can be added up into the final map, which will then include nine fire hazard parameters that can lastly be classified again into the desired "fire hazard categories".

Slope:

The parameter slope was generated from a digital elevation model. The output was a raster that was categorised from 0° to 90° slope in 1° steps. This was classified as follows. 1 (Very Low): 75 – 90°, 2 (Low): 0 – 15° and 60 – 75°, 3 (Moderate): 15 – 20° and 55 – 60°, 4 (High): 20 – 30° and 45 – 55°, 5 (Very high): 30 – 45°. Fire spreads faster with increase in slope angle. Vegetation on the other hand will become increasingly sparse and spread apart with increasing slope. There is a saturation point where the danger is the highest, lying around the value of 30 to 45° slope angle. Below that the decrease in slope will affect the fire spread rate. Above that, increasing distance between trees will limit fire spread rate. Lastly the raster cell size was resampled to be 10 by 10 meters.

Aspect:

The parameter aspect was also generated from a digital elevation model. The output was a raster that was categorised into the celestial directions of N, NE, E, SE, S, SW, W, NW. This was classified as follows. 1: North (0 – 22,5° and 337,5 – 360°), 2: North-east (22,5 – 67,5°) and North-west (292,5 – 337,5°), 3: East (67,5 – 112,5°) and West (247,5 – 292,5), 4: South-east (112,5 – 157,5°) and South-west (202,5 – 247,5°), 5: South (157,5 – 202,5°). Again, the raster cell size was resampled to be 10 by 10 meters.

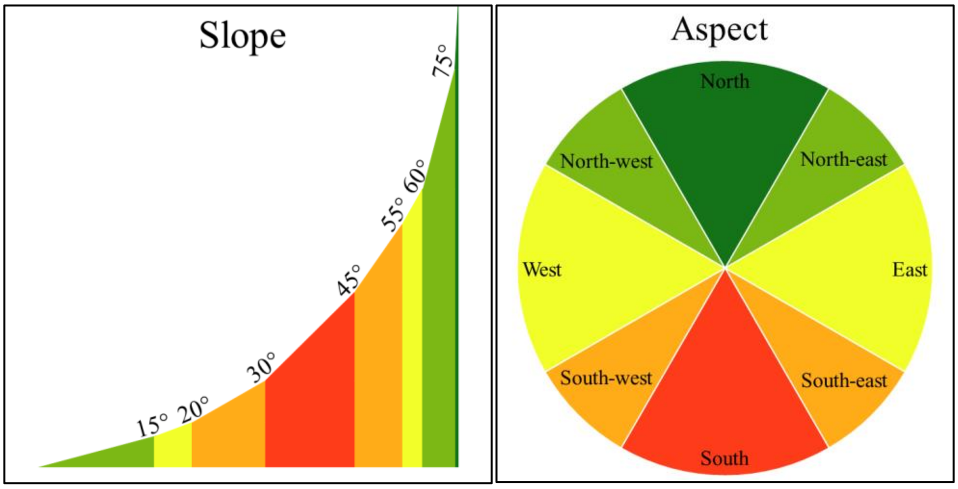

Figure 30: Schematic illustration of fire hazard categories for the parameters Slope and Aspect.

Wildland - Urban - Interface:

Distance to human infrastructure and railroads were two parameters that came as vector data. The idea behind this parameter is to create buffer zones around public and easily accessible human infrastructure and railroads. In this zone the ignition probability is very high, therefore this area will just have one "danger category" of 5 (Very high). The distance around these infrastructures will be 150 meters for public roads and buildings, and 50 meters around railroads. The roads that were used for this buffer area were highways, federal roads and communal roads. The buffer distances were based one past research from Pezzatti et al. (2016) and Arpaci et al. (2014). In their work a critical ignition distance of 160 meters around human infrastructure and a maximum distance of 100 meters for railroad was defined. To display the area of the WUI, the created buffer zones were masked by the current forest cover. After the WUI zone was create, the polygons were transformed into a raster, with the WUI zones having the value 5 and the rest having the value 0. This must be done in order to add all parameter layers up together.

Hiking paths and non-public forest roads were not used for the creation of buffer zones. Firstly, the dataset of the hiking paths was not complete and would not be representative for this study. Secondly, there is a lack of research into how the access to non-public forest roads will affect the fire hazard, as well as the uncertainty in buffer distance around these roads. Also, the frequency in usage and the difference in availability compared to public roads would bring up the question of how justified the classification into the same danger category is. Due to these reasons, the hiking paths and the non-public forest roads were not included.

Tree species composition:

The tree species classification was provided by the federal research centre for forest (BFW). The dataset consisted of a raster file with a spatial resolution of 10 by 10 meters, including the categorisation of 14 different tree species and tree species composition, as the following table 5 shows.

Table 5: Classification of tree species based on the BFW.

Tree species			
1	Spruce-Deciduous	8	Spruce-Larch-Stone Pine
2	Mountain Pine	9	Spruce-Pine
3	Pine	10	Larch-Deciduous
4	Beech	11	Larch
5	Spruce	12	Pine-Deciduous
6	Sparse vegetation	13	Green alder
7	Other Deciduous	14	Oak

As previous chapters already have discussed, the susceptibility to forest fire differs largely depending on the tree species and forest composition. Because flammability is such an important factor influencing the probability of ignition an essential component of the fire risk assessment for a certain area is the classification of vegetation according to their expected flammability (Dimitrakopoulos et al. 2001, p. 143).

To categorise the tree species according to their flammability and fire susceptibility traits, the study from Xanthopoulos et al. (2012) was chosen. Here an assessment of typical fire hazard for 60 vegetation types of Europe was done. The table in the study lists the vegetation type e.g., “Alpine Scots pine and Black pine forest”, the European forest type classification e.g., “Central European submountainous beech forest”, and the minimum, maximum and mean fire hazard value (between 1 and 5), which resulted from expert evaluation. Here, a value of 1 represents a very low hazard value and a value of 5 a very high one.

With that, the tree species now could be evaluated in terms of the fire hazard they pose. The Fire hazard categories for each tree species and forest type can be seen in table 6.

Table 6: Tree species and their according fire hazard category.

	Tree species	Fire hazard category		Tree species	Fire hazard category
1	Spruce-Deciduous	1	8	Spruce-Larch-Stone Pine	2
2	Mountain Pine	2	9	Spruce-Pine	4
3	Pine	3	10	Larch-Deciduous	1
4	Beech	1	11	Larch	2
5	Spruce	2	12	Pine-Deciduous	1
6	Sparse vegetation	1	13	Green alder	1
7	Other Deciduous	1	14	Oak	2

To be noted is the missing of a fire hazard category five. In Xanthopoulos et al. (2012), only a couple of forest types were given the category 5. These were, among others, Mixed heathland (*Erica, Ulex, Pterospartium*) and Olive forest. Also, a fire hazard categorization of different tree species as such must be viewed in a certain context. This proposed classification cannot be dissociated from the fire environment that the tree species is currently in, as the amount of fuel, specific topography, and current weather can easily override the given fire resistance classification. Thus, the management of this fire environment and especially the control of fuels is critical. Implying that the resistance of a tree species can increase with proper management (Fernandes et al. 2008, p. 252).

As the original file was already a raster type with the right cell size, the only modification was the reclassification into the fire hazard categories.

NDVI:

The generation of the fire danger classification from the NDVI was a little more elaborate as remote sensed data from the Sentinel – 2 mission, which is directed by the European Space Agency (ESA) had to be processed first. Campbell 2002 defines remote sensing as "the practice of deriving information about the earth's land and water surfaces using images acquired from an overhead perspective, using radiation in one or more regions of the electromagnetic spectrum reflected or emitted from the Earth's surface" (Campbell 2002, p.6). These modern applications provide a wide range of options for forest health measurement, such as vegetation and landscape classification, biomass mapping, water stress mapping, fire detection and insect infestation detection providing a quick evaluation of the vegetation status (Chivieco and Congalton 1989, p.147; Wang et al. 2010, p.28; Illera et al. 1995, p.1093). The vegetation indices that are currently used, usually compose of a combination of surface reflectance of specific wavelengths designed to highlight certain vegetation properties (Tuominen et al. 2009, p.29).

The NDVI is one of the most frequently used and well-known vegetation indices as it provides a good overall health measure of green vegetation (Tuominen et al. 2009, p.34). It uses the fact that healthy vegetation strongly absorbs red light by chlorophyll and reflects a lot of light in the near infrared spectrum, which stands out in contrast with most non plant objects. If the vegetation is dehydrated and unhealthy it will reflect less light in the near infrared spectrum, but the same amount in the visible range (Wang et al. 2010, p.33; Meneses-Tovar 2011, p.39; Valderrama-Landeros et al. 2018, p. 2). The discoloration of the plant itself can be an example of a symptom of deterioration that is relatively easy to monitor. It is very useful as an index for forest health (Tuominen et al. 2009, p.32).

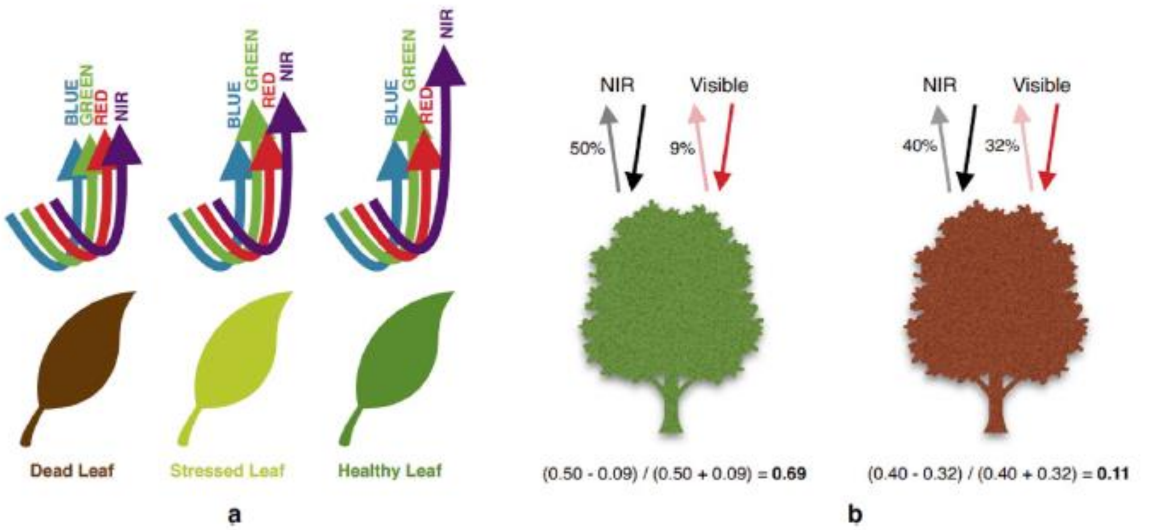

Figure 31: Schematic illustration of the reflection properties of different leave color characteristics (Evangelides and Nobajas 2019, p.3).

The NDVI can be calculated using the following equation:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \qquad \text{Eq. [1]}$$

(Pradhan et al. 2007, p.347)

where *NIR* refers to the Near Infrared band reflectance value and *RED* refers to the Red band reflectance value. The NDVI formula utilizes the difference and sum of reflectance values in the NIR and RED bands of electromagnetic radiation. The NIR band represents the vegetation's ability to reflect near-infrared light, while the RED band represents the reflectance of red light by vegetation. By taking the difference between NIR and RED and dividing it by their sum, the NDVI calculation produces a value ranging from -1 to +1. This value represents the density and health of vegetation in a given area.

A high positive NDVI value (closer to +1) indicates dense, healthy vegetation, such as forests or agricultural crops. A value close to zero suggests little to no vegetation or non-vegetated surfaces like bare soil or water. A negative NDVI value (closer to -1) often indicates non-vegetated surfaces, such as urban areas or rocky terrain. This value is important in assessing vegetation health, monitoring changes over time, and identifying areas prone to drought, deforestation, or other ecological conditions (Pradhan et al. 2007, p.347); (Zhang et al. 2016, p. 1); (Evangelides and Nobajas 2019, p.2)

The idea behind using the NDVI as an indicator of forest fire danger is that the vegetation index reflects the state of the vegetation, especially the current vegetation moisture (Illera et al. 1995, p.1099). As fuels dry, the reflectance increases in the water absorption bands. This effect will be visible using remote sensed data (Chuvieco et al. 2014, p.609). A decrease in NDVI levels suggest an increase in water stress that may result in an increase in fire danger (Illera et al. 1995, p.1100).

If unprocessed data is to be used, it needs to be atmospherically corrected. Without that process of filtering the effects of the atmosphere the data would not show accurate results (Tuominen et al. 2009, p.32). Here the remote sensed data that was acquired from the Sentinel-2 images is already atmospherically corrected.

Another difficulty with remote sensing products is the so-called mixed pixel problem. As in remote sensing data one pixel can represent many different materials. Data collected from forested areas may represent a mixture of different surfaces such as the tree canopy, soil and rock. This can lead to false results if the percentage of tree canopy is too low. That means that remote sensing data usually provides a good general information about a larger area rather than precise information of a single pixel (Tuominen et al. 2009, p.34). A solution to this problem is the usage of high-resolution data. The here used images have a cell size of 10 by 10 meters, which minimizes the mixed pixel problem significantly.

The data that was used to calculate the NDVI was a remote sensed image from the Sentinel-2 mission. It was captured on the 24th of august 2022. The date was chosen because timewise it had to be in summer, and the cloud cover had to be as little as possible. As the images are only captured every five days, the availability is limited. Therefore, having usable remote sensing data is not always guaranteed.

As the data from the Sentinel-2 missions can be downloaded, already atmospherically corrected, the calculation of the NDVI could begin. As only the section of the forested area is interesting from a fire hazard standpoint, the NDVI classification went as follows: 5. -1 – 0,5, 4. 0,51 – 0,6, 3. 0,61 – 0,7, 2. 0,71 – 0,8, 1. 0,81 – 1. This way the healthy vegetation will have a low danger value and unhealthy or dead vegetation will have a higher one.

Temperature and Precipitation:

The data for the yearly mean temperature and the precipitation sum was downloaded from the datahub from GeoSphere Austria. Here a climate map is available that shows the various climate parameters for the years 1971 – 2000. The downside to this is the time span, which is not up to date anymore, as 20 more years have passed, and the climate has already changed. As the intrinsic climate values are not the actual goal for this parameter but the classification into five danger categories, the assumption was made that the climatic change affected the region laterally and vertically equal, and the current climatic values would provide the same fire danger classification pattern.

The climatic conditions largely influence fire occurrence by providing the necessary conditions for dry fuel and low enough moisture values, as well as the fire behaviour, such as spread rate. The differentiation of similar regions by climatic conditions is very important. The same vegetation type in the same kind of topography can have different fire regimes due to different climatic conditions. For example, the submontane beech forests are currently less likely to support larger fire as the beech forests in the southern alps of northern Italy, due to climatic conditions, even if they are consisting of the same tree species in steep mountainous terrain.

The mean temperature in the study area ranges from -7,5 to 8,9 C° and the mean precipitation sum ranges from 716 to 2581 mm * y^{-1}. As there was no research evidence found to divide the climatic conditions into set danger categories, the temperature and precipitation range was divided into categories using natural breaks (Jenks). This provided the following danger classification for the mean temperature: 1. -7,5 – -2,03 C°, 2. -2,02 – 0,668 C°, 3. 0,669 – 3,2 C°, 4. 3,3 – 5,7 C°, 5. 5,8 – 8,9 C°. And for precipitation: 1. 1967 – 2581 mm, 2. 1616 – 1966 mm, 3. 1309 – 1615 mm, 4. 1038 – 1308 mm, 5. 716 – 1037 mm. After the classification, the raster cell size was resampled to 10 by 10 meters.

Lightning occurrence:

The lightning occurrence for the years 2013 – 2022 was provided by ALDIS. The raster data set ranges from 0 to 5,78 lightning flashes per square kilometre and year (lf / km² $*y^{-1}$). Lightning strike is the only important natural cause of forest fires in Austria. Therefore, the localisation of areas, where lightning strike is very common, will help to differentiate the spatial forest fire danger levels even further.

As before there is not enough data to support an own classification. The dividing was again done by using natural breaks (Jenks). The following classification into originated from it: 1. 0 – 1, 2. 1,3 – 2,5, 3. 2,6 – 3,5, 4. 3,6 – 4,6, 5. 4,7 – 5,8. The original raster had a size of 1 by 1 kilometre. This was resampled to match the required rater cell size of 10 by 10 meters. All resampling in this process has been done in ArcGIS Pro using the nearest neighbour method.

Below in table 7, all used parameters are listed with the corresponding forest fires danger classification from 1 (Very low) to 5 (Very high).

Table 7: Listing of the used fire parameters and the classification into the five fire danger categories.

Parameter	Danger category: 1	2	3	4	5
Slope (°)	76 – 90	0 – 15; 61 – 75	16 – 20: 56 – 60	21 – 30; 45 – 55	31 - 45
Aspect	N	NE; NW	E; W	SE; SW	S
Buildings, streets (m)	-	-	-	-	0 - 160
Railroads (m)	-	-	-	-	0 - 50
Tree species	1;4;6;7;10;12;13	2;5;8;11;14	3	9	-
NDVI	-1 – 0,5	0,51 – 0,6	0,61 – 0,7	0,71 – 0,8	0,81 - 1
Temperature (C°)	-7,5 – -2	-2,1 – 0,6	0,7 – 3,2	3,3 – 5,7	5,7 – 8,9
Precipitation (mm)	716 – 1037	1038 – 1308	1309 – 1615	1616 – 1966	1967- 2581
Lightning occurrence (lf / km² $*y^{1}$)	0 – 1,2	1,3 – 2,5	2,6 – 3,5	3,6 – 4,6	4,7 – 5,8

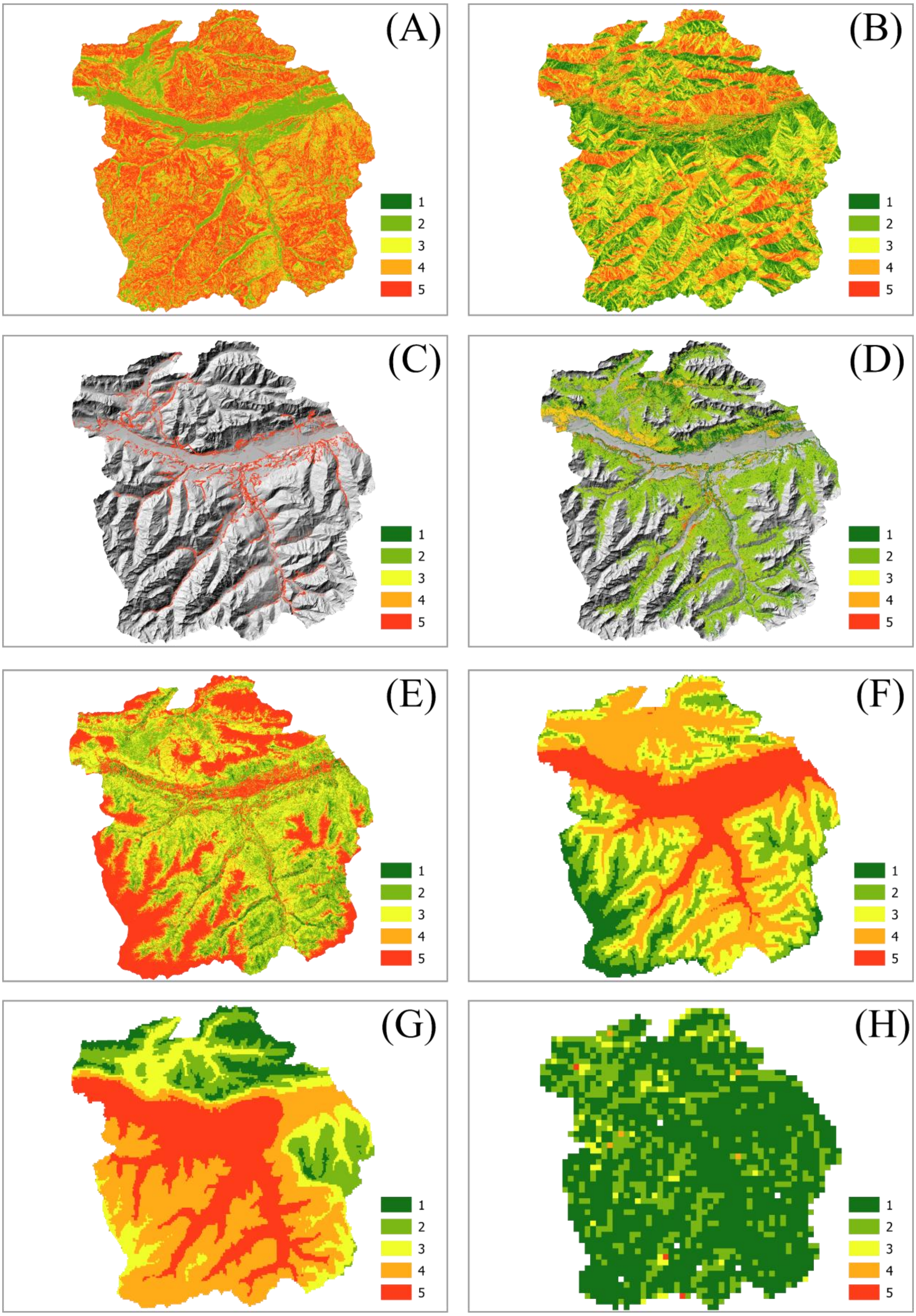

Figure 32: Resulting fire danger category maps for each fire hazard parameter: A – Slope, B – Aspect, C – WUI, D – Tree species, E – NDVI, F – Temperature, G – Precipitation, H – Lightning occurrence.

Figure 32 shows the final maps with all parameters classified into five danger categories. A is the slope, B the aspect, C the WUI, D the tree species, E the NDVI, F the temperature, G the precipitation and H the lightning occurrence. With the creation and classification of all these fire related parameters, the modelling of the overall fire hazard in the study area can begin.

9.3.5 Fire hazard modelling

All layers will be added up together, to create a final fire hazard value for all pixels. This can then be again classified into fire hazard categories, spanning from 1 (Very low) to 5 (Very high). This was done in ArcGIS Pro using the Raster Calculator. Below in figure 33 a schematic presentation of the raster calculation process is shown.

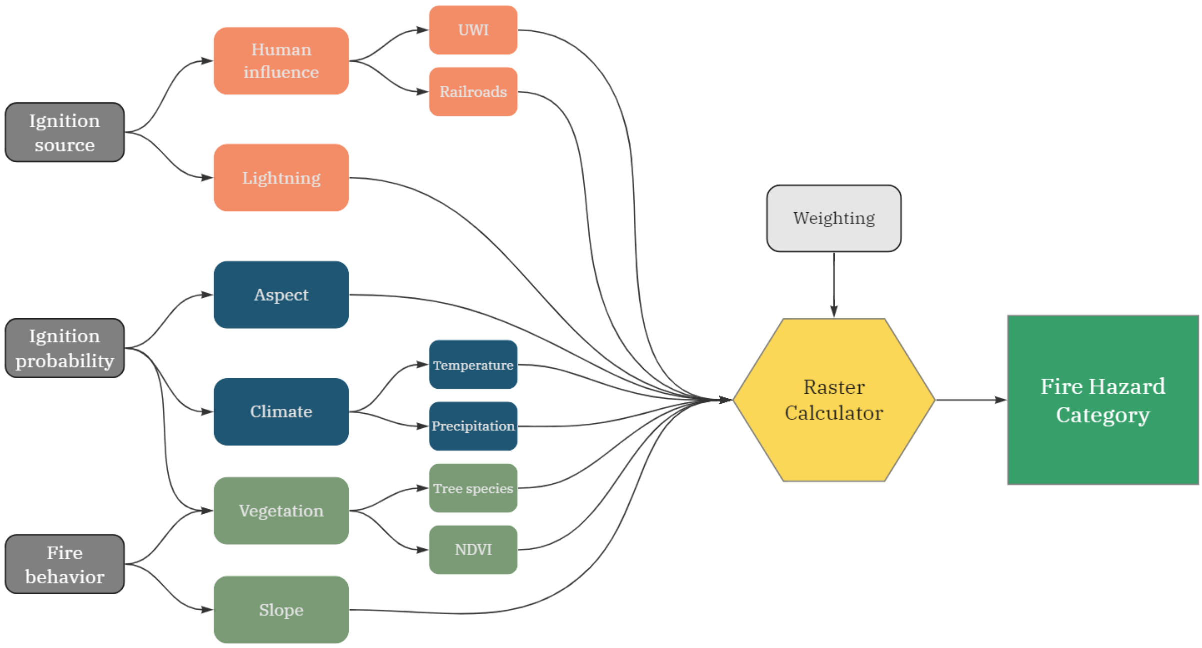

Figure 33: Schematic presentation of the calculation process to create a fire hazard map.

To model the fire hazard, a weighting of the fire hazard parameters is very important. A first approach can be the equal weighting of all parameters. This was also the first step that was done here. After the result has been analysed the weighting method can be changed to create a more precise hazard map.

All parameters equal (Variant 1): The following forest fire hazard map was created using every parameter and giving them each a weight of one, equalizing the weighting effect.

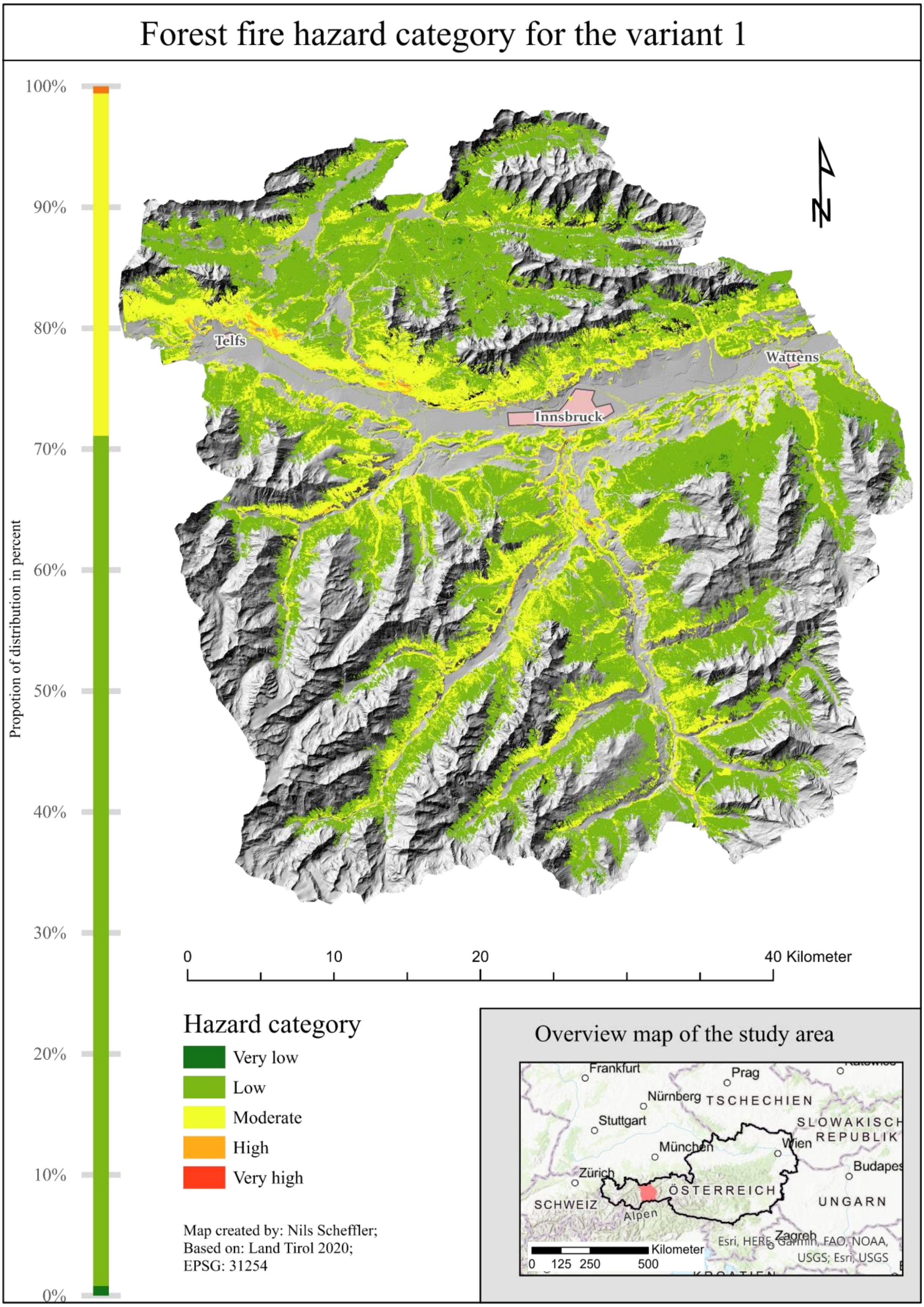

Figure 34: Modeled fire hazard map using the variant 1.

As all the parameters were weighted equally, the extend of calculated fire danger values ranges from 7 to 44. The value 7 is the lowest possible values if all parameters would have the value 1 and do not contain raster cells from the WUI. Vice versa, the highest value of 45 will be achieved if all parameter values are equal to 5. The value range was classified into five hazard categories, each having a range of 8 value points, except the last one with 6. The value ranges and the division into the hazard categories can be seen for all variants in table 8.

Using the variant 1 where all the parameters are weighted equal, a fire hazard map that is dominated by the hazard category “Low” is created. About 70% of the forested area fall into this category. The areas that show the highest values are at south facing, steeper slopes, close to the valley bottom. In particular the areas around Zirl and Telfs show a number of spots where the danger category reaches “Moderate” and “High”. Here the high values are generated from the parameters slope, aspect, and WUI, as well as temperature and precipitation, which have high hazard values in these areas. The danger category of “Very high” is not represented in the model output under variant 1.

Lowest danger values can be found at higher elevation, north facing slopes and large parts of the Seefeld plateau, the Karwendel mountains as well as the Tuxer mountains, due to overall lower parameter hazard values.

Now, to analyse how correct the modelling approach is, a few methods can be applied here. Firstly, the here created output can be compared to already existing maps from previous studies. During this process a pixel for pixel comparison takes place in which the difference can be determined and evaluated. After this follows an iterative process of 1.: Changing the weighting distribution, 2.: Determining the output difference and 3.: Analyse the deviation and a repetition of this process. This can be done until the model produces the expected outcome.

Using these methods brings some challenges along. Primarily there must be a comparative value, or in this case, a comparative fire hazard map, which can be used in the iterative process. This is an important step, because without this relative value, the model can’t be transformed to generate accurate outputs. Also, maps like the daily issued forest fire index maps can’t be used because the nature of the maps are a different one, while the created forest fire hazard map is a static one (static in terms of multiple decades). The forest fire index map is of variable nature as the estimation of forest fire index is calculated from the meteorological variables of air temperature, humidity, wind speed and precipitation amount, which changes daily. In the case of the master’s thesis, no comparative map was at hand to start the iterative transformation process. Therefore, another method had to be used.

The other method that that can be used to adjust the model to create more precise results is the use of already documented forest fires in the study area. Statistically these regions should show the highest danger toward ignition risk and overall fire hazard. These previously documented fires will be used in the same iterative process as the previously described method using an already existing fire hazard map.

Using this method could be challenging in terms of accuracy and availability of the data. The data set of previously documented forest fires might be unsuitable to be used in such a process. It may lack in temporal extend and only covers the last two years or does not provide the sufficient amount of data points, even when the temporal extend is adequate. Also, the spatial error in the documented data points can create incorrect outputs from the model. Lastly, the overall documentation could be lacking, as in only a few selected fires are documented and most are not, creating a false spatial distribution. That links this problem to the first one.

The method of using previously documented fires was applied in this master's thesis. The data that was used was provided by the Institute of Silviculture at the BOKU University of natural Resource of Life Science in Vienna. The data set consists of all the documented forest fires in Tyrol from 1993 to 2022. That is a total of 846 data points, equipped with metadata about the data, the exact location (inaccuracy still applied), the type of fire e.g., Forest Fire, Wildland-Fores Fire etc., the burned area in square meters, and the ignition source e.g., natural, human cause, or unclear.

This data set can be accessed via the webpage: https://fire.boku.ac.at/firedb/de/. The initiative behind the data collection was to gain a better understanding of the Austrian fire regime and to create better measurement strategies against forest fires. In 2008 the Institute of Silviculture at the University of Natural Resources and Life Science in Vienna launched the Austrian forest fire research initiative (AFFRI). One of the goals of the project was to create a fire database which encompasses all historic and current forest fires in Austria. It now has more than 6000 data entries which are accessible via a public GIS-interface. The data set consists of all collected fires from 1993 on, with added information about the date, the time and duration, the location in coordinates, the burned area, the cause of the fire, the affected vegetation, the fire type, the fire behavior, the number of action forces, helicopter and fire brigades involved (Müller et al. 2020a, p. 14).

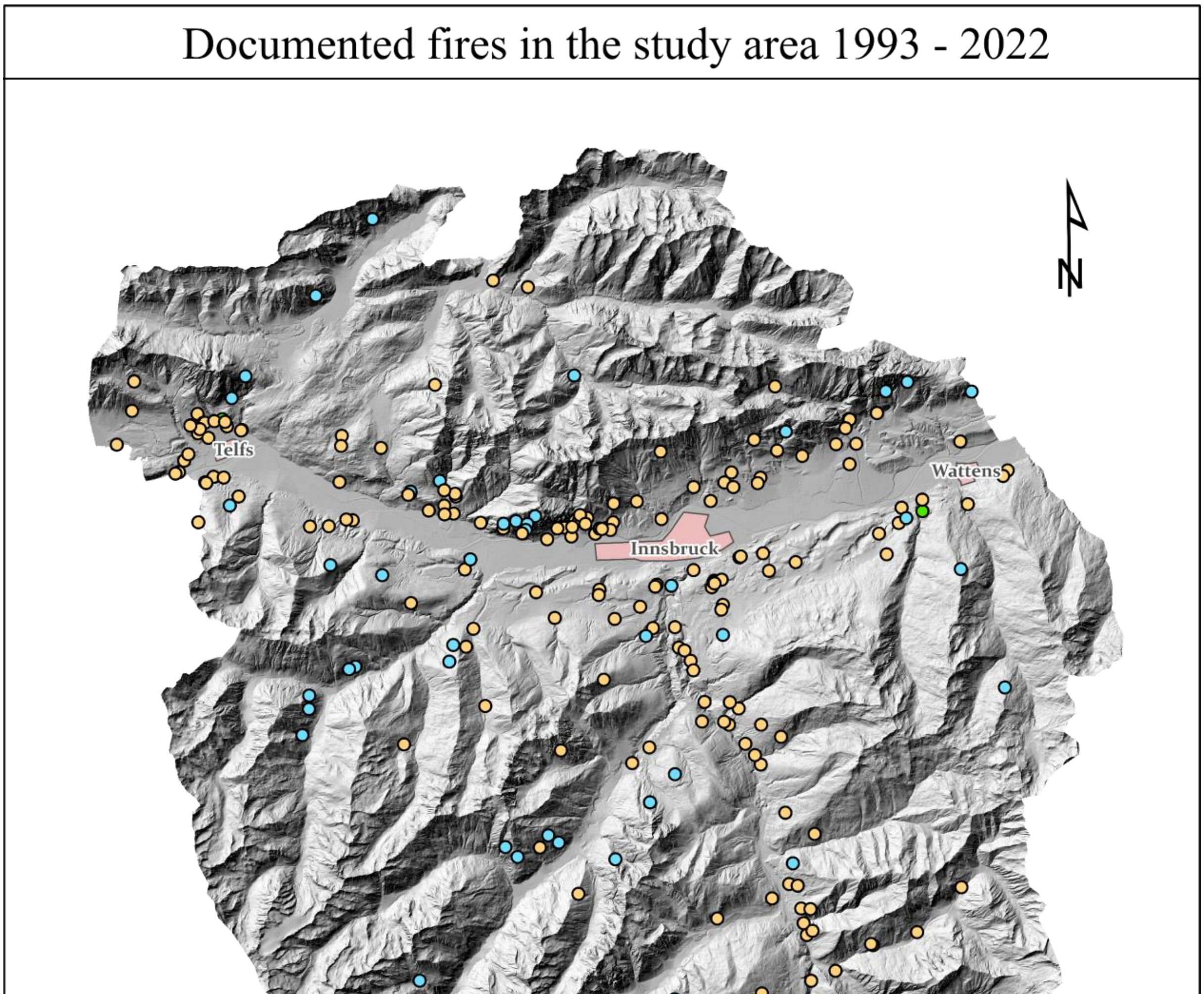

Figure 35: Location of the documented fires dating back to 1993 (based on: Waldbrand-Datenbank Österreich 2023, Institute of Silviculture at the BOKU University of natural Resources of Life Science, Vienna).

With the data now in place, the documented fires points can be used to generate the distribution of fire danger values from the modelled raster of variant 1 in the location of the data points. Below in figure 36 this distribution is shown. Due to the high spatial percentage share of the hazard category "Low" the number of fire points that were appointed was also quite high.

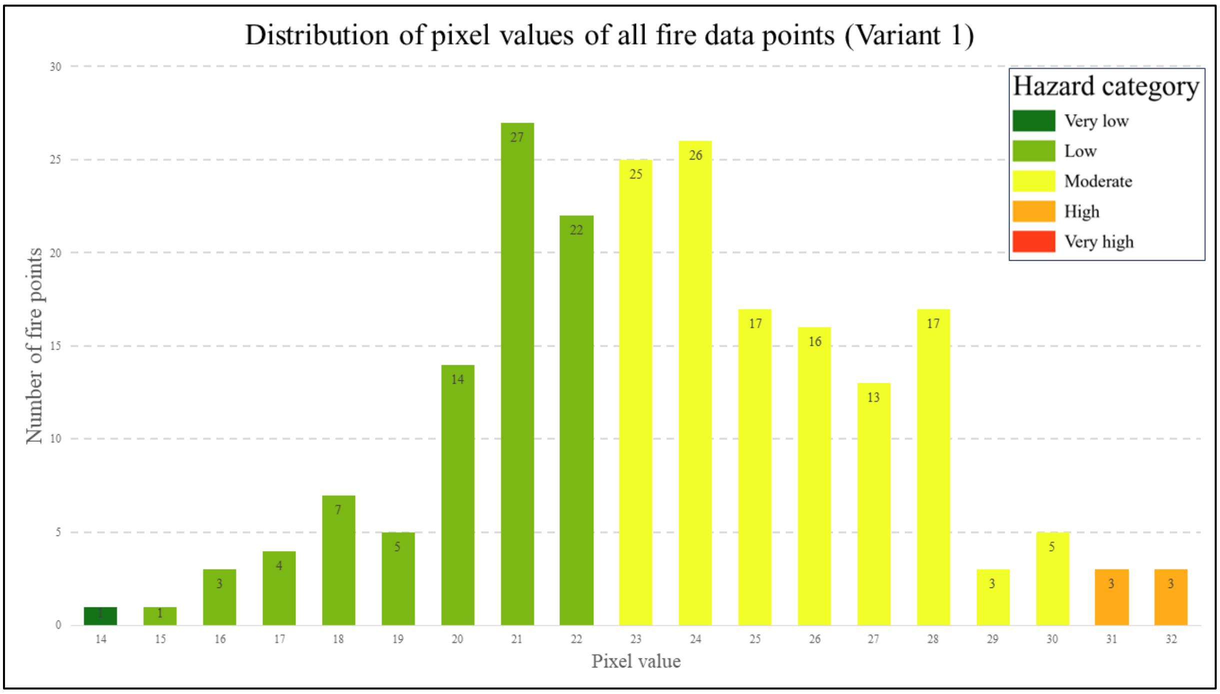

Figure 36: Distribution of pixel values that overlap with the documented fires using variant 1.

The distribution shows, that currently the fire hazard map underestimates the fire hazard as most of the fire points were appointed with "Low" and "Moderate" fire danger. The median in this distribution is 23, which also reinforces the statement that the variant 1 is not a great representation of the spatial fire hazard distribution in the study area.

Fuel hypothesis (Variant 2):

The next model variant is based on the fuel hypothesis. By this hypothesis it is assumed that the fuel conditions of an area will be the determining factor for the creation of fire hazards, and mostly disregards the climatic conditions. Therefore, the weighting of the parameters was changed in order to meet the requirement to this hypothesis. The parameter tree species and the NDVI have a weighting of 3 and 2, respectively, as the NDVI is a only a secondary vegetation parameter, while the rest remains at a standard weighting value of 1. This will create a fire hazard map that is relying mostly on the vegetation parameters. The model output can be seen below in figure 37.

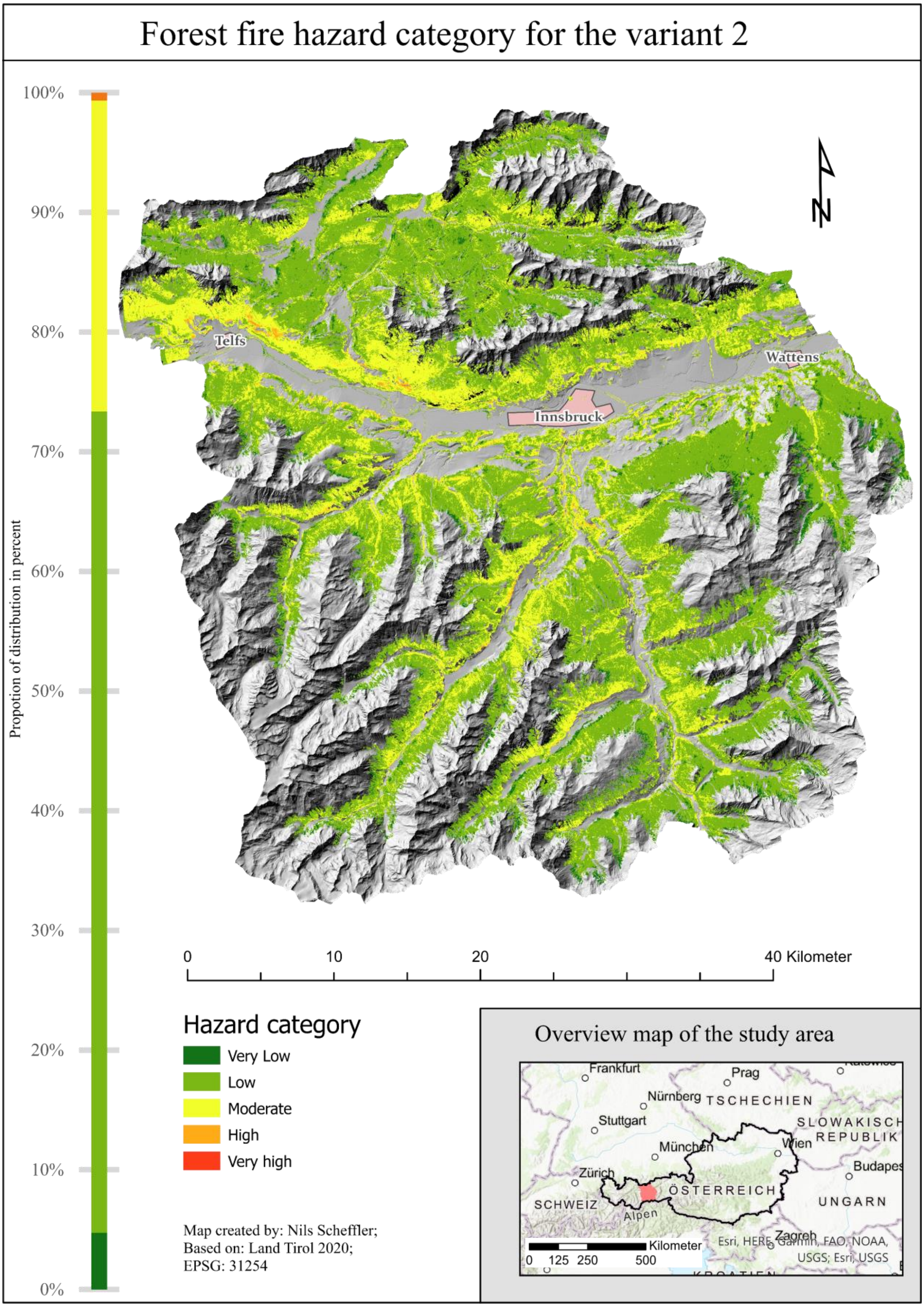

Figure 37: Modeled fire hazard map using the variant 2.

In the model variant 2 the extend of the fire danger values has a different range, compared to variant one, due to a change in weighting distribution. Now they range from 10 to 59 and are classified in to the five hazard categories with a category range of 10 value points.

Similar to the output of variant 1, the hazard category "Low" is spatially very dominant, taking up more than 60% of the forested area. Also similar, though slightly more, is the amount of danger category "Very Low". The amount of category "Moderate" is almost the same, although slightly higher.

As the vegetation is now the primary determent of the fire hazard category, areas with a low NDVI value and coniferous forest types, especially pine forest, will generally have a high overall pixel value. This can be seen on the southern slopes of the Inn valley from Innsbruck to Telfs. Here forested areas that are dominated by pine trees are common.

The lowest values can be found in deciduous forest around the Seefeld plateau and in the Karwendel mountains, as well as at higher altitudes and north facing slopes.

As before, the fire points were used to create a distribution of pixel values from the model output of variant 2 according to the location of the fire points. This can be seen below in figure 38.

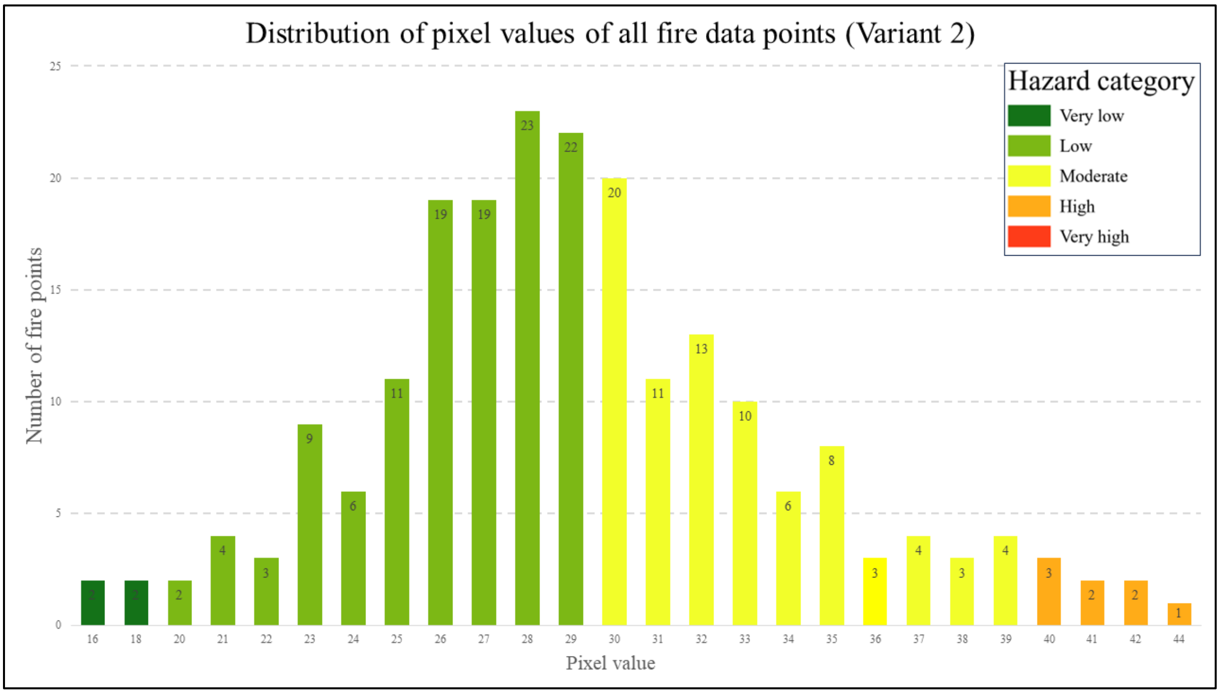

Figure 38: Distribution of pixel values that overlap with the documented fires using variant 2.

The number of values that belong to the category “Low” is still high. The median of this distribution is 29, which is the border between the category “Low” and “Moderate”. Towards the category “High” the distribution shows an overall lower number of fire points, but with an increasing range into the higher categories. The median in this distribution is still in the category “Low” while the median in the distribution from the model output of variant 1 was in the category “Moderate”. That could be an indicator for a lower performance. Overall, the model variant 2 did not exceed the variant 1, and is not a great fit for the determination of hazardous areas in regard to forest fire.

Temperature hypothesis (Variant 3):

The other hypothesis describes the reverse phenomenon, in that the climatic conditions are the most important factors for the occurrence of forest fires and will override any other parameter. To achieve this, the weighting of the parameters was changed again. The parameters Temperature and Precipitation were given a weighting of 3 each. The rest of the parameters remained unchanged with a standard weighting of 1. This will force the hazard map to be sensitive to the climatic conditions. The output of this model variant can be seen below in figure 39.

In the model variant 3 the extend of the fire danger values has a different range, compared to the previous two variants, again due to a change in weighting distribution. Now they range from 11 to 64 and are classified in to the five hazard categories with a category range of 11 value points, except for the last one with 10.

Using this weighting method, the result is dominated by the category “Moderate”, covering more than 60% of the area. The category “Very Low” is non-existing and “Low” has lost much of the spatial percentage share compared to the previous two variants. For the first time, the category “High” represents a visible portion of the area. Being more dominant than before with an advancing amount of over 10%.

As the climatic conditions are the main driver of the hazard category in this variant, the highest danger values can be found in areas with low annual precipitation and high overall temperature values. These are the Inn valley in the centre and the Stubai-Alps towards the South-West of the study area. Similar to the previous results, the lowest categories can be found in the northern and eastern parts of the map, e.g., the Seefeld plateau and Karwendel mountains, where annual mean temperature is lower, and precipitation sum higher.

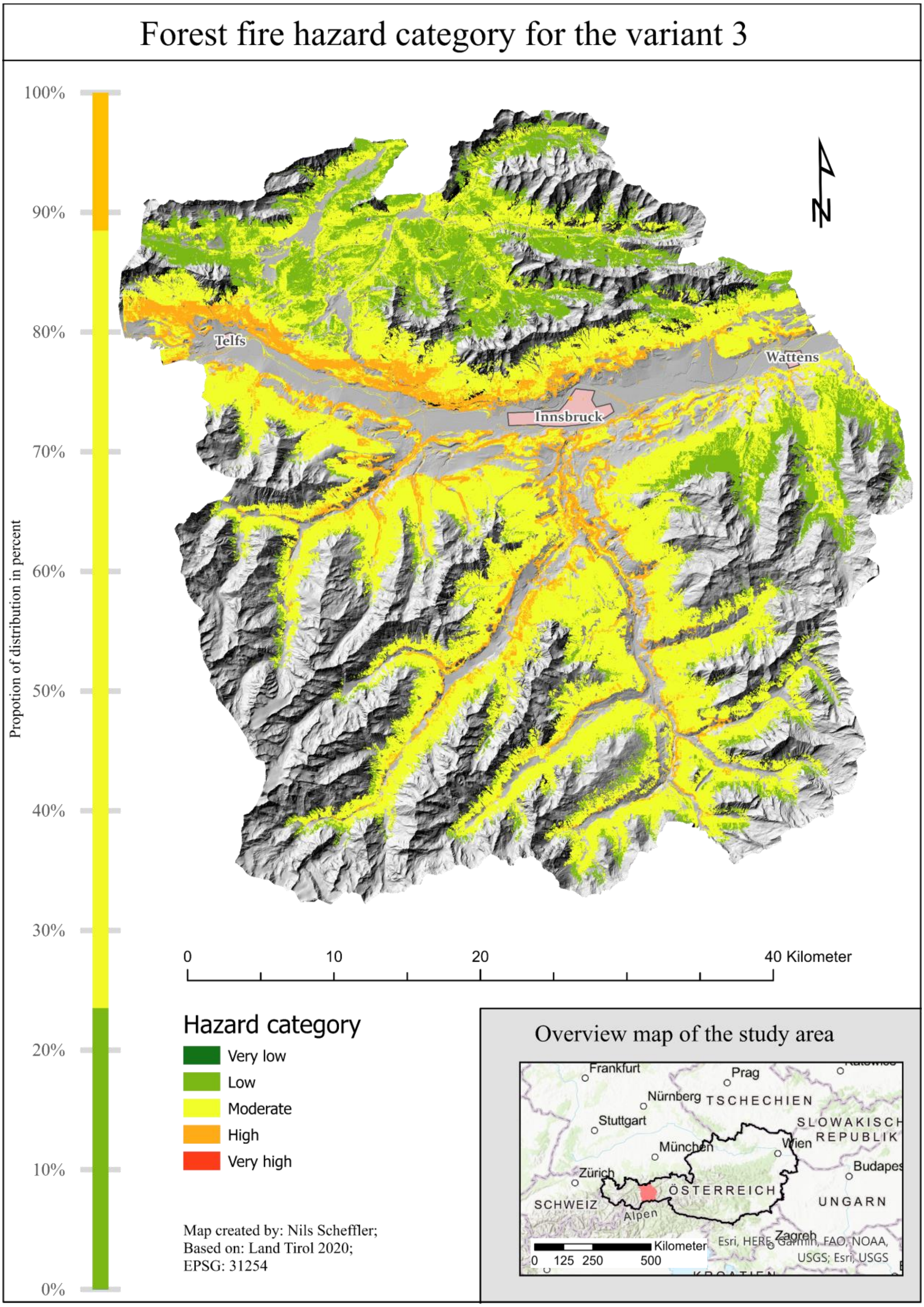

Figure 39: Modelled fire hazard map using the variant 3.

Same as before, the fire points were used to create a distribution of pixel values from the model output of variant 3 according to the location of the fire points. This can be seen below in figure 40.

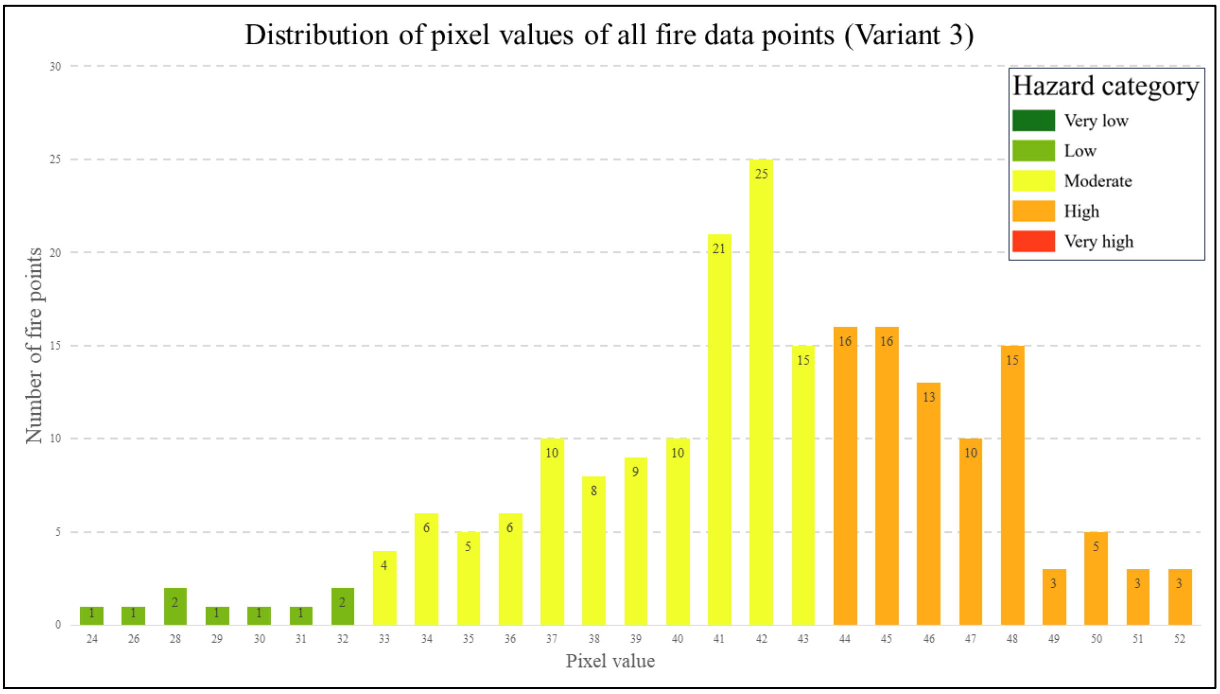

Figure 40: Distribution of pixel values that overlap with the documented fires using variant 3.

With the switch of the dominant category "Low" to "Moderate" using the model variant 3, the distribution of pixel values for the fire points has also changed substantially. Now there is a clear tendency toward higher categories. While "Low" is still present in the distribution, the amount of points that are in category "High" is far greater than before. The median here is by 42, which is at the upper value range of category "Moderate". This is a much better result compared to the previous ones.

From here on out the modelling approach could split into two ways. The first one would be to repeatably randomize the weighting distribution until a desired result emerges, and the second one would be to define parameters, that would result in sought after a distribution of pixel values for the fire points.

Fire point method (Variant 4):

For this master thesis, the latter was used. The goal is to differentiate between the different influences on documented fires. This might lead to a better understanding of the important parameters leading to fire prone areas. To approach this, the first step was the differentiation between the fire hazard parameters in terms of how much they affect the danger category in areas where the fire points are. To generate this data, the fire points were used to determine the corresponding danger category for each hazard parameter. The resulting distribution is shown below in figure 41.

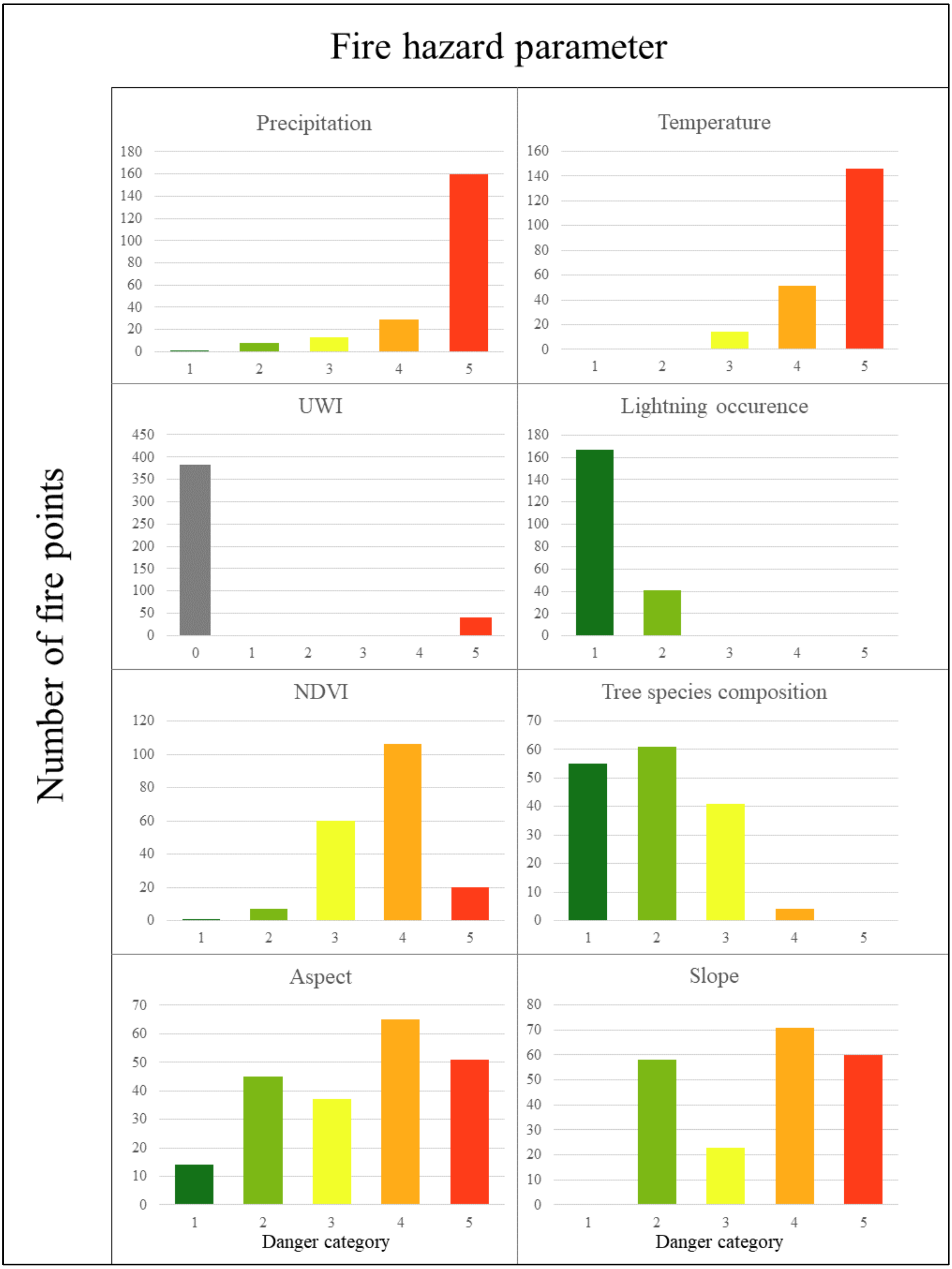

Figure 41: Distribution of danger categories for each fire hazard category.

Figure 41 represents the distribution of the number of fire points that fall into the different danger categories for each fire hazard parameter. Now, a clear distinction between the parameters can be made. For example, most fire points are in areas that show the highest danger category, when looking at the precipitation and temperature parameters. Quite the opposite can be said for the parameters tree species and lightning occurrence. Here most of the fire points are in areas that are of far lower danger categories. The WUI shows a high number of points with the value 0. This is because outside of the WUI, the raster file has the danger category 0. Also, the shown distribution for the WUI entails both the parameters related to the WUI.

Using this distribution, the parameters can be weighted in terms of their influence in the areas of the fire points. Therefore, the new weighting was chosen as follows: Precipitation and Temperature received a weighting of 3. Slope, Aspect, Tree species composition and NDVI were given a weighting of 2. The rest received a standard weighting of 1.

The weighting distribution resulted in the modelled fire hazard map, shown in figure 42 below. In the model variant 4 the extend of the fire danger values has again a different range, compared to the previous variants, due to a change in weighting distribution. Now they range from 15 to 85 and are classified into the five hazard categories with a category range of 14 value points, except for the last one with 15.

The output shows a clear dominance of the hazard category "Moderate". This is similar to the output of variant 3. The proportion of the category "High" is at 15% slightly higher than the previous variant and the proportion of category "Low" with also 15% slightly lower.

The similarities between the variants 3 and 4 result most likely from the prioritizing of the climatic conditions. In both models they received a weighting of 3. As before, the highest values can be found in the Inn valley between Innsbruck and Telfs. It's a warm and dry region, with the south facing, steep slopes having a high proportion of pine trees. This combination usually results in highest values, regardless of the weighting method.

Slightly higher is the proportion of the category "Moderate" in the area of the Seefeld plateau. As the tree species distribution and NDVI had a lower weighting in the previous variant 3, they play a more significant role in this variant 4. This led to a higher danger category in areas, that were previously classified as "Low".

As with the other tree variants, the fire points were used to create a distribution, which is used to quantify the model output. The distribution that resulted can be seen below in figure 42.

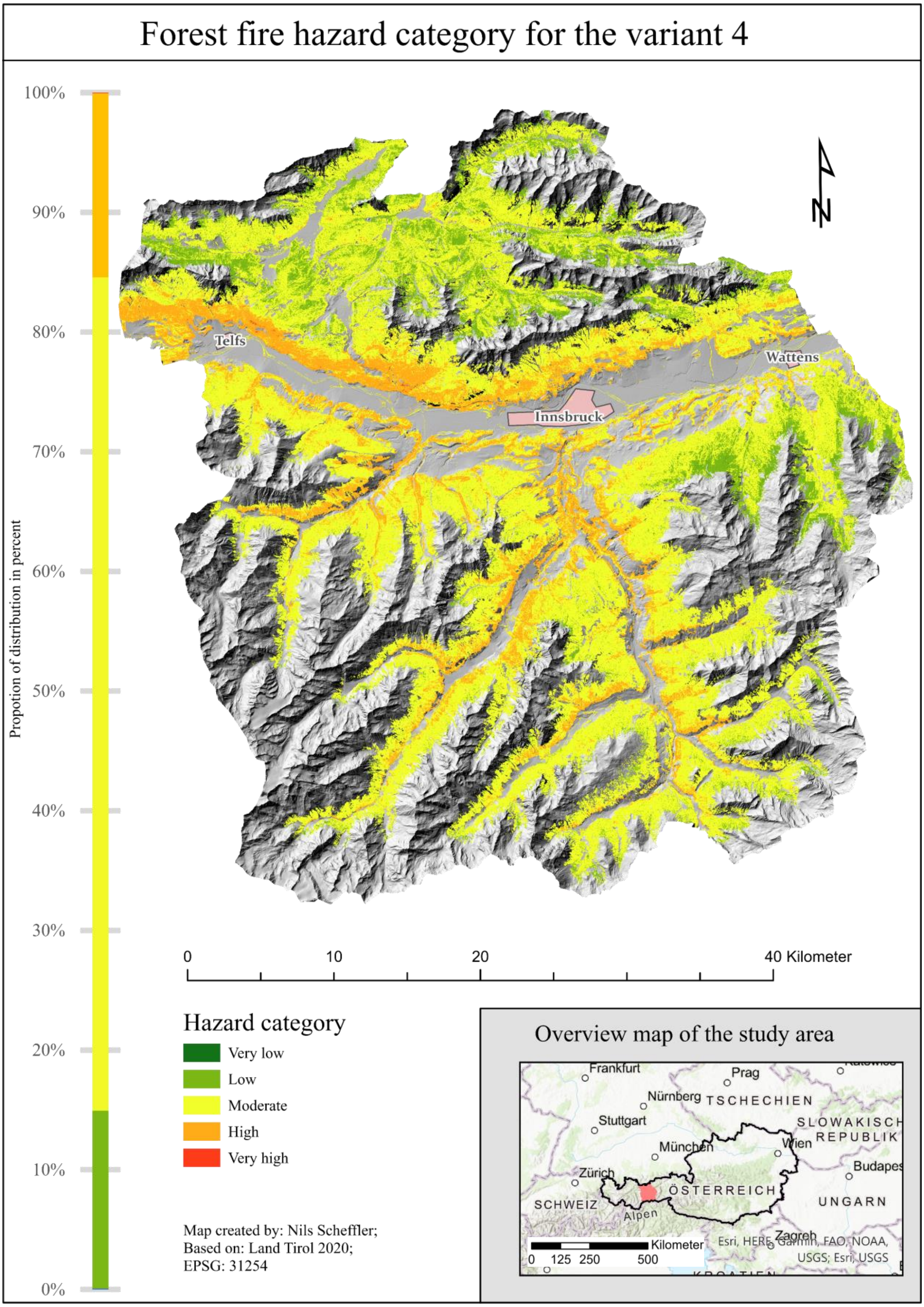

Figure 42: Modelled fire hazard map using the variant 4.

Here a clear distribution curve can be seen, which peaks at the upper values of the category "Moderate". The incline is much steeper coming from the lower values and the highest values almost reach the category "Very high". The median of the distribution is 55, which sits in the upper value range of the category "Moderate". The higher number of values that are in the category "High" (compared to the distribution from variant 3) are not surprising, as the overall spatial percentage share is higher in variant 4 than in variant 3.

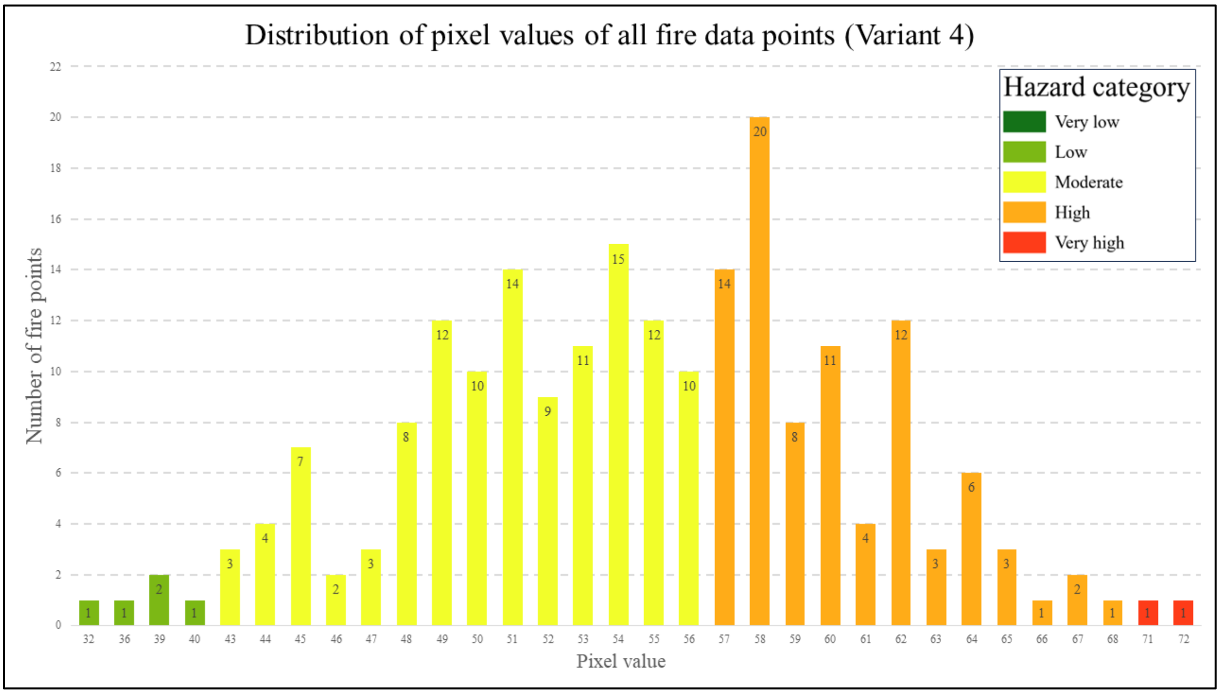

Figure 43: Distribution of pixel values that overlap with the documented fires using variant 4.

The results of this model output were also verified in the field. The verification using the fire points will only allow for random checks at a single pixel. Fieldwork allows for area-wide control of the modelled outputs. First was the selection of areas of interest. Here areas that stand out either with high or low danger categories were selected. These areas could then be inspected following the question: *Is the fire hazard category, that has been modelled in the area, plausible*?

Below in figure 44 and 45, two of the selected areas are shown. Figure 44 show the selected areas near Telfs, which has been modelled to be of a high danger category. In all variant output, this area always has the highest values in all of the study area.

The area has received such a high danger class because of unfavourable fire hazard conditions. Predominantly the warm and dry climate in the area, the steep, and southern facing slopes, pine tree as dominant forest type, and the close proximity to human infrastructure, all these parameters produce a high value model output.

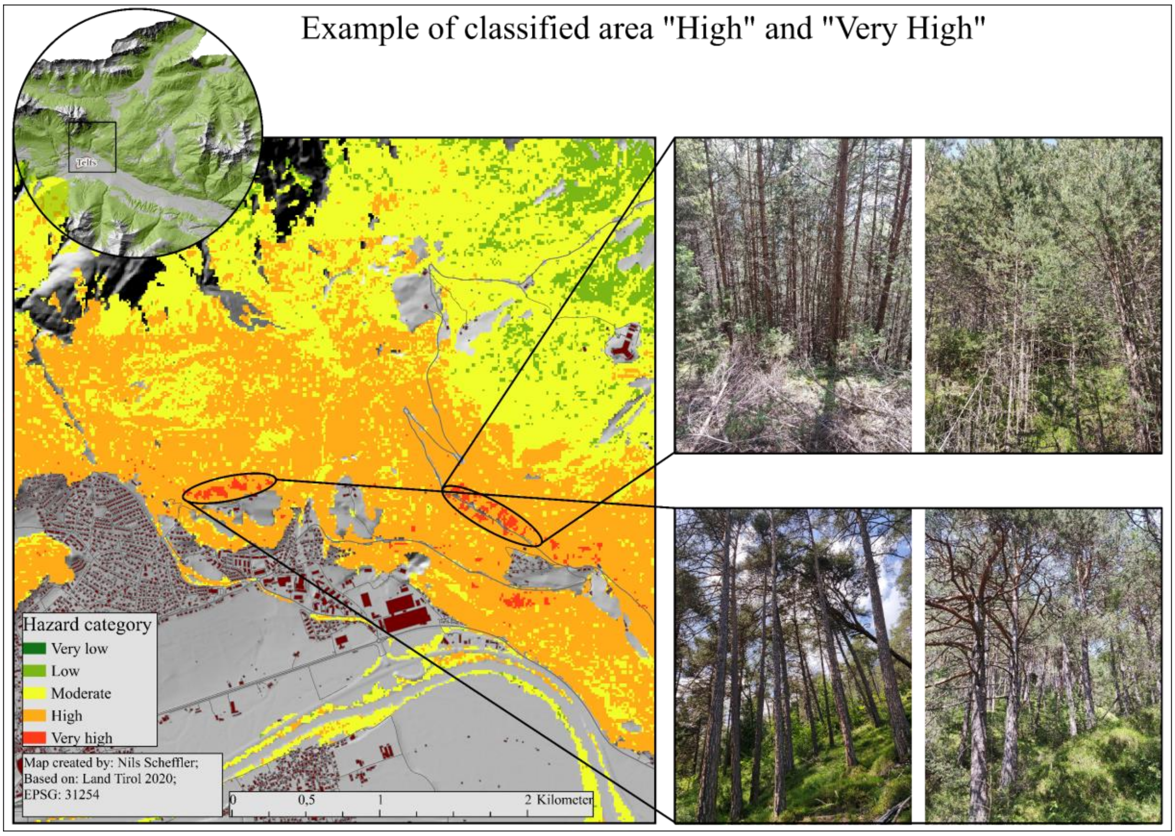

Figure 44: Exemplary area representing a modelling result of the category "High" and "Very high".

During the inspection of the areas that are shown in figure 44 above, the data that was used to produce the output has proven right. The area is dominated by pine forest on steep, southern slopes. Deadwood as fuel is abundant and very dry in both areas. The eastern area in figure 44 consists of a very young and close forest stand. This is highly favourable for fast fire spread conditions. Both areas are very close to human infrastructure and are crossed by hiking trails. Although hiking trails are not included in the modelling, they could very well be an ignition source and would only amplify the already high fire danger.

Figure 45 below shows the selected area near Leutasch, which indicates a low fire hazard. Similar to the presented area before, here, all model variants produce a low fire hazard as an output for this region. It's the wetter and colder climate (relative to the Inn valley), the shallow and northern facing slope, and the mixed deciduous-coniferous forest type which creates suitable conditions for a low fire hazard category.

On arrival in the area, a clear change of forest type was noticeable. The mixed forest on the shallow slope has a much different structure, with far less deadwood, and the ground conditions were perceived s much more wet. During inspection of the area, the output of the model was seen as fairly plausible, as further up-slope (the hazard category is "Moderate") is of clear differentiation compared to the area below.

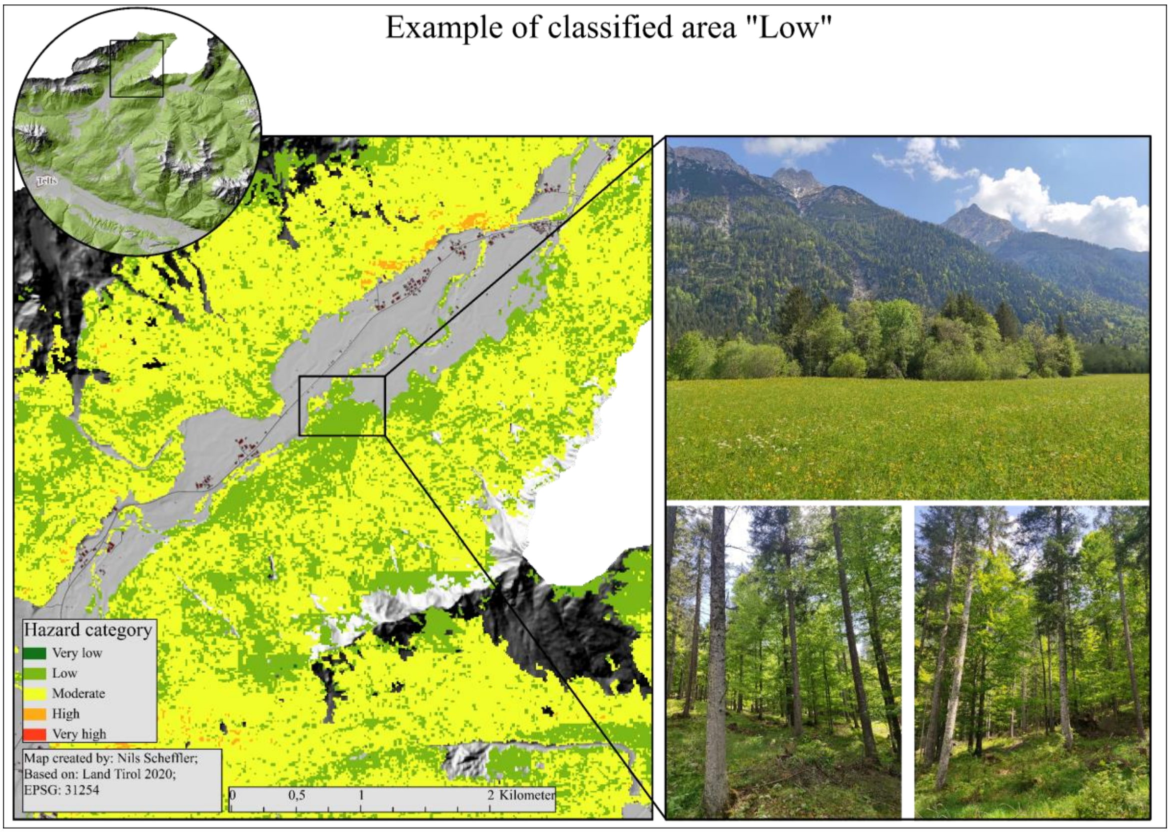

Figure 45: Exemplary area representing a modelling result of the category "Low".

During the inspection of the areas, a slight incongruity was noted. As there are only five hazard categories, the always include a number of modelled values and these are then standardized into one category. Although some pixels in the category "Moderate" are closer to the category "Low" than to "High" and others are the other way around, they will appear as the same hazard category. This could lead to false assumptions as the forested areas are so inhomogeneous and changes appear rapidly, which argues for a more differentiated hazard classification.

To approach this problem, the model output of variant 4 was given an adjusted classification, now with 13 categories. The idea behind this is the subdivision of the currently used five categories into sections which are close to the lower and higher neighbouring category. For example, the category "Moderate" was subdivided into "Moderate –", "Moderate" and "Moderate +".

The result of this reclassification can be seen in below in figure 46, which shows the adapted variant 4 as variant 4.1. The overall pixel values that result in the classification have not changed. It is just a modification of the hazard category number and size, which lead to a different look of the model output.

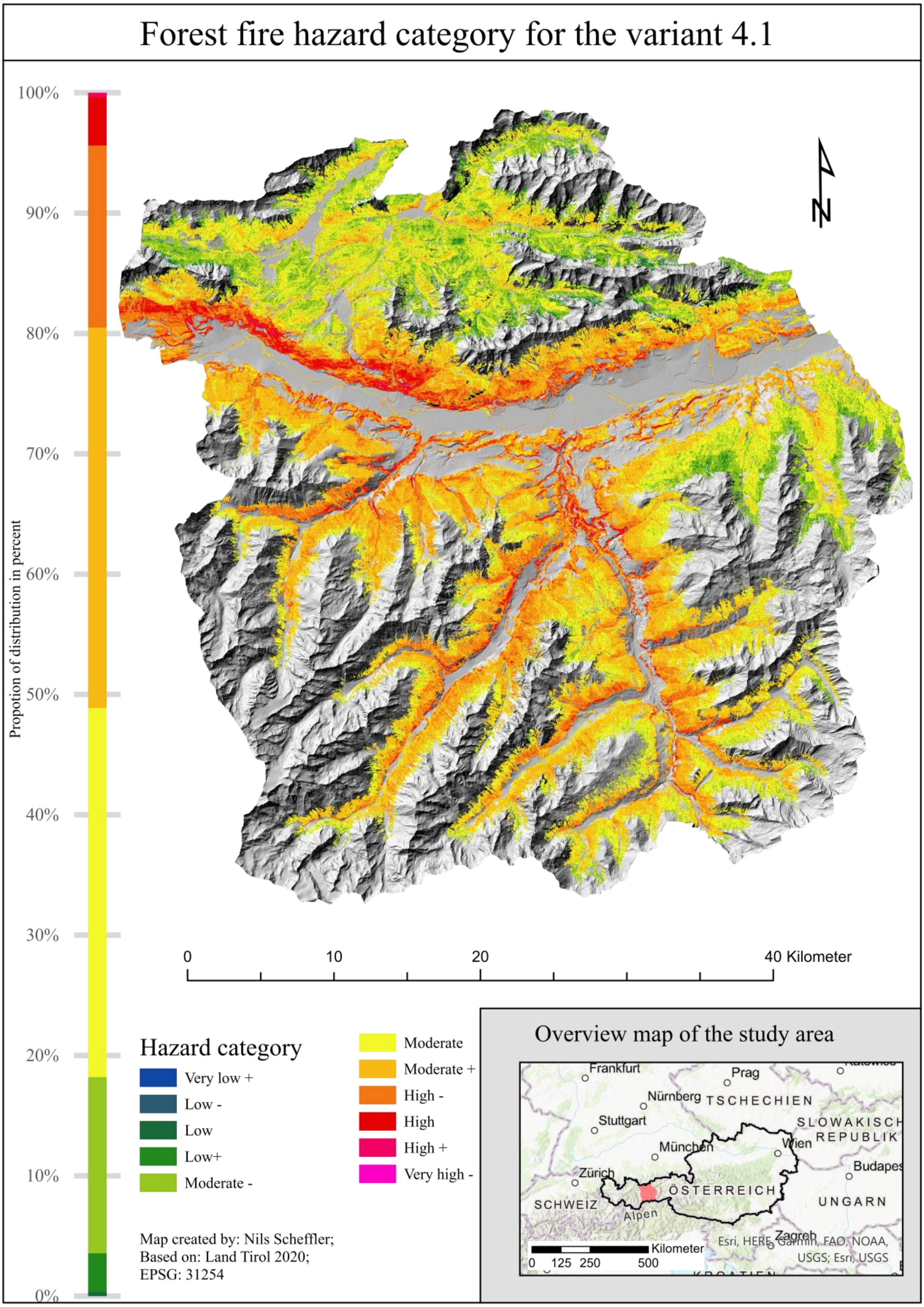

Figure 46: Modelled fire hazard map using the variant 4.1.

A clear distinction to the previous variant 4 is visible, as the differentiation between the classes is far clearer and more fine-tuned. Because the pixel values have not changed since variant 4, the areas with highest and lowest values stay the same. Larger areas that have been in the same category are now distinctly separated into subdivisions of that category.

Below in figure 47, the distribution of pixel values is shown. The distribution is the same as the one from variant 4. Just the classification is different in the one below.

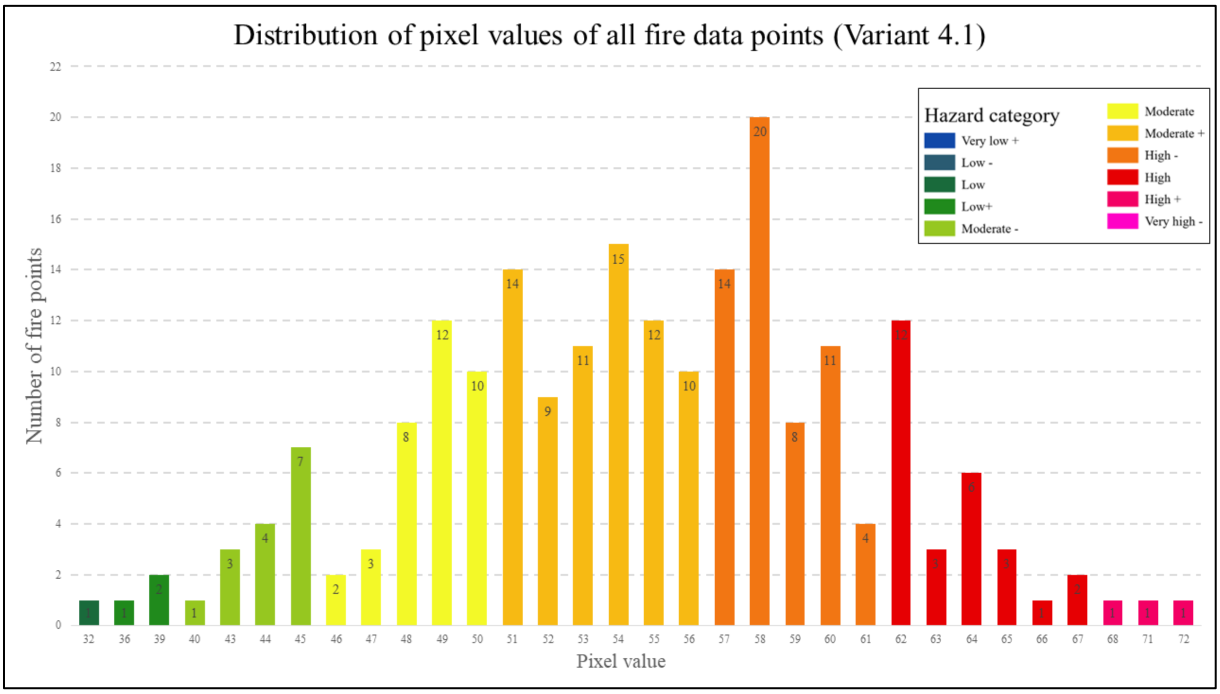

Figure 47: Distribution of pixel values that overlap with the documented fires using variant 4.1.

The differentiation can also be seen in figure 48. Here an excerpt of the hazard map for the two variants 4 and 4.1 is shown. It displays the distinct difference in the spatial hazard category distribution and the information regarding the fire hazard in the area around the Patscherkopfel.

Map B, as shown below in figure 48, is dominated by the hazard category "Moderate". It shows the same category for all aspects and for most of the altitudinal range. Map A on the other hand shows a clear distinction between aspects, altitudinal range, and the distance to human infrastructure. The small-scale subdivision is very noticeable, and areas with higher and lower danger categories can be recognized much more easily.

As the used data was originally in different resolution, the remains can still be seen as artefacts in the hazard maps. Even though the resolution was resampled to be 10 by 10 meters, sharp borders between hazard categories remain in the final output. These are much more noticeable in map A than map B, due to the fine-scale subdivision.

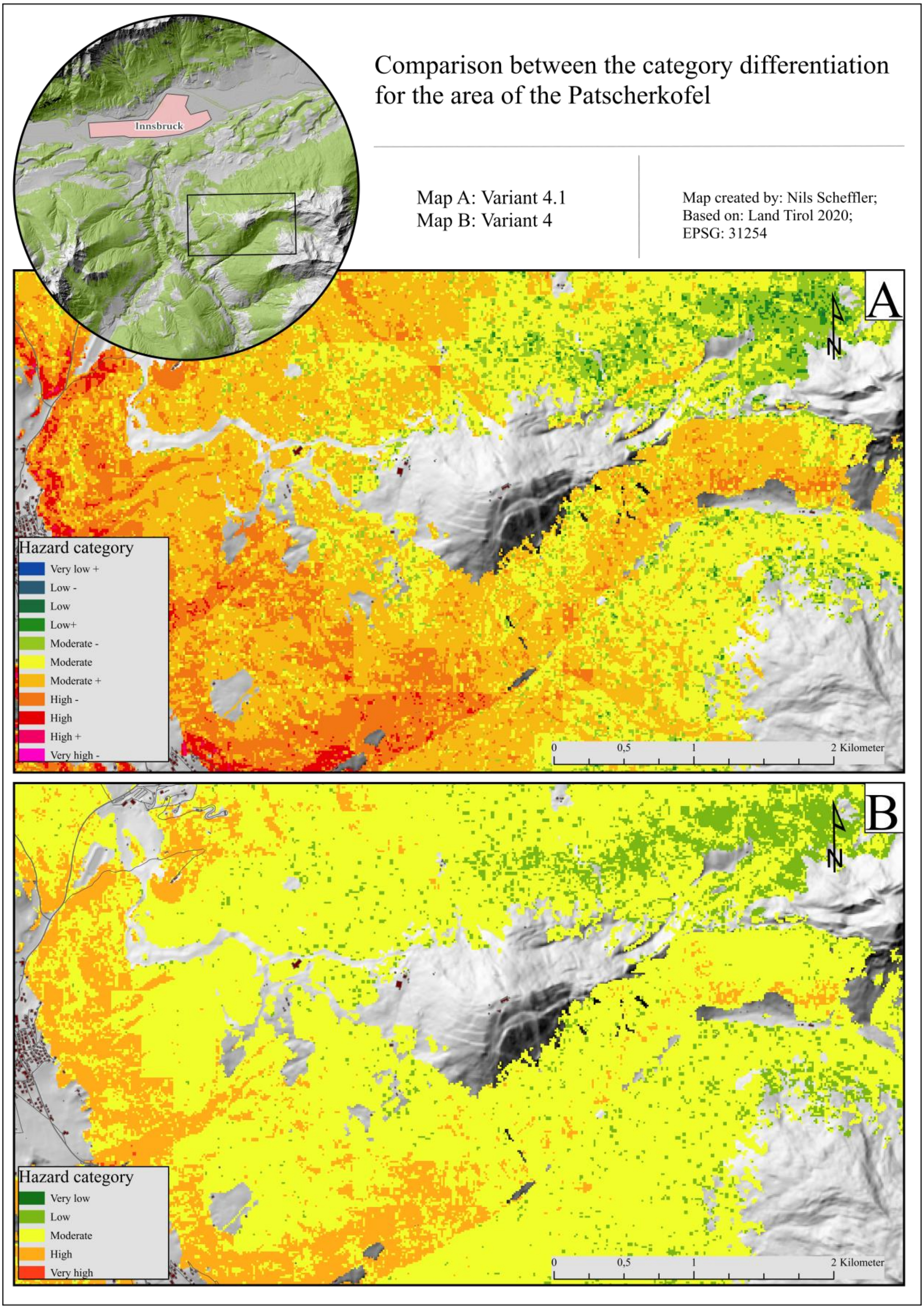

Figure 48: Comparison between the category differentiation for the area of the Patscherkofel.

Table 8: Value range and the subdivision of that into the hazard categories for each of the variants (Var.).

	Value range	Very Low	Low	Moderate	High	Very High
Var. 1	7 – 45	7 – 14	15 – 22	23 – 30	31 – 38	39 – 45
Var. 2	10 – 60	10 – 19	20 – 29	30 – 39	40 – 49	50 – 60
Var. 3	11 – 65	11 – 21	22 – 32	33 – 43	44 – 54	55 – 65
Var. 4	15 – 85	15 – 28	29 – 42	43 – 56	57 – 70	71 – 85

	Very Low	Very Low +	Low –	Low	Low +	Moderate –	Moderate	Moderate +	High –	High	High +	Very high –	Very High
Var. 4.1	15–17	18–23	24–28	29–34	35–39	40–45	46–50	51–56	57–61	62–67	68–72	73–78	79-85

9.3.6 Discussion of the modelling results

The here presented maps show the static fire hazard in the area of Innsbruck-Land and Innsbruck-Stadt. They were modelled using geodata from different sources using the GIS software ArcGIS Pro. A weighting system was applied to generate different outputs even though these maps are all based on the same fire hazard parameters. These differences may imply that not all parameters, that influence the occurrence of forest fires, have the same effect on it.

Using an equal weighting for all parameters resulted in a hazard map that was dominated by a low hazard category, only in areas where all the hazard parameters have a high danger value, the danger category would be modelled higher. Although not perfectly accurate, this variant gave a rough idea, where the highest values might be modelled using the other variants.

The second variant was to test the fuel hypothesis. This hypothesis is based on the idea, that only the local fuel conditions will affect the fire occurrence, disregarding other influences such as climate. The weighting was dominated by the vegetation parameters of tree species composition and the NDVI. It resulted in a quiet similar map compared to variant 1, which was surprising considering the weighting of 3 and 2 respectively.

The third variant tested the temperature hypothesis, which is similar to the fuel hypothesis, in that it is based on the thought, that fire occurrence is dependent predominantly on climatic conditions. As before the two parameters temperature and precipitation were given a weighting of 3 each and the rest stayed at a weighting of 1. Using this weighting approach created a much different output than the two previous ones. The area was now dominated by the category “Moderate” and showed a clear spatial distinction in regions with different climatic conditions. This was also supported by the use of the fire points to create a distribution of pixel values which are located at these fire points. The distribution showed a clear siding to the higher hazard categories, which the two previous approaches did not accomplish.

For the last model attempt, the mentioned fire points were used to determine which parameters are most important and have the highest effect on a high danger value in these areas, which have been fire effected previously. The analysis showed a clear support of the temperature hypothesis, as the temperature and the precipitation both were parameters in which the fire points were dominantly situated in high and very high hazard categories. With this information on hand, a new weighting system could be used for the model variant 4. Here the parameters of temperature and precipitation both received a weighting of 3. Slope, aspect, NDVI and the tree species composition a weighting of 2, and the rest of the parameters the weighting of 1.

The output of this approach was similar to the variant 3, probably because of the same weighting of climatic conditions. Although being similar, it was more dominated by the category “Moderate” and had a higher percentage of areas with category “High” and “Very high”. As before the distinction between climatic different regions is visible, although now that other important parameters play a more important role, the result is more distinct.

Looking at the distribution, the majority of values lies in the range of the higher categories. Comparing the distribution solely on the median, the output of the variant 4 is not necessarily better, than the one from variant 3. But the range into higher values is much greater in variant 4. Even some fire points were located in category “Very high”. This could be taken as an improvement, when comparing the model outputs based on previous documented fires. Therefore, this variant was used in the creation of the forest fire risk map, which follows in the next chapters.

As mentioned before, the hazard categories were subdivided for variant 4.1. This step was taken due to the heterogenous vegetation and landscape environment. Changes in those appear rather fast and to cramp very different fire prone environments into the same hazard category, because the value range is so large, could create issues when direct action is supposed to be taken to prevent forest fires. Therefore, the categories were subdivided into ones with a smaller value range. The resulting map and the comparison proved, that this step can help to gain a better understanding and assessment of the environment regarding forest fires.

Model limitations:

The here presented model outputs are certainly not without flaw as uncertainties in the data accuracy, the modelling approach, and the category fitting will always remain. The biggest problem to this hazard map approach is the accurate comparison of different outputs to a true base. This true base would be something which can help to adjust different model parameters to create an approximately accurate representation of the current fire hazard situation.

The true base that was used here were previously documented fires in the study area. Multiple problems were noticed using this. The first one is the overall data accuracy. The data that was provided ranges from the years 1993 to 2022, although the early years lack accurate representation. Therefore, data might be missing and could not be used for the pixel value distribution in the later steps. Also, the data comes in points shapes with approximate locations. This fact brings along more difficulties. First of all, the location accuracy might be off by multiple tens of meters. This implies, an inexact distribution of the pixel values, due to the fact, that the actual location of the fire could be a different and therefore the pixel value would change. The second problem is the size of the documented fire. Most of the fires had the data on the burned area. This could be used to create a mean pixel value for each fire. However, the shape of the fire could also be important in this case. As seen in variant 4.1, the pixel values are spatially very inhomogeneous and a false representation of the shape of the burned area could again bring inaccuracy into the distribution of the pixel values.

Using this true base means manipulating the weighting until all the fire points would be situated in areas of “High” or “Very high” hazard categories. Again, this approach is flawed. If the goal is to create a higher fire hazard value in the areas where fires have been documented, it might lead to the over-estimation of the actual fire hazard. To explain this using an example, the weighting of the climatic conditions could be increased until most of the fire points are in high hazard categories. Such a scenario was examined, and the resulting distribution graph is shown below in figure 49.

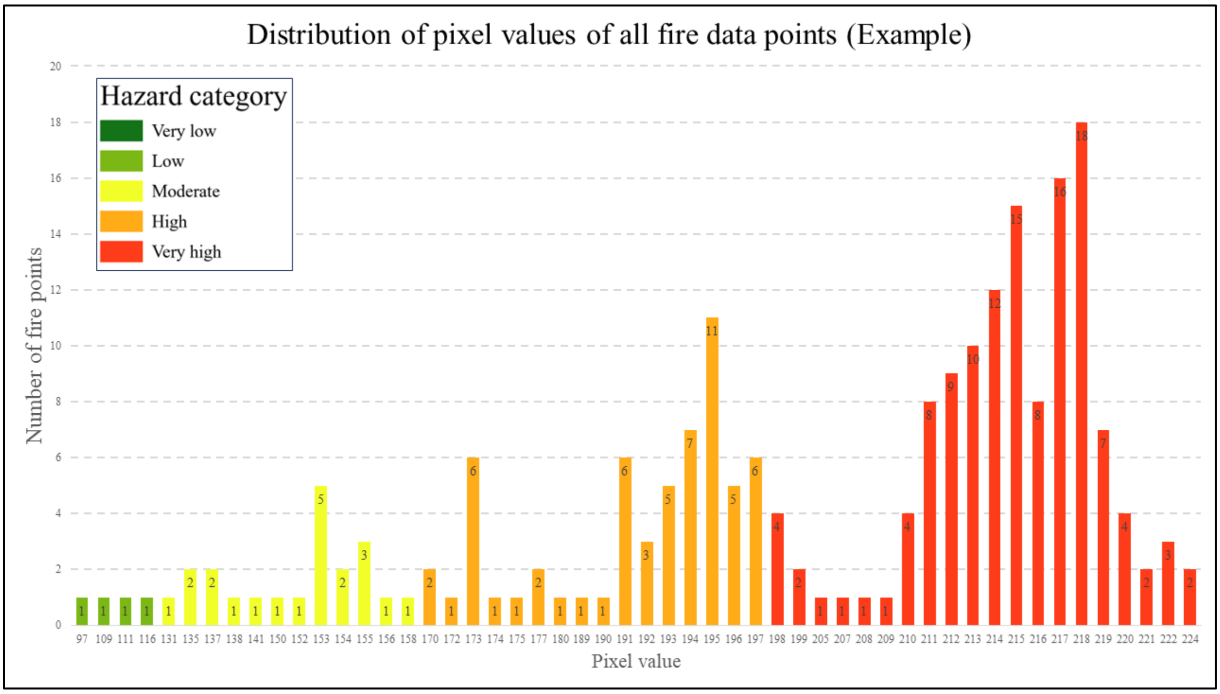

Figure 49: Distribution of pixel values that overlap with the documented fires using the exaggerated climate example.

Here a clear distribution into the higher hazard categories is noticeable. The values have never been so high compared to the other variants. This is also supported by the median at 211, which sits in the category “Very high”. Now, only looking at the distribution and the median, this would imply, that the here presented model will predict the fire hazard with a high accuracy, surrounding most documented fires with fairly high hazard categories.

Looking at the reason behind this distribution is clear. More than 50 % of the area is categorized as “High” and “Very high”. The difference to the other variants is very prominent. Especially the lack of the hazard categories “Very low” and “Low” shows, that the strong weighting of climatic conditions leads to an overestimation of the fire hazard situation.

In trying to change the distribution into the desired outcome, the overall output of the model has worsened. The distribution itself can’t be seen as accurate, because it was achieved by just creating more area of higher hazard categories. This will eventually lead to more fire points being represented by a higher hazard category. It might seem correct at first, but the rest of the area, which now is categorized as a high fire hazard area, might not be so and is falsely categorized. For this example, the model was weighted heavily towards the climatic conditions. The parameters Temperature and precipitation reviewed a weighting of 20, while the rest of the parameters stayed at the base weighting of 1. The model output can be seen below in figure 50.

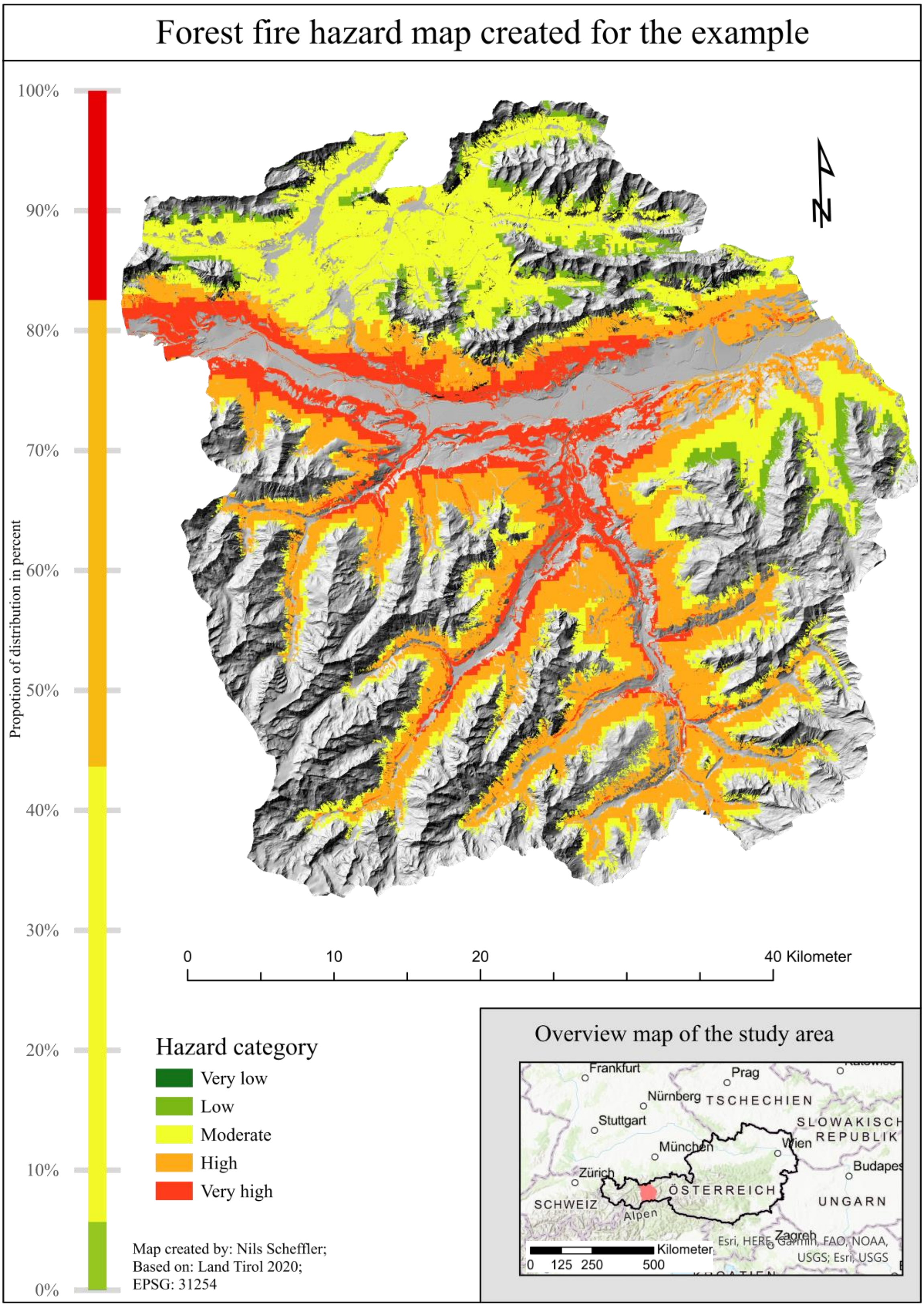

Figure 50: Modelled hazard map using the exaggerated climate example.

This flawed validation method has been noted in a previous study regarding fire hazard mapping. In that study, the model output was verified using previously documented fires. The result came back showing a good outcome, as all of the fire points could be appointed to areas with medium and high modelled fire danger level. This sound good but is not surprising, as more than 95% of the area was categorized as medium and high danger level. The location of the documented forest fires in these areas is almost certain if 95% of the area is dominated by them. This begs the question of how good the validation method is. Using this form of a true base, the validation should have another goal. Currently the model that creates the distribution with the highest mean pixel values is seen as the best. Although, as just demonstrated, this is often not the case. The goal should be the appropriate balance between how much area is covered by higher hazard categories and the median of the distribution of the pixel values using which represent the location of the fire points.

Regardless of al the uncertainties, that currently exist, the geospatial technology, such as remote sensing and geographic information systems (GIS), presents itself with the necessary information and tools to construct a comprehensive forest fire hazard map. This map serves as a valuable resource for identifying, classifying, and mapping areas that are prone to fire hazards. By applying the ability of geospatial technology, the risks associated with forest fires can be effectively managed and mitigated, ensuring the safety of both human population and natural ecosystems (Pradhan et al. 2007, p.345).

9.4 Fire risk map

The previously presented map showed the static fire hazard conditions in the forested areas located in the study area. A fire risk map would need to include a vulnerability parameter in combination with the hazard. Former studies have mentioned the importance of fire risk maps, as a fire hazard map might not be sufficient to make important decisions regarding the protection of human lives, infrastructure, and the environment.

The later presented fire risk map will include the hazard map from variant 4 and a vulnerability map, consisting of the forest function, which is shown below in figure 54. The object, which represents the vulnerability, can be chosen to fit the purpose of the question. For example, human infrastructure can be used as the vulnerability factor to create risk maps regarding natural gravitational hazards such as avalanches.

As only forested areas were included in the hazard map, the use of human infrastructure would be nonsensical, as the two maps (hazard and vulnerability) would not overlay to create a risk map. Therefore, the forest function was used to display the vulnerability aspect. This has to been seen not in terms of how vulnerable a certain forest function is, but more the question of how vulnerable the loss of this forest would make the surrounding area to hazards which might result after an event that clears a forested area. The mountain forest in the Alps have numerous functions, including an economical one and a protective one. Looking at the vulnerability aspect of these forest, the loss of forest that serve a protective function would be more detrimental, than the loss of a commercially used one.

As the fire hazard map was already created, only the data of forest function needed to be gathered and applied to the map. The data on forest function is freely available on the webpage of the open government data – Tirol/tiris using the url: https://data-tiris.opendata.arcgis.com/datasets/waldkategorien/explore.

The forested area in this data set is divided into five categories of function, from protective forest to commercial forest. The categories can be seen below in table 9. This classification resulted in the map seen in figure 53 below. Here about 70% of the forested area serve at least some protective function and are a highly valuable asset. The rest of the forests are strictly commercial forest having a far less protective function to human settlement and infrastructure. This leads to the following classification of the forest functions, which can be seen in table 9 below.

Table 9: Display of forest function with the according vulnerability score.

Forest function		Vulnerability
1	Protective forest out of yield	3
2	Protective forest out of yield - Krummholz	3
3	Protective forest in yield	3
4	Commercial forest	1
5	Commercial forest – moderate protective function	2

Here, forests that serve mainly a protective function have been classified with a higher vulnerability potential. The lowest classification was given to the commercially used forest areas. This resulted in the map seen in figure 54 below.

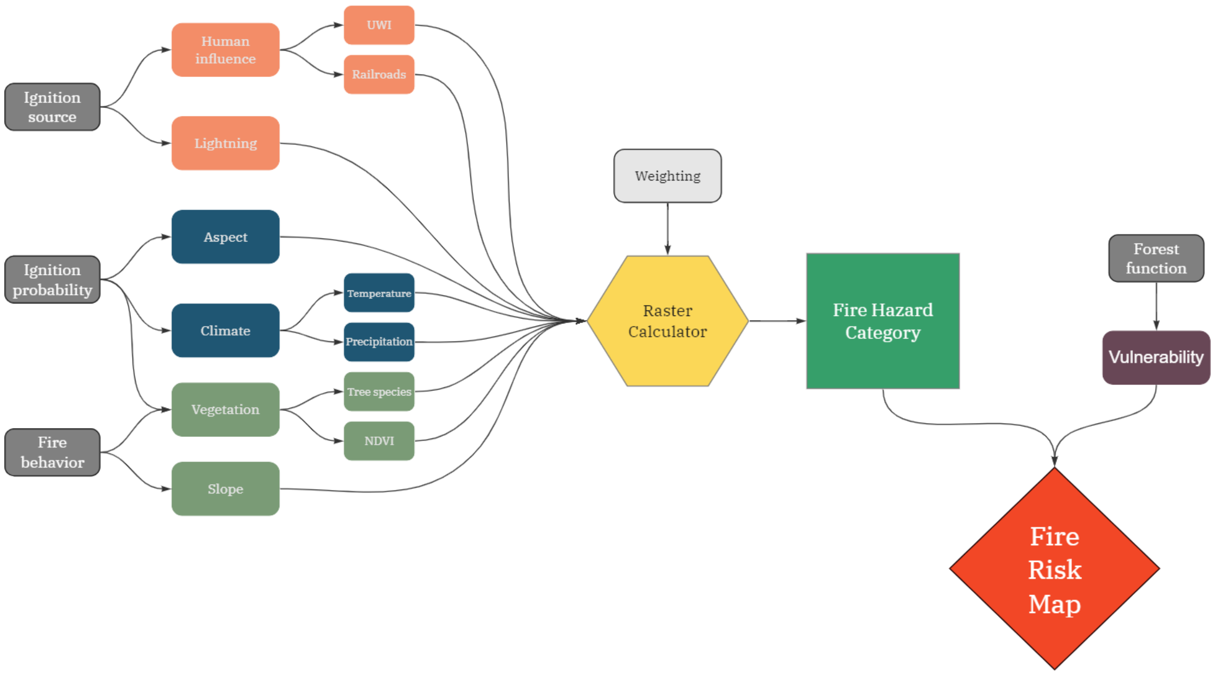

Figure 51: Schematic depiction of the steps to create a forest fire risk map.

Now to create a forest fire risk map, which is based on the static fire hazard map created in the chapter above and the in this chapter created forest vulnerability map, based on forest function the two maps need to be combined. This step is again done in ArcGIS Pro, in multiplying the two raster files with each other. A schematic depiction of this is shown in figure 51. This creates a third map with values ranging from 1 to 15. Low values will be generated in areas where the risk and the vulnerability are both low. On the contrary, the highest values will be found in areas where both the fire hazard and the vulnerability is high.

The forest fire risk categories can be seen in figure 52 and the resulting forest fire risk map in figure 55.

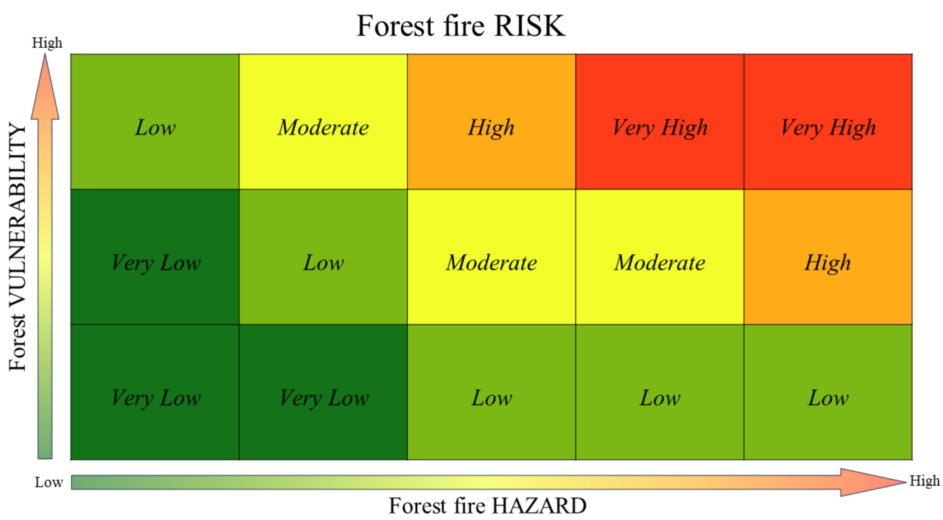

Figure 52: Raster categorization of the forest fire mix as a result of forest vulnerability and fire hazard categories.

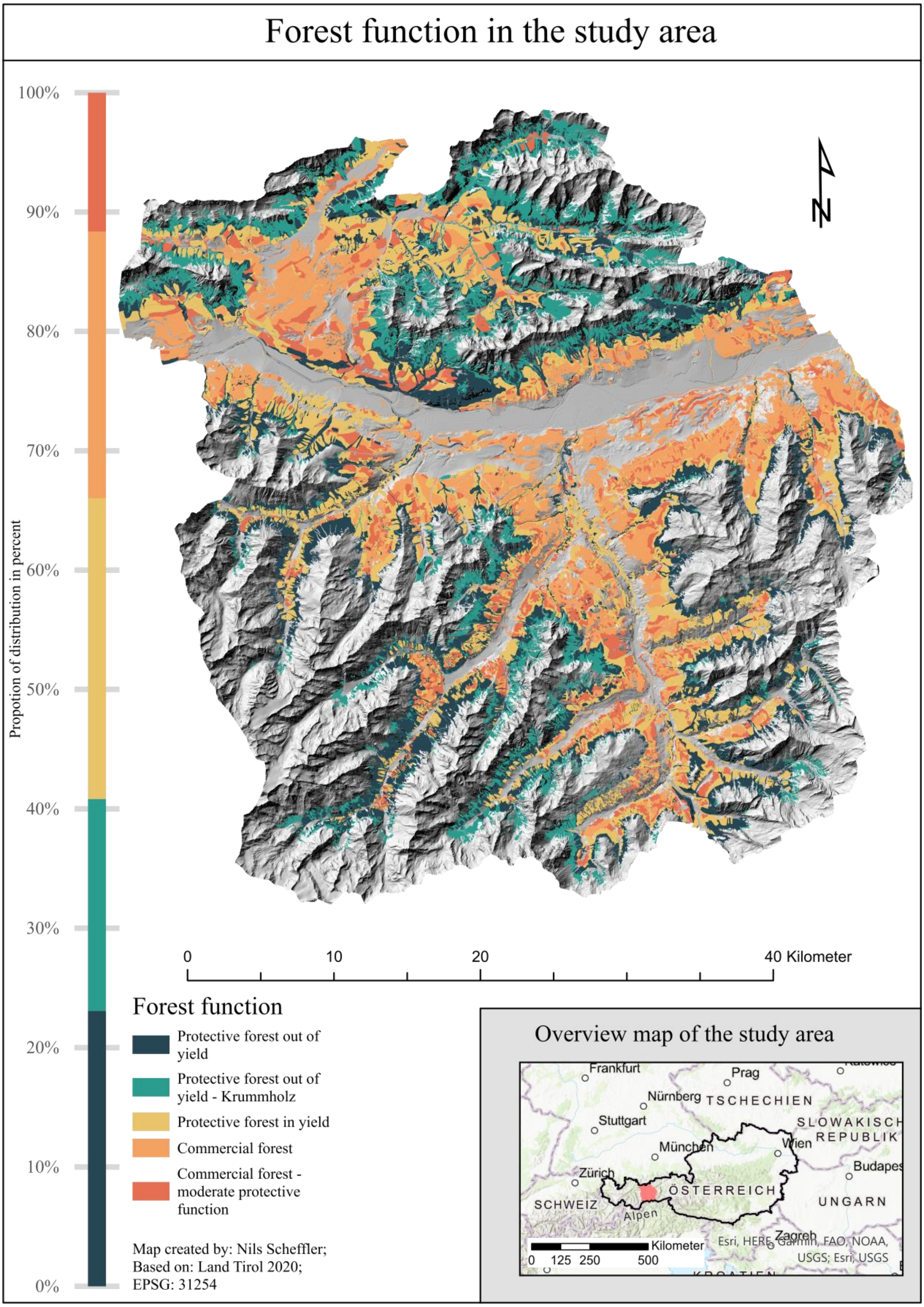

Figure 53: Forested area classified into the forest functions.

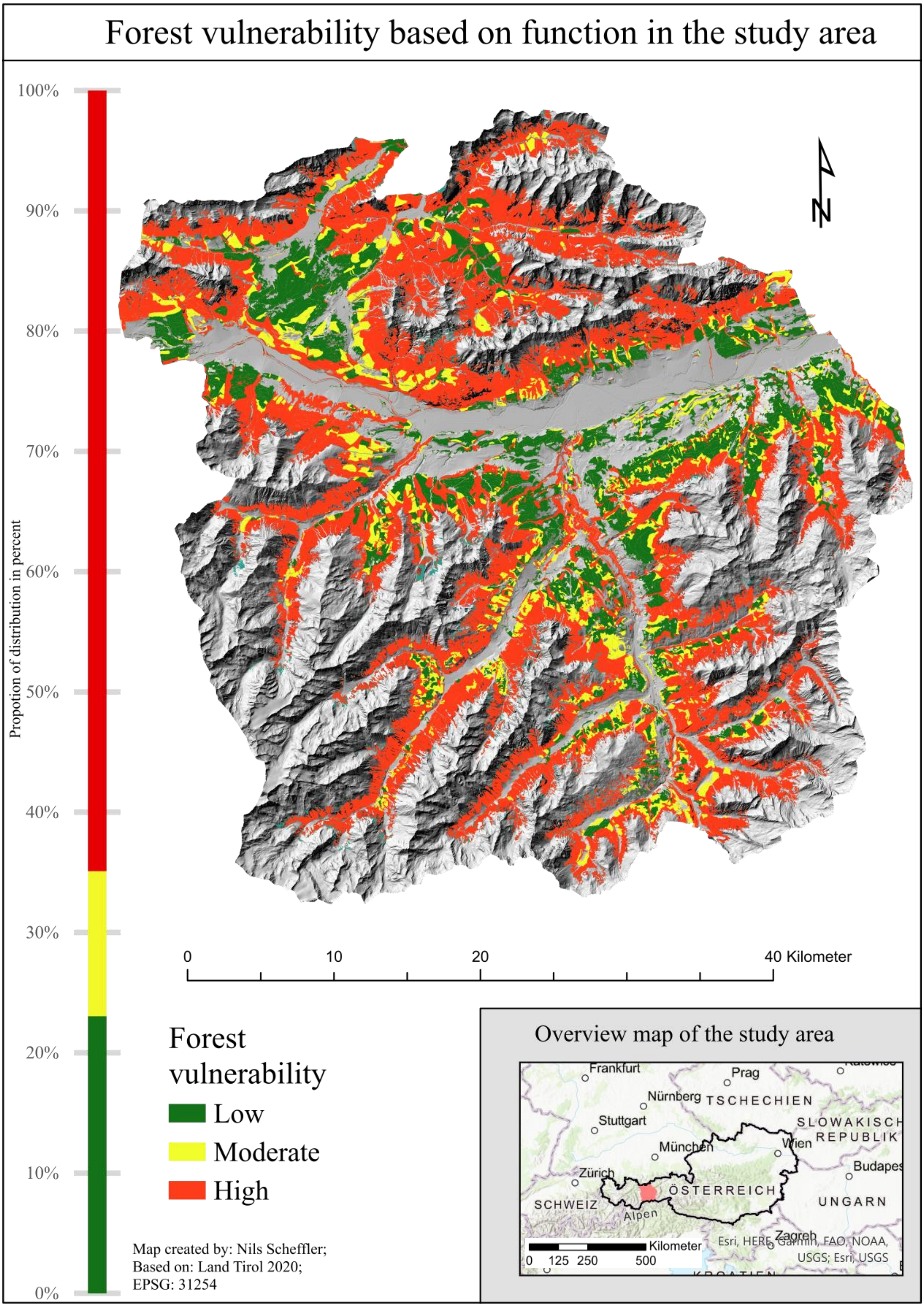

Figure 54: Vulnerability classification of the forested area based on forest function.

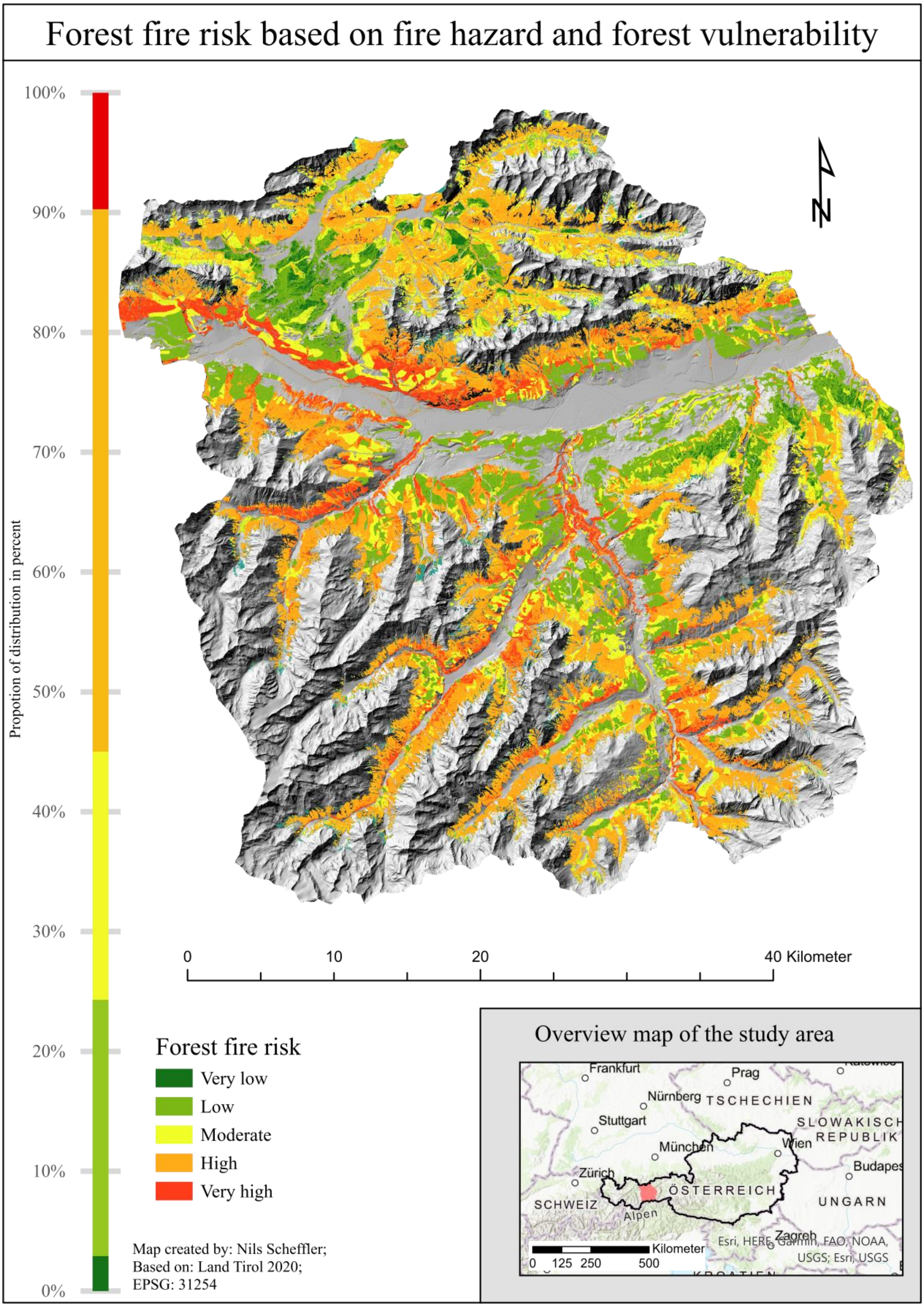

Figure 55: Modelled forest fire risk map based on the modeled forest fire hazard map variant 4 and the vulnerability map.

The resulting fire risk map in figure 54 shows, that the largest spatial portion is covered by a "High" risk, with more than 40%. These areas which are most at risk are closer to the valley floor and distributed all over the study area. Especially the western part of the Inn valley, have a high amount of "Very high" risk areas. This is due to the high fire hazard combined with a high vulnerability class in this particular area. Areas with the lowest risk can be found on the Seefeld plateau, the Karwendel mountains and the Tuxer mountains. Especially the Seefeld plateau has large, connected areas where the fire risk is low.

It must be noted that this map only includes the forest function as the vulnerability parameter. It does not take any other infrastructure or human parameters into account. In doing so the risk map could be fine-tuned, and a possibly more accurate representation would be possible. The idea behind this risk map was foremost the creation of one and the display of the process that is integrated into it, as highly detailed forest fire risk maps are currently very sparse or not available at all.

Overall, the forest fire risk map can help to further distinguish areas where the fire prevention measures have to be taken to reduce the fires risk, in order to help save human lives and the important forest ecosystems.

As years progress, the fire hazard will definitely change. Either through human influence, climate and environmental change, or probably both. This calls for a continues effort in creating updated forest fire hazard and vulnerability maps, to create accurate and current forest fire risk maps, to keep up with a changing environment.

How these changes look like is still not exactly clear, but studies show, that these maps, predicting future fire regime, and hazard zones, including future forest fire hotspots are currently needed, as silvicultural measurements can't be implemented on short notices and must be meticulously planned and execute. They have to rely on the current scientific knowledge about prediction of future change. What these changes may look like in the alpine regions will be shown and discussed in the next chapters.

10. Climate change and the consequences

Climate change and the consequences that will inevitably follow, is a pressing and highly complex topic, which is yet not fully understood, and rises many open questions. As the mountainous regions of the Alps are expected to be highly affected by climate change, it is important to discuss possible future climate scenarios and what outcomes might await, regarding the state of the Austrian forest ecosystem and the possible new fire regimes.

10.1 Current climate change scenarios

Currently most of Austria can be classified as temperate- to alpine climate, with average temperatures ranging from - 10 degrees Celsius in winter and 20 degrees Celsius in summer (Arndt et al. 2013, p. 316). A changing climate will inevitably alter future weather patterns (Maringer et al. 2016, p.699). Climate models show that the Alps will be a region most affected by climate change, with the last decade already exceeding several drought and temperature records (Müller et al. 2020a, p. 42).

Worldwide an increase in temperature is predicted. The human induced increase in global average temperature is very likely to rise above 2 degrees Celsius. This number must be considered as a global average, and naturally some regions will experience more and some region less than two degrees celsius increase (Elkin et al. 2013, pp.1827). Models predict that the alpine region will experience a higher increase in temperature compared to the global average (Lindner et al. 2010, p.703).

The temperature in the Alps have already risen with 1.6 times the average rate of the northern hemisphere in the last 50 years (Pezzatti et al. 2016, p.224). Müller et al. (2012) suggest even a twice fold increase of temperature compared to the global average (Müller et al. 2012, p. 1). Looking at the projections of regional climate models for Austria, an increase in temperature is predicted to be between 2 °C and 6 °C for Austria until the end of the 21st century (Lexer and Seidl 2007, p.1; Müller et al. 2015, p. 904: Gobiet et al. 2014, p. 6; Schumacher and Bugmann 2006, p.1435).

Again, the rate of change for the near surface temperature will vary depending on the elevation. It is predicted that higher rates of warming will occur in higher elevations. This elevation dependent warming has to be viewed with caution. Although predicted, this trend does not necessarily have to occur in every region. Also, the trend of elevation dependent change in precipitation is much more incoherent and should be viewed with caution (Gobiet et al. 2014, p. 6).

Mountainous areas act as water towers and provide 50% of the worldwide consumed freshwater and a change in precipitation in those areas could have severe consequences (Fagre et al. 2003, p.278). Climate models indicate a considerable change in precipitation pattern with an increase in winter precipitation and a decrease in summer and autumn precipitation (Gobiet et al. 2014, p. 6; Müller et al. 2015, p. 904).

Warmer temperatures will influence the state of the precipitation, in reducing the appearance of solid precipitation as snow. Since the 1960s the snow cover and especially the total snow height has already significantly decreased in the West and South of Austria in all elevations. If the climate change trend continues as is, the reduction of snow cover can reach 50 to 90% until the end of the 21st century (Freudenschuß et al. 2021, p.46).

The combination of warmer temperatures and a decrease in summer precipitation will lead to longer periods of drought. Also, the increased evaporation will only enhance droughts in the future (Freudenschuß et al. 2021, p.46). Models suggest that central Europe will experience an increase in the length of the average longest annual drought period by three to 15 days (Lindner et al. 2014, p.72).

The current projections for wind speed are still unclear and no clear assumption can be made (Lindner et al. 2014, p.72). High windspeeds often occur with extreme weather events and thunderstorms. An increase in extreme weather events can be expected in the future, with intense rain, heavy thunderstorms, heatwaves, and prolonged periods of drought (Mößmer 2008, p.11; Wohlgemuth et al. 2008, p.336). With more thunderstorms, an increase in lightning activity is assumed in the future (Vacik and Müller 2017, p. 27). A rise in extreme precipitation events has been observed in Austria, as the precipitation intensity increases about 7% for each degree Celsius of temperature increase (Freudenschuß et al. 2021, p.46).

The cause of this rapid climate change is quite clear and has been known for multiple decades. The change in climate with an increase in temperature and a changing precipitation pattern has been linked to human activity (Wastl et al. 2012, p.1). Even though human activity has the most share in this change, Bowman et al. (2009) estimate that 19% of the anthropogenic radiative forcing have been contributed due to fires (Bowman et al. 2009, p.1).

Current simulations using simple scenarios with a few climate variables pose limitations and capturing the full picture of likely changes which are expected to see in the future is very difficult. These predictions are still limited due to the overall complexity and numerous interconnected factors that influence the earth's climate system (Lindner et al. 2014, p.71).

That's why current predictions are still coupled with sometimes large uncertainties. Also, due to the complex and in short distances rapidly changing environmental and topographical conditions of the landscape in the Alps, estimations of future climatic conditions pose a considerable challenge for climate models and researchers (Gobiet et al. 2014, p. 1).

10.2 Climate-fire relationship

The climate-fire relationship is quite complex and needs to be understood to effectively implement policies that contribute to the management of forest fires. Carbon emission and CO_2 intake, heat fluctuations, change of atmospheric conditions, and future outcomes of different climate change scenarios are only a small portion of all the climate-fire interactions that happen. Climate change seems to contribute to the recent increase in fire activity if the interrelation between fire season, fuel aridity, the observed vapor pressure deficit (VPD), fire danger indices, and climatic water deficit over the past several decades is taken into account (Abatzoglou, Williams 2008, p. 11770).

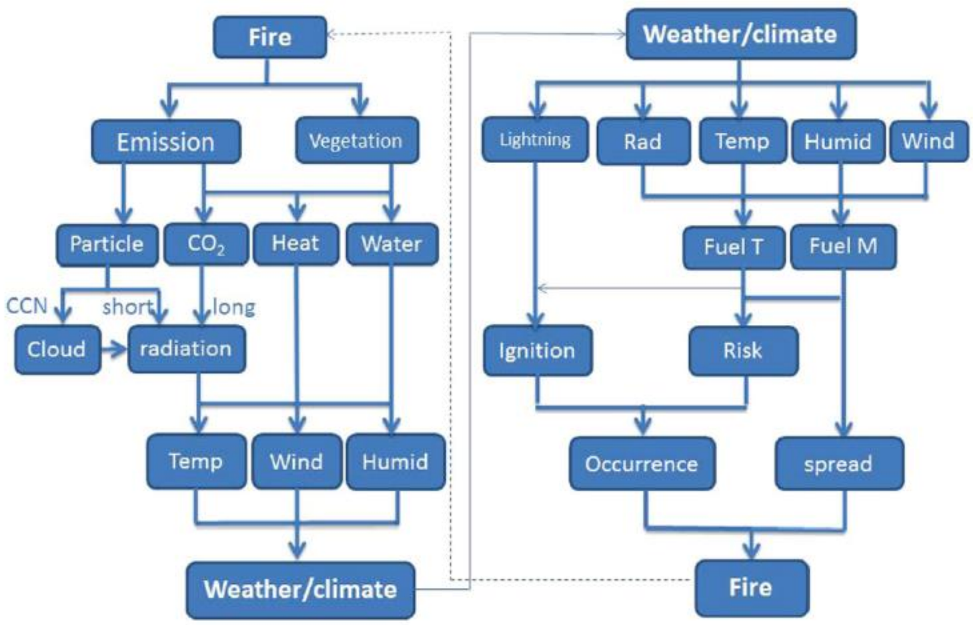

Figure 56: Diagram of physical processes for fire's impacts on weather and climate and feedbacks (Liu et al. 2014, p. 81).

Due to climate change, many regions have already experienced a drastic change in the fire regime. Particularly the frequency as well as the burnt area has increased (Zumbrunnen et al. 2010, p.2188). Worldwide, the current fire regimes are expected to fall outside the natural range of variability within the next few decades as a consequent of environmental changes. This poses a threat to the integrity of the forest ecosystems (Generies et al. 2012, p.1; Wastl et al. 2012, p.2; Maringer et al. 2016, p.699). The general trend is leading to an increase in both size and frequency of forest fires, but shows large regional differences (Wastl et al. 2012, p.2). This change will lead to forest fires becoming more likely to affect forest ecosystems that have previously been less affected by fire (Maringer et al. 2016, p.699). Therefore, forest fires will become more and more present and can turn into a serious issue (Müller et al. 2020a, p. 10).

Overall, the consensus is quite clear that climate change will lead to larger, more intense, and more frequent fires (Marlon et al. 2008, p.2519; Müller et al. 2015, p. 904; BML 2022, p.6; Stephens et al. 2013, p.41; Arpaci et al. 2014, p.258; Gossow et al. 2007, p.1). Simulations showed a regional increase in days with high forest fire danger by more than 40 days in the alps (Müller et al. 2020a, p. 42).

Reasons for this change in fire regime is mostly caused by an increase in temperature and a change in precipitation patterns that could result in prolonged periods of drought (Blarquez and Carcaillet 2010, p.1). This combination will likely lead to drier surface and vegetation conditions, which may lead to more forest fires, as fuels become more ignitable (Groisman et al. 2007, p.371; Müller et al. 2015, p. 904; Zumbrunnen et al. 2010, p.2197; Schumacher and Bugmann 2006, p.1435; Pezzatti et al. 2016, pp.225).

Also, an increase in temperature combined with a decrease in spring snow cover and the extension of the growing season promotes vegetation growth and therefore evapotranspiration (Groisman et al. 2007, p.371). The extension of the growing season can also lead to the accumulation of fuels and the increased connectivity of forest stands which may increase the risk of forest fires (Blarquez and Carcaillet 2010, p.1).

A change in the fire regime can shape the vegetation. For example, it can reduce individual species due to fire pressure while other species that are more adapted to fire, might become more frequent in a particular area. This might reduce the potential for future fires after the new fire-resistant vegetation has become dominant (Zumbrunnen et al. 2010, p.2189).

Climate change and a new fire regime will also affect the Alps and Austria. Wastl et al. 2012 presented that the northern Alps showed an overall slight increase in mean fire danger over the past 60 years (Wastl et al. 2012, p.7). The activity of forest fires in the alpine region will most likely increase in the future due to climate change which brings prolonged periods of drought, heat waves, and a different precipitation pattern. Also, the change in snowpack height in the winter will lead to drier conditions in late winter and spring which could lead to more forest fires (Müller et al. 2020a, pp. 3).

With a changing climate the role of lightning induced forest fires might increase in the coming decades, with climate models predicting higher temperatures and regional increase in droughts (Müller et al. 2012, p. 9; Wastl et al. 2012, p.2). While the number of lightning strikes seems to have decreased over the last years, the number of fires ignited by lightning strike has seen an increase. This can be traced back to an overall drier environment that can be ignited more easily by lightning (Müller et al. 2020a, p. 43; Arpaci et al. 2014, p.258).

Although dry and hot weather conditions are favorable for forest fires, the fire season does not necessarily have to be more severe. In Austria, during the summers of 2016 and 2018 the total amount of burned area was particularly low, even though these years had prolonged periods of drought and exceptionally hot summers. Reasons for that could be that particularly dry areas in Austria have less forested areas. In the summer months the wind speed was generally low, while high-speed wind speeds are important for fast spread of fire. The alpine areas kept a higher fuel moisture due to reoccurring rain showers. Also, fire brigades communicated the importance of correct behavior in areas of high fire danger clear (Müller and Vacik 2019, p.16).

This effect has also been previously described before: for example, Groismann et al. 2007 found no statistically significant changes in potential forest fire danger over northern Europe during the past 50 years. Significant warming in areas was always coupled with an increase in precipitation (Groisman et al. 2007, p.378). Elkin et al. 2013 did not find an increase in the average fire occurrence under the two-degree Celsius warming scenario. But larger fires will be more likely in exceptionally dry years (Elkin et al. 2013, p.1837).

10.3 Implications for the Austrian forest

This chapter will focus on the important and complex question of how climate change will impact the forest ecosystems in the Alps, especially in mountain areas of Austria. As our planet's climate keeps changing, it's causing various challenges for forests. Understanding these changes and the future challenges is an important step into an adapted and sustainable forest fire management.

During the last couple of decades, the already occurred change in temperature, levels of atmospheric carbon dioxide, and the precipitation patterns, combined with an increasing occurrence of extreme weather events have had a notable impact on the world's forest health (Tuominen et al. 2009, p.31).

Environmental factors used to keep a relative constant for a long period of time until the climate change brought a stronger oscillation into the system (Freudenschuß et al. 2021, p.16). These disturbances will affect the response of forest ecosystems to future climate change (Heon et al. 2014, p.13888; Carcaillet et al. 2001, p.930). Europe will not be unaffected by climate change and the European mountain forest will be one of the regions that is most affected by it (Vacik and Müller 2017, p. 27). Especially forest ecosystems are susceptible to rapid and drastic climatic changes. Because of their longevity, forest cannot adapt to changes in such a short time span. It simply exceeds their ability to adapt to changes (Lexer and Seidl 2007, p.1).

These mountain forests provide a number of services including the protective forest function as well as the provision of drinking water. Climate change might substantially affect the capability of forest ecosystems to provide ecosystem services. For example, intensified large scale disturbances like forest fires, wind throws, and pest outbreaks may lead to a change in runoff as well as in percolation and water quality (Lindner et al. 2010, p.703; Lorz et al. 2010, p. 920; Elkin et al. 2013, p.1827).

In addition to climate change, forests have to cope with other stress factors such as browsing damage by wild animals and beetle infestation, which adds to the susceptibility of a changing environment (Lexer and Seidl 2007, p.2).

Due to the heterogenic characteristics of mountainous areas the local sensitivity and response to climate change will vary strongly at local and regional scales (Lindner et al. 2010, p.703). Some tree species react sensitive to very small climatic shifts that exceeds the species tolerance (Elkin et al. 2013, pp.1827).

The changes in climatic environmental conditions will alter the site-specific conditions, and therefore also the composition of vegetation might change. That could for instance, result in a shift in the competitive relationships among tree species. While certain tree species may no longer be competitive on specific sites due to exceeding their ecophysiological limits, the effects of previous constraints (such as cold stress) could potentially be diminished or alleviated by climate change (Lexer and Seidl 2007, p.4).

How tolerant a tree is against the range and speed of environmental changes depends on the type of species. Each tree species has an ecological niche that covers an amplitude of certain environmental factors. The most important ones are temperature and precipitation (Mößmer 2008, p.16).

Warmer temperatures and higher CO_2 content in the atmosphere will increase the growth potential (Mößmer 2008, p.15) and sites that are currently limited by temperature will generally benefit as a result of warming (Lindner et al. 2010, p.703; Pezzatti et al. 2016, p.225; Freudenschuß et al. 2021, p.16). With that, the tree line will respond to warming by an upward shift of multiple hundreds of meters. With that change, tree species and forest stand types will change due to the changing site-specific conditions (Freudenschuß et al. 2021, p.16; Lindner et al. 2010, p.703). This rising height of the tree line could potentially lead to a small increase in lightning induced forest fires (Pezzatti et al. 2016, p.240).

The increase in temperature may be beneficial during colder seasons and on temperature limited sites but it will also increase the forest stress during warmer seasons in lower elevations (Tuominen et al. 2009, p.31; Mößmer 2008, p.14). A modelled temperature increase of 5 degrees Celsius will lead to an increase of growth rate in higher altitudes and an immense decrease at lower elevations (Ledermann and Kindermann 2013, p.16). Tree species that are currently at low elevations are predicted to respond to climate warming by moving up slope, previous high elevation specialists are particularly threatened due to a loss of suitable habitat. Forests below 1800 meters of elevation will be most vulnerable due to climate change during the next 100 years, because the current suitable temperature and precipitation conditions will change drastically (Elkin et al. 2013, pp.1837).

As water supply is a limiting growth factor, higher temperature might not always be beneficial if the precipitation does not rise adequately. Reduction of growth, an increase of drought induced mortality, and a change species distribution have already been observed in context of a changing precipitation pattern (Lindner et al. 2014, p.70).

Tree growth is generally expected to decrease on water limited sites due to increased drought stress (Lindner et al. 2010, p.703). This potential increase in drought and the weakened tree health will result in a higher probability of forest fires. That includes forests that until now have been excluded from forest fires. For example, beech forest in the northern Alps, with their dry leave dominated litter, will have a higher chance of ignition (Wohlgemuth et al. 2008, p.338).

Also, due to overall drier conditions, areas that have been recently affected by wind throw will have a high chance of ignition during the dry summer months, due to a large accumulation of very dry deadwood (Wohlgemuth et al. 2008, p.338).

Additionally, warmer temperatures will affect the appearance of bark beetles. Milder winter will help pest insects to survive and increase the development rate (Lindner et al. 2014, p.76).

Being a cold-blooded animal, the European spruce bark beetle is directly influenced by temperature: It thrives in higher temperatures (Hoch 2013, p.14). Also prolonged periods of drought have an impact on the tree physiology and can potentially weaken it. Especially when the trees are under stress or damage due to climate factors, they are more vulnerable to bug infestations (Mößmer 2008, p.14; Tuominen et al. 2009, p.31; Hoch 2013, p.14). This trend can already be witnessed, as data shows that bug infestation has increased in the past (Freudenschuß et al. 2021, p.51; Mößmer 2008, p.14).

With deteriorating health, the occurrence of windthrow will rise. This, coupled with long periods of hot and dry weather conditions can cause a beetle infestation in these areas (Wohlgemuth et al. 2008, p.336).

As mentioned before, mountain forest serves a protective function. If the appearance and intensity of forest fires in the alpine region increases as they are thought to be, the protective function against natural hazards of the forest cover will most likely see a decrease. It could lead to more destruction of infrastructure and create a higher risk on human lives, also resulting in a much higher cost in terms of risk mitigation measurements (Müller et al. 2020a, p. 50). Bug infestation is another problem, that already represents a danger to the protective forests (Freudenschuß et al. 2021, p.52).

On the other hand, the upward movement of the tree line, which is a temperature induced effect, will improve protection against natural hazards by stabilizing soils and erodible masses, reducing avalanche starting zones, and dampening run of peaks (Lindner et al. 2010, p.703).

As spruce is the dominant tree species in Austria, the climatic changes on this tree species will have large consequences for the Austrian forest. Spruce dominated forests in lower altitudes are already struggling with higher temperatures and drier conditions and will face serious difficulties, if the climate changes as we expect it to (Müller et al. 2020a, p. 10; Müller et al. 2020b, p.1). This implicates that in some areas Norway spruce forests will not have a future with rising temperatures, increasing drought stress, and the pressure due to bug infections (Schüler et al. 2013, p.12). Although Norway spruce will face severe problems in lower elevations forest model simulations suggest that the growth rate of the Norway spruce at higher altitudes will increase due to a temperature rise (Fritz 2013, p.31; Ledermann and Kindermann 2013, p.16). This reflects the previously mentioned change of suitable habitat, that differs for each tree species.

But not only the change in climate will put pressure on Norway spruce stands. They are also a tree species that can be attacked by a number of different insects. Due to the shallow root system the danger of windthrow is increased and in periods of drought the water stress is damaging the tree. The water stress decreases the protective function against insects (Hoch 2013, p.13).

Already, the European spruce bark beetle, and the spruce wood engraver has the highest influence considering damaging factors on Norway spruce trees. The likelihood of bug infestation in Norway spruce stands will only increase with rising temperatures, because of more suitable host conditions (Hoch 2013, pp.14).

The question of how the forested areas will change has not been a recent one. Many previous studies have tried to provide answers to this simple sounding but extremely complex question. One of those has been the forest modelling approach of Schumacher and Bugmann 2006. Here the future development of the current forest area in the Dischma valley, Switzerland, was simulated under a future climate change scenario. The output resulted in a considerable shift of vegetation composition for the year 2100 and beyond (Schumacher and Bugmann 2006, p.1446).

Between 2000 and 2050 simulations showed a phase of increase growth followed by a phase of strong biomass reduction. This is mainly caused by drought induced diebacks of today's forest stand, accompanied by the gradual invasion of new tree species. Simulation results suggest that during this process an upward shift of vegetation will occur, given that alpine pastures will no longer be used with the same intensity as today, in which spontaneous reforestation is almost impossible as long as domestic grazing continues. In addition, the results show that by 2050 the current vegetation cover has already shifted up 100 meters upwards compared to the situation in 2000. During the following decades the upward shift continued, and biomass increased at higher elevations. Particularly the tree species *Larix decidua* accumulates a considerable amount of biomass just below and above the current tree line (Schumacher and Bugmann 2006, p.1446).

Schumacher and Bugmann 2006 found that models predict a rapid dieback of Norway spruce around 2050. Norway spruce was modeled to be replaced mainly by Sorbus and Pinus. After 2100 biomass increased at higher elevations while at lower elevations it decreased further. The abundance of Norway spruce decreased even further at lower elevations and made way for new tree species to establish (Schumacher and Bugmann 2006, pp.1442).

Another similar study was done for the Saas Vally, Switzerland. Elkin et al. (2013) investigated the changes in forest ecosystem functions under the future climates. The study found a strong reduction in forest biomass in low elevations in the Saas valley under all CH2011 scenarios, primarily due to increased drought and reduction in soil moisture. The here used CH2011 is a regional downscale climate scenario for Switzerland and is based on the two non-intervention emission scenarios A2 and A1B (Elkin et al. 2013, pp.1829).

Elkin et al. (2013) Found that under all scenarios the protection against snow avalanches and rockfall will decrease in intermediate elevations and at low and intermediate elevation under all scenarios respectively. Results showed similarities to the previous study from Schumacher and Bugmann 2006, in that forests are not strongly impacted by climate change during the first half of the 21st century. However, forest structure will start to change quickly after the middle of the century. This time lag in changes is a result of biological threshold, such as species specific resistance to drought (Elkin et al. 2013, pp.1833).

A 2 degree Celsius increase in global average temperature, which today is not far from likely, will have substantial impacts on forest ecosystems and the services that they provide. Coinciding with many other studies, the results showed that substantial changes are expected at intermediate and low elevations. The response of mountain forest ecosystems will heavily depend on changes in temperature and precipitation – especially the seasonal changes of precipitation during the growing season. The main statement was clear; “A two-degree Celsius increase cannot be seen as safe for the maintenance of mountain forest ecosystem services” (Elkin et al. 2013, pp.1836).

Other earlier studies also tried modelling forest dynamics for the Austrian forest. Lexer 2001, Lexer et al. (2001) and Lexer et al. (2002) found that 78% of the Austrian forest area would experience change in tree composition when temperature increase 2 °C and summer precipitation decreased 15%. While deciduous tree species will mostly increase their grow rate under the simulated climatic changes, *Picea abies* will face problems with warmer and drier climate (Lexer and Seidl 2007, pp.4).

Seidl et al. (2011) found that the Austrian federal forests under its current stand treatment program is highly vulnerable to climate change and without change this will only increase going further in to the 21st century (Seidl et al. 2011, p. 700).

The often appearing pure Norway spruce stands are already at a high risk from various factors that are predicted to increase with global warming such as drought, forest fires and bark beetle infestation (Müller et al. 2020a, p. 45). But it is not just the Norway spruce that will likely face difficulties in finding suitable habitats under future climate. Deciduous forest types are not immune to severe changes. Especially for the European beech evidence already shows drought induced growth decrease throughout the distribution area of the species (Lindner et al. 2014, p.73). This climate induced habitat change will let the beech forest move upwards into new altitudes if the conditions allow for that (Mößmer 2008, p.18).

With the mountainous forest being so heterogenous, the species-specific response to climate change can vary dramatically. Species that are accustomed to warmer temperatures will profit from climate change. Chestnut and oak will be some of them. Or for example the Pine trees, which can resist long periods of drought and are accustomed to low precipitation (Mößmer 2008, pp.18).

The heterogenous nature of these forest is one reason why considerable uncertainties still exist when assessing the likely response of forest ecosystems towards the end of the century due to the projected change of climate. Many forest ecosystem responses are to extremes rather than to means and the uncertainties of change in the range of the extreme oh making the predicted change of the forest ecosystem so difficult (Lindner et al. 2014, p.70).

Extreme events both in temperature and precipitation will likely increase in the future. The response of forest ecosystem to these extremes are likely to be more intense than to a gradual change off climatic factors (Lindner et al. 2014, p.72).

The potential change in fire regime will likely happen rapidly rather than steadily, which means that very intense fire seasons could follow years of low intensity seasons, with weather condition that are like the ones in 2003 occurring every two years (Müller et al. 2020a, p. 42). Considering this, the predicted change to rapid change in fire regime poses another complex question, as to how fast the adaptation of the forest ecosystem can occur.

Still unclear is how much the water use efficiency of trees may benefit from the enhanced CO_2 concentration, because high water use efficiency could at least partly counteract increasing water shortage under climate change. Another unresolved query that arises is how improved growth condition in average years interspersed with a few exceptional years of adverse growth conditions will affect forest ecosystems (Lindner et al. 2014, pp.74).

Studies suggest that there is a considerable difference in time lag for adjusting the habitable range for different species due to very slow migration rates. Although to what extend this will occur can not be said exactly. Also, still unclear is to what extent and at what rate species will decline at the rear edge of the distribution, posing the question if the physiological limits of species are usually wider than the boundaries of their current distribution range (Lindner et al. 2014, p.76).

Lastly, the scope of the predicted change is hard to measure. As studies found that the effect of climate change on future species composition of German forest was minor compared to the effects of forest management (Lindner et al. 2014, p.77), the question arises, of how different the scope of climate and anthropogenic change will be.

Even though there are still many unanswered questions and there is still a significant gap in knowledge in terms of expected changes for mountain forests considering the changing climate, the overall consensus implies that climate change will to a large extent influence forest vegetation, biomass distribution as well as forest species composition (Arpaci et al. 2014, p.258). Critical and irreversible changes to the mountain forest can already occur at a temperature increase of two degrees Celsius (Freudenschuß et al. 2021, p.16).

11. Annotations for future forest- and fire-management

The lack of precise climate projections calls for strategies that increase to resilience of forest systems, where resilience is defined as the capacity of an ecosystem to absorb disturbance and retain its function and structure. Searching for "no regret"-strategies that yield benefits considering many projected climates and favoring reversible options over irreversible choices is of high importance (Lindner et al. 2014, p.78). Finding these strategies and forest management measures that will cope with the changing climate and fire regimes in the future will not be easy because of the complexity of local to regional dynamics, that are making uniform, simple, or unchanging policy and management strategies ineffective (Stephens et al. 2013, p.42).

The topic of declining forest health and the need for new policies is not new. The management of forests has undergone drastic changes and new systems such as ecosystem management and sustainable forest management have found their way into everyday practice (Seidl et al. 2011, p. 695). The first step into the right direction has already been taken, although considering the extent of new challenges and difficulties the forest ecosystem will face, it is not enough yet.

In the first paragraph of the Austrian forest act, it states that the forest management must permanently preserve biodiversity in addition to productivity and regenerative capacity (Neumann et al. 2013, p.20). That is the reason why a modification of the forest management practices is crucial in Austria to sustain forest function throughout the end of the century and preferably further on (Seidl et al. 2011, p. 704). Also, the trend of more and especially more intense forest fires in the Alps, calls for effective strategies of fire prevention, suppression, and post-fire treatment, which are essential parts of the overall forest management system (Müller et al. 2020a, p. 47). The goal of future forest management strategies should be a balanced and sustainable forest management that can sustain itself even under future climate scenarios (Faivre et al. 2018, p. 12).

To achieve this goal, numerous strategies have to be adapted, changed and improved. A distinct change in forest structure and landscape will be needed to cope with the effects of a changing climate (Seidl et al. 2011, p. 704). Currently, forest management still lacks silvicultural measures to minimize the forest fire danger. For example, the choice of tree species or adequate care measures have to be implemented (Freudenschuß et al. 2021, p.49).

The forested areas of Austria are in dire need for more deciduous and mixed forests (Pickenpack 2013, p.24). While planning forest management strategies, it is of high importance to include the current scientific knowledge. In terms of fire hazard in forest management, rethinking the tree species composition in forests will likely help the adaptation process of those forests to current and future fires (Müller et al. 2020a, p. 45).

As mentioned before, pure stands of Norway spruce and other coniferous tree species are especially at risk due to a changing climate, and therefore should not be considered as suitable to be reforested at lower elevation. Taking these areas consisting of pure Norway spruce and converting then into mixed forests or deciduous forests would be desirable from a nature conservation standpoint (Pickenpack 2013, p.24; Mößmer 2008, p.24; Leitgeb et al. 2013, p.9).

Neumann et al. (2013) state that it's not the Norway spruce as such that causes disaster but rather the inadequate forest management with wrong planting methods, lack and absence of stand maintenance, and the disregard of site conditions (Neumann et al. 2013, p.22). That why it is important for the good of the forest to consider a healthy and sustainable middle course in which deciduous and coniferous trees can play out their advantage together (Pickenpack 2013, p.24).

A major challenge is to identify those tree species that will be suitable and appropriate to be reforested, especially on fire damaged sites (Müller et al. 2020a, p. 50). Stand replacing fires present a good opportunity to alternate the forest type (Valleijo et al. 2012, p. 105). During the reforestation of burnt down sites, the forest management experts have to think about the fact that there are three species being currently suitable for a reforestation project at this location but with a change in climate they may become unsuitable in the future (Müller et al. 2020a, p. 50). That’s why it is important that forest management needs to take climate change into account if areas are being reforested (Mößmer 2008, p.21).

The change from monocultures to mixed forest types can help to increase the overall resilience of the forest. That's why future forest management cannot rely on a single “super” tree species but needs to find the right mixture of certain species (Mößmer 2008, p.23). For example, a change of choice in tree species composition that would be sustainable and reduce the likelihood of severe forest fires is to simply add a higher proportion of deciduous trees in areas where pure Norway spruce stands are dominant (Müller et al. 2020a, p. 61).

Another idea would be the change from burned pine forest into mixed wood forest, if the location is suitable. This will increase diversity and fire resilience and reduce pest outbreaks (Valleijo et al. 2012, p. 106), because the specific local conditions might not allow every tree species to be reforested. This issue has to be included in the search for a new and resilient tree species composition (Müller et al. 2020a, p. 45).

As temperatures will rise and precipitation patterns change, the lower elevations will experience a strong change in forest health and structure. A sustainable mixed tree forest stand has to be established at those low elevations (Fritz 2013, p.31). Especially considering the protective function of the forest. To keep this function against natural gravitational hazards, it is important to increase the part of mixed tree as pure Norway spruce stands might be weakend or removed due to natural circumstances (Freudenschuß et al. 2021, pp.28).

There is also an economical side to this. As Norway spruce and other coniferous tree species are important parts of the Austrian wood production, they can’t be completely removed from every site. It is going to be a difficult balance between as much mixed forest as needed and keeping as many economically important tree species as possible (Fritz 2013, p.31).

If there have been decisions made on changing tree species composition in a certain area, another problem arises, which is the reforestation itself. Game browsing is a considerable challenge during reforestation, as this process and the rejuvenation of the protective forest can be compromised due to excessive browsing by game (Freudenschuß et al. 2021, p.58). To establish those mixed tree forests browsing due to game must be reduce to a minimum (Fritz 2013, p.31).

Another problem in implementing new measurements against forest fires is the overall owner structure. Of all of the forested areas in the Alps, over 50% is owned by people with an average of less than five hectares. Some owners do not have the necessary expertise in forest management which can lead to unfavorable maintenance of their forest. Currently the protective measurements against a number of other threats such as bark beetle infestation and windthrow are more relevant than the appropriate implication of preventive measurements against forest fires. This issue can only be resolved if the overall awareness of landowners in the Alpine region would rise (Müller et al. 2020a, p. 46).

An effective measurement to mitigate fire susceptibility by the reduction of fuel loads is either by thinning, manual fuel removal, or prescribed burning (Gustafson et al. 2003, p.327). Deadwood as a potential fire hazard can be removed, although the use of deadwood in forest areas must be appropriated considering the ecological function of it and the danger it brings in terms of forest fires (Freudenschuß et al. 2021, p.50; Wohlgemuth et al. 2008, p.338).

The quantity of deadwood leads on one hand to a biodiversity increase and on the other hand increases the potential of higher fire intensity. In today's forest management approach deadwood is seen as an important measure for nature conservation and not as much as a potential threat regarding forest fires. Large amount of deadwood can also restrain the firefighting activity and may also lead to the ignition of new fires if lying deadwood or stumps are already burning and a rolling down the slope. This can also be a potential hazard for the fire brigades working below a forest fire in steeper terrain (Müller et al. 2020a, p. 46).

A problem with this measurement is the time and cost efficiency. The removal of deadwood from forest sites can be time and cost consuming. This measurement should only be carried out after a comprehensive one side assessment of the potential risk that this that would bring regarding forest fire in the area (Müller et al. 2020a, p. 61). The amount of fuel and the structure of the vegetation in forested areas serving a protective function have to be recorded. This can happen using the previously described fuel maps (Freudenschuß et al. 2021, p.50).

If areas with a high WUI cannot be depopulated, the establishment of protection zones that include proper fuel management can help to minimize the hazard and risk around those areas (Faivre et al. 2018, p. 16). This buffer zone should be examined in a fire preventive manner. In these buffer zones other fire relevant information, such as ignition probability, fire spread probability, and the vulnerability of infrastructure should be included to make better sense of the fire hazard in the wildland urban interface (Pezzatti et al. 2016, p.239).

Larger clear cuts that act as fuel breaks do make sense in areas where large fires are expected, but in mountain areas such as the Alps, these measurements are especially hard to implement coming with high cost and a potential risk for erosion and wind-throw (Müller et al. 2020a, p. 45).

A first step into the prevention of forest fires is the analysis of areas that show a high static fire danger level, independent from temporal fluctuations, which are typically presented with the current fire danger indices. In terms of long-term fire prevention, a danger map identifying the current and future hotspot areas is of high importance (BML 2022, p.21; Müller et al. 2020a, p. 45). If areas with a high forest fire hazard have been identified, they can be then adequately managed. Also forest fire preventive measurements have to be carried out, such as the reduction of accumulated fuels to reduce the fire hazard and the potential risk it poses on the population living close by (Pezzatti et al. 2016, pp.223). Modifying forest landscapes to be less susceptible to fire ignition and spread should also be considered (Gustafson et al. 2003, p.327). This usually includes a change of tree species composition.

This danger map needs to be a spatially highly resolved map, because of the high variability and heterogeneity of the alpine environment. Furthermore, a depiction of the spatial and temporal change of the forest fire danger in Austria is highly needed. This includes changes in climatic parameters and potential changes in the vegetation composition. At the moment, forest fire danger maps do not include climate change scenarios and do not depict any possible future outcomes (Freudenschuß et al. 2021, p.50).

In Austria the first fire hazard maps that include vegetation, topography and potential fire triggers have been recently developed, but are not yet publicly available. These do not include a vulnerability analysis which would result in a fire risk map (Müller et al. 2020a, p. 45).

Precise fire mapping and statistical analysis that describe wildfires are essential for the assessment of driving factors such as the climate, vegetation, topography and other land-based features. Additionally, over a longer period, the new policies regarding forest fire management can be assessed. Evaluating these spatial temporal trends can help to manage fire prone landscapes and to evaluate the most efficient strategies regarding preventive measurements (Faivre et al. 2018, p. 14).

As of right now, most of the money spent regarding forest fire expense, is due to fire suppression, with little focus on fire prevention. Also not enough measures are currently used. With pressing danger in the future, this needs to change (Müller et al. 2020a, p. 42). The focus should shift from suppression to prevention, calling for more effective science-based forest fire management and risk informed decision making (Faivre et al. 2018, p. 12).

The cause of forest fires is very clear. Human impact is mostly the cause of ignition. Therefore, a great measurement is the increase of forest fire danger awareness. As this is currently very low, the awareness in the population should be drastically increased (Faivre et al. 2018, p. 12). With an increase in human activity in forests due to tourism and other recreational purposes, public awareness of potential forest fire hazards has to be spread. Adequate behavior in terms of forced fire prevention must be the key message (Pezzatti et al. 2016, p.240). Public education on correct behavior regarding forest fires needs to be implemented in new policies and strategies making sure that the misconception of forest fire prevention being the sole responsibility of the fire department is addressed (Faivre et al. 2018, p. 16).

Figure 57: An old and unreadable sign, informing about the forest fire danger and why campfires in the forest can be dangerous (photos: Nils Scheffler).

A higher potential for forest fire does not necessarily mean there will be more frequent and larger fires. The potential for forest fires does not solely rely on the changing climate but also on the human presence and behavior. Being the most common ignition source for forest fires adequate behavior regarding forest fires could very well minimize frequency and size of forest fires in the future (Badeck et al. 2003, p.4). As stated by the fire chief Mr. Friedl, the population has to be made aware regarding proper behavior in forested areas during high fire probability. This effect is already evident in parts of France. There, a distinct decrease in the number of forest fires in the southeast of France can be seen likely linked to a new set of policies regarding firefighting since the 1990s (Müller et al. 2020a, p. 16).

If all preventive fire suppression measures have failed, fire suppression needs to work flawlessly to combat the potential threat. During firefighting an essential challenge can be forest roads: They might be not wide enough for the large fire trucks or are not suitable to reverse on. While planning new roads, the accessibility for fire trucks should be considered. Speaking of accessibility, especially in remote and dry areas the accessibility of water can also create problems during firefighting. Water tanks, ponds or fire hydrants are not always widely available. These open gaps in the availability could be filled with proper planning (Müller et al. 2020a, p. 48).

As helicopters are essential for firefighting in the Alps, the availability of helicopters might be a restricting factor considering effective firefighting in the difficult terrain (Müller et al. 2020a, p. 44). This problem could be solved with an upgrade of the Austrian helicopter fleet.

Another problem is the clothing the firefighters wear during a forest fire: It was developed for fighting fires in buildings, what makes this type of uniform unfit to be used in a forest fire fighting scenario. Due to the limited mobility of the uniform in difficult terrain and due to higher physical activity, the heat accumulation inside the uniform may lead to the firefighters working in shorts and shirts, putting some at an increased risk of injury (Müller et al. 2020a, p. 48). During the interview, Mr. Friedl and Mr. Löffler were very satisfied with the current situation regarding the state of training of personnel and the equipment which is applied and in use during forest fire fighting in the area around Innsbruck.

After severe fires, the landscape is often barren and without vegetation. This induces severe danger of soil erosion due to lack of stabilising vegetation above and below the ground. The most dominant factors in soil erosion risk are the topography, the rainfall intensity and the soil erodibility. Post-fire management should prioritize the reduction of soil erosion and the runoff risk, for ecological and safety reason. Preventive mitigation against erosion can be mulching, erosion barriers, slash spreading as well as planting and seeding. The open soils are also highly sensitive to trampling and mechanical operation. Salvage logging shortly after a fire can therefore cause more erosion damage then the fire itself (Valleijo et al. 2012, pp. 101).

A future forest management brings a lot of challenges with it. One challenge in terms of practicality is the financial aspect of these measurements as a detailed economic analysis of operational adaptation is still not on hand (Seidl et al. 2011, p. 704). Although the current cost of firefighting, restoration of forests, and prevention measures will only increase in the future if changes will not be implemented (Müller et al. 2020b, p.1).

One costly aspect is the reforestation after a fire, with expenses from acquiring new plants or seedlings, transportation cost to plant site, site preparation, equipment, fertilizer and human labour, just to name a few. Considering this, natural regeneration should be considered if the site conditions allow for it (Valleijo et al. 2012, p. 106). After a fire has cleared out a certain forested area, the overall time of restoration and reforestation of this area can vary from site to site. In certain cases the topsoil that lies above the bedrock has been washed out due to rain and erosion after a fire head cleared all the vegetation that previously protected this layer. Then the reforestation might be very difficult to impossible due to a lack of topsoil. This leads to forest fire affected areas to be missing forest cover for decades or centuries (Müller et al. 2020a, p. 50).

Additionally, the mountainous areas of Austria can pose difficulties to reinstate the pre fire forest stand on often steep and shallow mountain slopes (Arpaci et al. 2014, p.258). In steeper terrain the natural regeneration of the vegetation after a forest fire can take considerably longer which allows heightened geomorphic process intensity over longer periods of time (Sass et al. 2012, p. 117).

If site conditions allow for reforestation, game browsing is another task that needs to be managed. Browsing can put the newly planted trees under a much higher pressure and disrupts the forest growth that is needed to restore the pre fire vegetation stand (Müller et al. 2020a, p. 51). Regenerating plants and seedling are very susceptible to animal consumption, due to high digestibility. These plants must be protected from herbivores (Valleijo et al. 2012, p. 108).

12. Conclusion

This master's thesis attends to the topic of forest fire hazard and risk in the districts of Innsbruck-Stand and Innsbruck-Land, two districts in the state of Tyrol, Austria. The thesis is divided into three parts:

The first one covers the overall topic of forest fires to create suitable knowledge for the coming parts. It describes the often-used terminology in regard to forest fires and looks at the reasons behind ignition sources, fire spread related parameters and the overall fire behaviour. Furthermore, the current methods of fire prevention and suppression used in the Alps is described.

The second part is about the own methods and research outcomes which are displayed and analysed. Starting with an introduction of the study area, including a compact summary of the current state of the Austrian forest and the fire regime currently present in Austria. Then follows the individual explanation of the used research methods, with the methodological approach, the findings, and the short discussion having a standalone part.

At last, climate change and the consequences for the topics of forest fires and forest health is discussed, with a subsequential part on annotations for future forest and fire management. Here an outlook into the predicted future is given, assessing upcoming challenges, which could prompt adversity managing these difficulties.

12.1 Synopsis of the results

Expert interview:

The transcript of the conducted interview can be seen in the appendix and is used throughout the thesis. The interview was an important part in the process of understanding the local forest fire related conditions. The statements which concluded from the interview were used to support or oppose statements from other research. The key points from this interview were that the fire occurrence in the area shows substantial variation between the years and is usually moderately low, with a predicted increase in the coming years. Also, helicopters are an essential part in the fight of forest fire, and fire suppression would not work without the help from above. Lastly a very interesting thought was the negligence of early forest fire warning systems. The local knowledge of the area and the fire prone regions is far greater than the benefit of early warning systems.

Fuel and deadwood mapping:

The fuel and deadwood mapping had multiple objectives. The first one was to create a fuel and deadwood hazard map, which could be used as a hazard parameter in the creation of hazard maps such as in chapter 9.3. It would further enhance the accuracy of the fire hazard modelling as another crucial part of information is used in the modelling process. The second objective was the experimentation if the in situ mapping approach would come beneficial compared to other methods regarding accuracy.

The result of the mapping exercise showed a large part of the mapping area in danger category “Moderate”, some even in “High”. Although other, to a degree more essential areas around infrastructure and housing, indicated low levels of danger regarding the state fuel and deadwood accumulation. Some areas in the danger category “High” consist of very dense, sometimes shrub like beech forest. Here the density of the forest stands and the amount of deadwood lead to a categorisation into a higher danger category. Other area, often dominated by spruce show relative low danger category. Here, the forest is used commercially, which regulates the amount of deadwood accumulation and the tree density in the area, leading to a lower danger category.

As for the second objective, to answer the question of how beneficial such a mapping approach is, the result tends toward disapprove of it. The method can become very time and cost inefficient as such on-site research usually takes time and conducts a certain number of personnel.

Forest fire hazard and risk modelling:

Similar to the fuel and deadwood mapping, the modelling of the fire hazard and risk maps had a similar objective. That was to create a map, which indicated current forest fire hazard hotspots and in combination with the forest vulnerability, the forest fire risk for the study area.

The result of this modelling showed several results. As various weighting variants were used, the performance of those variants was assessed, and the weighting adapted to be re-evaluated. The first model weighted every fire hazard parameter as an equal. This led to a hazard map which comparatively large extend of low hazard categories. The distribution of pixel values in the location of the fire points showed, that this modelling approach did not exactly fit and the weighting had to be changed.

The second approach focused on the vegetation parameters and create a very similar outcome to the first modelling result. Again, the distribution led to believe, that this weighting is still inaccurate.

A better result achieved the third attempt. Here the focused of the weighting was set on to the climatic parameters. More of the map was now classified with a moderate danger category. The distribution of the pixel values also showed good improvement, compared to the previous approaches.

For the creation of the own weighting system, the documented fire points were used to generate distribution of danger categories for each fire hazard parameter, in order to prioritize parameters in the weighting, which will have a larger influence on the later pixel value distribution. The resulting map showed similarities to the variant 3, probably due to the similar weighting of the climatic parameters. The resulting distribution showed promising results and therefore was intended to be used in later processes.

In addition, the categories were subdivided to generate a more detailed fire hazard map, as it presents a far more in-depth account of small local fire hazards, and the spatial variability is seen more comprehensively.

At last, the forest fire risk map was created using the fire hazard map from variant 4 and a vulnerability map which is based on the forest function. The map depicts more than 70% of the forested area to be at a moderate to very high risk of forest fires. Especially forest areas which serve a protective function are often at high or very high risk.

12.2 Advantages and limitations of the presented study

This chapter aims to assess the here presented study's strengths and weaknesses thoroughly. An in-depth analysis of the study's benefits reveals the positive aspects and contributions that the research adds to the field of forest fire mitigation and management. Likewise, an intensive evaluation of the study's limitations reveals the boundaries and challenges experienced throughout the research process. Although the results have been shortly discussed before, the combination of the overall evaluation of the study is very important. The aim of this impartial analysis is to give an unbiased evaluation of the study's methods and results, providing valuable observations into its importance whilst recognising the surrounding limitations that have impacted its development.

Expert interview:

Conducting expert interview is certainly a known and well established qualitative social science method, used in many fields and suitable for a wide range of applications. The here conducted interview with the fire chief gave first hand expertise and in-depth knowledge, which is otherwise difficult to obtain. For example, the context specific information about the local specifications and the firefighting community dynamics in regards to firefighting. The questions could be tailored to fit very specific research related knowledge gaps, or to broaden the topic spectrum to gain insight into adjacent topics. That could lead to new questions and information exchange, which had not been covered by the prepared questions.

The interview revealed knowledge which was surprising and very helpful to the future proceedings during the study. As the interview was conducted before the fire hazard maps had been create, it helped to better understand the overall forest fire situation specific to the study area and how the process of actual firefighting works. This knowledge is very valuable considering the fact that the process of fire mitigation and management is a symbiosis between researchers, the political institutions, the community and lastly the task forces e.g., fire brigades and other emergency responders.

Although the expert interview is a conductive method, the results can lead to shortcomings. The interviewer has to rely on the interviewees perspective which brings a certain degree of subjectivity and the provided answers will usually be influenced by their personal experience and biases. This does not necessarily have to create a problem but should be reviewed when considering interview partners and selecting adequate questions.

The conducted interview sometimes lacked the detailedness in the response and some response digressed in other directions than anticipated. This is not uncommon in such interviews and can be handled with the proper design of the questionnaire. As this was the first expert interview conducted, the preparedness can certainly be improved and the conducted interview can be better steered into the proper direction, which it was originally intended for.

Another point of uncertainty is the timing of the interview. It was purposefully conducted before the work on the modelling started, to gain insights and receive answers to questions that are related to the modelling approach, which followed after. Now it could be debated if maybe a second interview could have been beneficial to discuss results from the modelling and converse about the finding with the fire department. However, this would have gone beyond the scope of this master’s thesis. This could potentially be a future scientific investigation but was never truly considered as the time resource was limited on both sides of the interview arrangement.

Fuel mapping:

Fuel mapping in forests is a valuable technique for developing hazard maps related to forest fires. This approach involves characterizing the distribution and composition of flammable vegetation and other combustible materials within a forested area. While it offers numerous advantages, it also comes with certain limitations that need to be considered for effective forest fire management.

Evidently, the precision which an in-situ mapping approach provides is of advantage to other methods such as remote sensing. On-site fuel mapping allows for detailed assessment of the spatial distribution and types of flammable materials, which enables a more accurate estimation and modeling result regarding forest fire hazard and the potential risk. The small-scale approach leads to more detailed maps which can more easily identify areas with varying fuel loads. Fire management strategies can then be tailored to specific zones, which could help to optimize resource allocation and firefighting efforts. On-site fuel mapping can also help to enhance the ecological understanding of the area of interest by revealing patterns of vegetation distribution and can help to aid in habitat management decisions. All these factors do support the methodological approach of an in-situ fuel mapping.

The previously presented result of the fuel and deadwood mapping show the just explained factors. The result is a high-resolution fuel and deadwood map, subdivided into five possible danger categories, which can help to improve forest fire hazard modelling approaches in the mapped area. It also shows which areas would need silvicultural treatment. This result might not have been possible just using remotes sensed data or with an estimation based on selected, similar forest sites, as previously done before.

Using the collected point data, many important ecological factors such as deadwood accumulation or tree health have been collected and can be used to implement silvicultural measures regarding biodiversity and forest health projects. Therefore, the data which resulted from this mapping exercise can be used for multiple applications and does not only serve one purpose. This again can’t be quiet achieved using remote sensed data or the mentioned estimation based on sample plots.

While the advantages of our method for fuel mapping are undoubtedly significant and hold the potential to enhance our understanding of fire risk assessment, it is equally essential to acknowledge the inherent limitations and challenges that accompany this approach.

Firstly, the complexity of fuel types, and their arrangement can make the on-site assessment very intricate. As different fuel types have varying combustion behaviours, the accurate categorisation and quantification of diverse fuels can become very challenging and requires specialized expertise and knowledge in the field. As the field work is very time consuming, the fuel mapping can’t be repeated in short intervals, creating a temporal variability issue. Fuel loads will vary based on seasonal and annual changes, which impacts the accuracy of hazard maps if they are not regularly updated.

In the case of this study, the created fuel and deadwood map only depicts the status for a moment in time. As the forest is in the mapping area is not excluded from management, the forest structure, fuel load, and deadwood accumulation will change in the coming months and years. This makes the map only relevant for a short amount of time and the need for an updated map will grow with each year. It could be argued that this on-site mapping exercise is only relevant in areas around homes and important infrastructure. This would cut much of the time and cost, which is otherwise consumed at large using this approach.

Conducting the on-site evaluation of fuel and deadwood parameters as fire hazard components showed that the effectiveness of this approach does not lie in large scale mapping. It is not viable to map larger areas in-situ simply based on a time factor. It works great for local small-scale areas but can not be done large scale or nationwide.

A substantial portion of the uncertainties that occurred before, during and after field work was the personal lack of experience in preparing, conducting, analysing, and evaluating such a mapping exercise. This was mostly due to a lack of sufficient amounts of previous studies regarding this kind of fuel mapping approach.

The mapping approach, which was used in this study shows which limitations still exist in obtaining spatially high resolved, accurate, and sufficient data on fire hazard parameters such as fuel distribution. The approach should be done in areas in the Wildland – Urban – Interface and in areas where models predict either a high accumulation of fuel or a high static fire danger. If done correctly, silvicultural measures can be implemented to remove excess fuels to lower the potential of forest fire ignition and protect vulnerable environments and communities.

Forest fire hazard and risk modelling:

Forest fire hazard modelling is a vital part of the forest fire management. It can help to assess areas where the hazard and the risk of a forest fire and the ignition probability is higher. Forest fire hazard modelling using a multi-parameter GIS analysis offers several advantages, but it is important to also recognize its limitations for effective forest fire management.

The here used modelling approach provides a comprehensive GIS analysis which allows for the integration of various factors, including topography, climate, vegetation, human influence, and recently documented fires. A combination of these factors is essential to create best output, as most of the influential parameters have been taken into account during the modelling process.

Another clear advantage is the raster-data resolution of the used parameters. As the resulting maps has a resolution of 10 by 10 meters, the spatial distinction between hazard and risk categories is much easier and tailored management strategies can be implemented for smaller areas. This leads to less cost and time intensive work when high hazard or risk areas can be specifically targeted. Highly detailed maps, created using a GIS, can help to aid in the effective communication with stakeholders and the public using visually compelling hazard and risk maps.

As previously stated is the occurrence and the behaviour influenced by a multitude of factors. While other fire hazard modelling approaches use only climatic conditions, the multi parameters approach enables incorporation of different data sources, enhancing the potential accuracy and reliability of the model output.

The internal program flexibility of a GIS allows for the testing of various scenarios, allowing for easy manipulation of modelling outputs by shifting the weighting distribution. This enables the incorporation of new research insights regarding the various influential forest fire factors, as the weighting of certain parameters can be easily manipulated later on.

The flexibility of the system also has some disadvantages. The complexity of multi parameter analysis will multiply with an increase of utilized forest fire parameters. The development and the maintaining of these models can become very resource intensive in terms of time, data, and expertise. The model also relies on a certain degree of assumptions about factors like fire behaviour, which can affect the accuracy of the system. This was certainly a challenge during the modelling process, as many assumptions had to be made, based on sometimes sparse research outcome availability.

As the datasets are of different data types and resolutions the data compatibility can be compromised. Ensuring the compatibility between the various datasets which are used in the model can be challenging due to the different formats, scales, and quality. For example, some datasets had to be manipulated in order to fit the raster resolution of the other parameters. This can lead to inaccuracy and possibly false claims regarding the fire hazard or fire risk assessment.

The model approach also heavily relies on the availability and the quality of the used datasets. This does not specifically affect only the here used approach but rather all models. The output of the model is definitely limited by what is fed into the system. Inaccurate results might not be the researcher's or modeller's fault but can be traced back to inaccurate and limited data. This is still a problem in many fields of science and in regions with a low data coverage. If this is the case, sometimes the needed data has to be collected for certain applications, which again can be very cost and time consuming.

As for the validation process, which has been shortly discussed before, it currently is the best option for validating the model output. Again, the data accuracy of the here used true base has to be acknowledged when comparing results of the validations of different model variant outputs. The here used data might not perfectly represent the so called "Hot Spots" in terms of high fire danger. If not recognized by the modeller, the approach of adapting the model output until it perfectly fits the desired outcome based on the used true base can lead to false or inaccurate predictions and claims regarding the forest fire hazard and risk assessment.

The results of the here presented forest fire hazard and risk model can be seen as a first approach into the direction of a static forest fire hazard and risk map, using a multi parameters GIS model approach. It takes many highly influential forest fire parameters into account and showed reasonable results using a weighting approach based on previously documented fires in the study area. Although challenges have emerged regarding the overall data accuracy, the assumptions regarding forest fire behaviour, vegetation flammability and ignition probability, and lastly the validation of the results using a somewhat flawed true base the results are still contenting. They are also to a point reasonable where confident decisions regarding forest fire management can now be made based on these results.

12.3 Comparison to previous studies

The following chapter presents a short comparative analysis of the presented findings with results from previous, similar studies focussing on fuel mapping, and forest fire hazard and - risk modelling. This comparison aims to identify similarities, differences and insights that contributed to the contextualization and validation of this master's thesis.

Before the comparison of the findings, the display of methodological variations and similarities among studies is essential. Small and large deviation in data forms (including availability, type, resolution, and accuracy), modelling approaches, and analytical techniques can be highly influential on the resulting outcome. Therefore, the understanding of these distinctions is crucial for interpreting and understanding the comparative results.

Key studies

1. Forest fire modelling:

- *Towards an integrated forest fire danger assessment system for the European Alps* by **Müller et al. 2020b**.
- *Integrating geospatial information into fire risk assessment* by **Chuvieco et al. (2014)**.
- *Development of a framework for fire risk assessment using remote sensing and geographic information system technologies* by **Chuvieco et al. (2010)**.
- *Forest and land fire vulnerability mapping based on land physical parameters in Sumatra and Kalimantan region of Indonesia* by **Yananto et al. (2017)**.
- *Modelling human-caused forest fire ignition for assessing forest fire danger in Austria* by **Arndt et al. (2013)**.
- *Using multi variate data mining techniques for estimating fire susceptibility of Tyrolean forests* by **Arpaci et al. (2014)**.

2. Fuel mapping:

- *Fuel loads and structure in Austrian coniferous forests* by **Neumann et al. (2022)**.

Structure and differences of the studies

As the structure of the presented studies is very complex, an in-depth dive into the theoretical and technical details cannot be provided. Therefore, the following descriptions of the studies are kept short. For a further comprehensive analysis, reading the studies is highly recommended.

The study from Müller et al. (2020b) focusses on the implementation of an integrated forest fire danger system for Austria, which includes spatial data of fire weather indices, human activity, lightning occurrence, forest fuels and a topography-based fire hazard estimation. This was combined into a fire danger map and validated using 2018-2019 forest fire data.

Chuvieco et al. (2010), Chuvieco et al. (2014), as well as Yananto et al. (2017) used a similar approach to Müller et al. (2020b). The objective of these studies was to improve the overall fire danger and fire risk estimation in Spain and Indonesia. Geographic information systems were used to combine a multitude of physical land parameters, some consisting of remote sensed data, and vulnerability parameters into a forest fire hazard and -risk map. The largest difference to Müller et al. (2020b) is in the use of data. This includes data selection as well as integration and modelling process of the data into the resulting map.

The goal of the study from Arndt et al. (2013) differs from the previous three as the goal is to present a modelling approach for predicting human-caused forest fire ignition using a range of socio-economic factors that are associated with an increase in forest fire danger in Austria. The study used 59 different independent socio-economic variables in the modelling approach to find out which of those are most influential to forest fires.

In the study from Arpaci et al. (2014) the main goal was to understand driving forces in forest fires. This was done by using two machine learning algorithms (MaxEnt and RandomForest) to compare historic fire data to environmental parameters such as topography, vegetation, climate, and socio-economic datasets. This differs from all the other studies as it uses machine learning algorithms to differentiate between the effects of environmental and socio-economic parameters on the susceptibility of the Tyrolean forest to forest fires.

The study from Neumann et al. (2022) has the goal to create better understanding of the fuel structure in the Austrian forest. The fuel load and structure of 93 sample plots in Austrian coniferous forest were quantified and compared to fuel types and fuels collected in other regions and biomes. The plots were all placed beside recently burned forest to ensure similar site and structural conditions. The collected data consisted of basal area, stem volume, stem density, average tree height, fuel bed depth, live fuel load and dead fuel load.

Contrasting study outcomes

The comparison of the results from previous studies to a new presented study results can entail many benefits. A systematic comparison using previous studies server as a cornerstone of some analysis, which can allow for the unveiling of patterns, the validation of methodological approaches and the contribution of new insights, which helps to broaden the understanding of the subject in question.

Although beneficial, the intricacies of this comparative analysis should be overlooked. As just mentioned, the multifaceted nature of forest fire research and differences in modelling approaches can introduce a complex dynamic. Simple differences in data source, quality, and availability can hinder a straightforward comparison of modelling results. Larger differences, such as the location of the study area, may prevent a comparative approach almost completely, as only the modelling approach can be used to contrast results.

As the availability of suitable comparable studies is limited, the evaluation of previous study outputs and the here presented modelling approach and output is very confined. A “pixel by pixel” comparison would not be very suitable, as the number of model outputs is not representative and different modelling approaches lead to different results.

However, a simple evaluation of the modelling approaches and -outputs can be made. Similarities can be found between Müller et al. (2020), Chuvieco et al. (2010), Chuvieco et al. (2014), as well as Yananto et al. (2017) and the presented modelling approach of this study. The use of a multi-parameter GIS approach is not new and has been successfully used before. Large differences lie in the use of parameters, the study area itself and the modelling approach. The most similarities with the presented study shares Müller et al. (2020b). The theoretical approach, usage of parameters, and modelling process display parallels. A further step could be the comparison of the two resulting maps, finding differences and analysing those, while keeping in mind the still existing methodological differences. A comparison based on simply looking at modelling results will not lead to any useful insight or findings to be used in future research. Therefore, no real comparison can be made or shown for this study.

The same thing applies for the comparison of the results from the study from Neumann et al. (2022) and the results from the presented fuel mapping exercise. Nation-wide sample plot analysis cannot be simply compared to in situ fuel mapping. Although again a simple comparison of results can be made but won’t represent a full-on analysis of the results. The results do not differ dramatically and show some similarities. For example, the conduced in situ fuel mapping showed a high fuel load in areas with spruce and pine, coinciding with findings from Neumann et al. (2022). Difficulties in the comparison emerge when looking at the deciduous trees. Neumann et al. (2022) did not examine any deciduous forest stand, only coniferous ones. As the forest in the study area of the in situ exercise shows a large proportion of deciduous trees, much of it can’t be compared to the study.

This shows the still existing difficulties considering forest fire research in the Alps. What potential future research directions will be and where the focuses for the coming years should lie will be addressed in the next and last chapter of this master’s thesis.

12.4 Outlook into implications and opportunities for future research

In the realm of fire hazard and risk modelling, forest fire management, and forest management, ongoing research is a vital part for addressing the ever-evolving challenges posed by wildfires and climate change. This chapter explores the implications derived from current research findings and highlights the promising opportunities that await future investigations in these interdisciplinary fields. By examining the current limitations, pressing issues, and envisioning innovative paths forward, more effective strategies for mitigating the impact of forest fires on ecosystems, communities, and the environment can be established.

A necessary step for future research is the integration of climate change. The escalating impact of climate change on fire behavior necessitates deeper research into modeling approaches that seamlessly integrate changing climatic conditions, enabling more accurate long-term fire hazard and risk assessments.

Using advanced modelling approaches in combination with machine learning and artificial intelligence should be considered. Leveraging these for fire risk modelling holds great promise. Future research should focus on enhancing predictive models through the integration of advanced algorithms and big data analytics.

A greater understanding of fuel structures and flammability of European forest is necessary to incorporate new and more accurate data into the modelling approaches. Although it is a difficult task, the acquired data could help to better understand fire hazard and fire risk, due to the enhanced comprehension of fire behaviour and fire ignition danger. Coupled with this, a better understanding of the different weighting variants for future modelling must be achieved. This again will only enhance accuracy of the prediction. Furthermore, the advancements in remote sensing technologies, coupled with Geographic Information Systems, present opportunities for more accurate fire hazard assessments and real-time monitoring in the challenging Alpine terrain.

As human influence and infrastructure is the main source of ignition, but also suffers from the consequences of forest fires, the resilience of the affected or potentially affected communities must be a key part of future research and mitigation measures. Investigating the human dimension of fire management, particularly community preparedness and resilience, is essential. This entails researching effective communication strategies, evacuation plans, and community-level risk reduction initiatives. Alongside this, more research is needed on the socioeconomic consequences, including economic losses, public health effects, and the long-term well-being of affected communities to achieve a full and comprehensive assessments of the impacts of forest fires.

As for the fire prone environments, understanding the role of fire in ecosystem dynamics is crucial. Future research should explore innovative approaches to post-fire ecosystem restoration and rehabilitation that consider ecological diversity and resilience. New tree species should be considered, which will create a healthy and sustainable forest ecosystem in the future.

The firefighters are always at the forefront when a fire ignites, and firefighting safety has to be the priority. Developing innovative technologies and strategies for ensuring the safety and well-being of firefighters during fire suppression efforts, including improved equipment, communication systems, and decision support tools is crucial. Also researching and promoting the concept of fire-adaptive communities, where residents are educated and equipped to coexist with fire-prone landscapes through proactive mitigation measures, could help the firefighting crew to concentrate more on active firefighting rather than on evacuating the local population.

The topic of forest fires is very widespread, and a multitude of factors play a role in fire occurrence, fire behaviour, and the damage these forest fires can cause. The domains of fire hazard and risk modelling, forest fire management, and forest management are at the forefront of addressing the complex and pressing issue of wildfires. In an era of changing climatic conditions and increased fire risks, the implications and opportunities presented by ongoing research are instrumental in forging a path toward resilience and sustainability.

13. Sources

Albel, B. (2016): Waldfachplan zur Verbesserung der Waldbrandbekämpfung und -vorsorge im Raum Villach. Masterarbeit. Institut für Waldbau, Department für Wald- und Bodenwissenschaften, Universität für Bodenkultur, Wien.

Alkhatib, A. (2014): A Review on Forest Fire Detection Techniques. In: International Journal of Distributed Sensor Networks, 10(3). Doi: 2014. 10.1155/2014/597368.

Amt der Tiroler Landesregierung, Abteilung Forstplanung (eds) (2019a): Wuchsgebietsbeschreibung 4.1 Nördliche Randalpen – Westteil. Innsbruck.

Amt der Tiroler Landesregierung, Abteilung Forstplanung (eds) (2019b): Wuchsgebietsbeschreibung1.2 Subkontinentale Innenalpen – Westteil. Innsbruck.

Amt der Tiroler Landesregierung, Abteilung Forstplanung (eds) (2019c): Wuchsgebietsbeschreibung 2.1 Nördliche Zwischenalpen – Westteil. Innsbruck.

Anderson, H., E. (1982): Aids to determining fuel models for estimating fire behavior. USDA For. Serv. Gen. Tech. Rep. INT-122. lntermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Arndt N., Vacik H., Koch V., Arpaci A., Gossow H. (2013): Modeling human-caused forest fire ignition for assessing forest fire danger in Austria. In: iForest 6: 315-325. Doi: 10.3832/ifor0936-006

Arpaci, A., Malowerschnig, B., Sass, O., Vacik, H. (2014): Using multi variate data mining techniques for estimating fire susceptibility of Tyrolean forests. In: Applied Geography. 53. 258–270. Doi: 10.1016/j.apgeog.2014.05.015.

Arroyo, L., Pascual, C., Manzanera, J. (2008): Fire models and methods to map fuel types: The role of remote sensing. In: Forest Ecology and Management. 256. 1239-1252. Doi: 10.1016/j.foreco.2008.06.048.

Austrian Lightning Detection and Information System (ALDIS) (2023): ALDIS Blitzdaten. URL: https://www.aldis.at/

Badeck, F., W., Lasch, P., Hauf, Y., Rock, J., Suckow, F., Thonicke, K. (2003): Steigendes klimatisches Waldbrandrisiko. In: AFZ-DerWald. 59. 90-93.

Baker, W.,L. (2003): Fires and Climate in Forested Landscapes of the U.S. Rocky Mountains. In: Veblen, T.,T., Baker, W.,L., Montenegro, G., Swetnam, T.,W. (eds): Fire and Climatic Change in Temperate Ecosystems of the Western Americas. In: Ecological Studies, 160. Springer, New York, NY. Doi: 10.1007/0-387-21710-X_5

Bär, A., Mayr, S. (2020): Bark insulation: Ten Central Alpine tree species compared. In: Forest Ecology and Management, 474. doi:10.1016/j.foreco.2020.118361

Bärić, Z., Bojovic, S., Stefanović Marković, M., Cerdà, A. (2021): Tree species flammability based on plant traits: A synthesis. In: Science of The Total Environment. 800. Doi: 10.1016/j.scitotenv.2021.149625.

Baur, P. (2006): Die Rückkehr des Waldes im südlichen Alpenraum der Schweiz: Hintergründe eines Landschaftswandels. In: Agrarwirtschaft und Agrarsoziologie. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL) (Hrsg.), Birmensdorf.

Bebi, P., Kulakowski, D., Veblen, T. (2003): Interactions Between Fire and Spruce Beetles in a Subalpine Rocky Mountain Forest Landscape. In Ecology. 84(2). 362-371. Doi: 10.1890/0012-9658

Benscoter, B., W., Thompson, B., D., K., WaddingtonB, J., M., Flannigan, M., D., Wotton C, B., M., De Groot, W., J., Turetsky, M., R. (2011): Interactive effects of vegetation, soil moisture and bulk density on depth of burning of thick organic soils. In: International Journal of Wildland Fire 2011, 20, 418–429.

BFW (Bundesforschungszentrum für Wald) (2023): Baumartenkarte. Institut für Waldinventur, Bundesforschungszentrum für Wald. URL: https://waldinventur.at/?x=1249484.54297&y=5993686.22478&z=11.20334&r=0&l=1111#/map/1/mBaumartenkarte/Bundesland/erg9

Blarquez, O., Carcaillet, C. (2010): Fire, Fuel Composition and Resilience Threshold in Subalpine Ecosystem. In: PloS one. 5(8). Doi: 10.1371/journal.pone.0012480.

Blauw, L., Logtestijn, R., Broekman, R., Aerts, R., Cornelissen, J. (2017): Tree species identity in high-latitude forests determines fire spread through fuel ladders from branches to soil and vice versa. In: Forest Ecology and Management. 400. 475-484. Doi: 10.1016/j.foreco.2017.06.023.

BML (Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft) (Hrsg.) (2022): Brennpunkt Wald. Aktionsprogramm Waldbrand: Wahrnehmen – Vermeiden – Bekämpfen. Wien.

Bohle, H., G., and Glade, T. (2007): Vulnerabilitätskonzepte in Sozial-und Naturwissenschaften. In: Naturrisiken und Sozialkatastrophen. 99–119. Elsevier.
Bond, W., J., Van Wilgen, B., W. (1996): Fire and Plants. In: Population and community biology series, 14, London. DOl: 10.10071978-94-009-1499-5

Bowman, D., M., J., S., Balch, J., K., Artaxo, P., Bond, W., J., Carlso, J., M., Cocharen, M., A., Antonio, C., M., DeFries, R., S., Doyle, J., C., Harrison, S., P., Johnston, F., H., Keeley, J., E., Krawchuk, M., A., Kull, C., A., Marston, J., B., Moritz, M., A., Prentice, I., C., Roos, C., I., Scott, A., C., Swetman, T., W., Vann der werf, G., R., Pyne, S., J., (2009): Fire in the Earth system. Supporting online material. In: Science, 324. Doi: 10.1126/science.1163886

Brillinger, D., Preisler, H., Benoit, J. (2003): Risk Assessment: A Forest Fire Example. In: Lecture Notes-Monograph. 40. 177–96. Doi: 10.2307/4356185.

Büchsenmeister. R. (2013): Verbreitung und Leistung der Fichte in Österreich. In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 3-6. ISSN: 1815-3895.

Campbell, J., B. (2002): Introduction to remote sensing. The Guilford Press: New York 2002.

Cane, D., Wastl, C., Barbarino, S., Renier, L., Schunk, C., Menzel, A. (2014): Projection of fire potential to future climate scenarios in the Alpine area: Some methodological considerations. In: Climatic Change. 119. 733-746. Doi: 10.1007/s10584-013-0775-7.

Carcaillet, C., Bergeron, Y., Richard, P., Fréchette, B., Gauthier, S., Prairie, Yves. (2001): Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? In: Journal of Ecology. 89. 930-946. Doi: 10.1111/j.1365-2745.2001.00614.x.

Castillo Soto, M. (2012): The identification and assessment of areas at risk of forest fire using fuzzy methodology. In: Applied Geography. 35. 199–207. Doi: 10.1016/j.apgeog.2012.07.001.

Chuvieco, E., Aguado, I., Jurdao, S., Pettinari, M., L., Yebra, M., Salas, J., Hantson, S., Riva, J. (2014): Integrating geospatial information into fire risk assessment. In: International Journal of Wildland Fire. 23. 606-619. Doi: 10.1071/WF12052.

Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Martín, M., Vilar, L., Martinez-Vega, J., Padrón, D., Martín, S., Salas, J. (2008): Development of a framework for fire danger assessment using remote sensing and GIS technologies. In: Ecological Modelling. 221. 46-58. Doi: 10.1016/j.ecolmodel.2008.11.017

Chuvieco, E., Congalton, R. (1989): Application of remote sensing and geographic information systems to forest fire hazard mapping. In: Remote Sensing of Environment. 29. 147-159. Doi: 10.1016/0034-4257(89)90023-0.

Climate-Data.org (2023): Klima Tirol. URL: https://de.climate-data.org/europa/oesterreich/tirol-420/ (acsessed: 29.07.2023).

Conedera, M., Cesti, G., Pezzatti, G., Zumbrunnen, T., Spinedi, F. (2006): Lightning-induced fires in the Alpine region: An increasing problem. In: Forest Ecology and Management. 234. Doi: 10.1016/j.foreco.2006.08.096.

Conedera, M., Krebs, P., Valese, E., Giampaolo, C., Schunk, C., Menzel, A., Vacik, H., Cane, D., Japelj, A., Muri, B., Ricotta, C., Oliveri, S., Pezzatti, G. (2018): Characterizing Alpine pyrogeography from fire statistics. In: Applied Geography. 98. 87-99. Doi: 10.1016/j.apgeog.2018.07.011.

Conedera, M., Tonini, M., Oleggini, L., Vega Orozco, C., Leuenberger, M., Pezzatti, G. (2015): Geospatial approach for defining the Wildland-Urban Interface in the Alpine environment. In: Computers, Environment and Urban Systems. 52. Doi: 10.1016/j.compenvurbsys.2015.02.003.

Cseresnyes, I., Szecsy, O., Csontos, P. (2011): Fire risk in Austrian pine (Pinus nigra) plantations under various temperature and wind conditions. In: Acta Botanica Croatica, 70(2), 157-166. DOI: 10.2478/v10184-010-0022-5

Dehane, B., Madrigal, J., Hernando, C., Bouhraoua, R., Guijarro, M. (2015): New bench-scale protocols for characterizing bark flammability and fire resistance in trees: Application to Algerian cork. In: Journal of Fire Sciences. 33(3). 202-217. Doi: 10.1177/0734904114568858.

Dimitrakopoulos, A., P., Mitsopoulos, I., D., Kaliva, A. (2013): Comparing flammability traits among fire-stricken (low elevation) and non-fire-stricken (high elevation) conifer forest species of Europe: a test of the Mutch hypothesis. In: Forest Systems. 22(1), 134-137. Doi: 10.5424/fs/2013221-02475

Dimitrakopoulos, A., P., Papaioannou, K., K. (2001): Flammability Assessment of Mediterranean Forest Fuels. In Fire Technology, 37, 143-152. DOI: 10.1023/A:1011641601076

Eberhart, T., L., So, C., L., Luduc, D., Labbe, N., warren, J., M. (2015): Changes in bark composition from long-term elevated CO2 treatment: implications for the management of sweetgum as a wood energy crop. In: Proceedings of the 18th Biennial southern silviculture research conference. United states department of Agriculture.

EEA (European environmental agency) (Hrsg.) (2007): European forest types. Categories and types for sustainable forest management reporting and policy. In: EEA Technical report, 9, 1-114.

Elkin, C., Gutierrez, A., Leuzinger, S., Manusch, C., Temperli, C., Rasche, L., Bugmann, H. (2013): A 2 °C warmer world is not safe for ecosystem services in the European Alps. In. Global change biology. 19. 1827-1840. Doi: 19. 10.1111/gcb.12156.

Environment and Sustainable Resource Development (ESRD) (Hrsg.) (2012): How different tree species impact the spread of wildfire. Edmonton.

European Space Agency (ESA) (2023): Sentinel – 2 Data. Copernicus Open Access hub. URL: https://scihub.copernicus.eu/

European Environment Agency (EEA) (eds) (2018): Corine Land Cover (CLC) - 2018 Version. Retrieved from URL: https://www.data.gv.at/katalog/dataset/clc2018#resources (accessed: 27.07.2023).

Evangelides, C., Nobajas, Al. (2020): Red-Edge Normalised Difference Vegetation Index (NDVI705) from Sentinel-2 imagery to assess post-fire regeneration. In: Remote Sensing Applications Society and Environment. 17. 100283. 10.1016/j.rsase.2019.100283.

Fagre, D., Peterson, D., Hessl, A. (2003): Taking the Pulse of Mountains: Ecosystem Responses to Climatic Variability. In: Climatic Change. 59. 263-282 Doi: 10.1023/A:1024427803359.

Faivre, N., Xanthopoulos, F., Moreno, J., Calzada, V., Xanthopoulos, G. (2018): Forest Fires - Sparking firesmart policies in the EU. DOI: 10.2777/181450.

Fernandes, P., M., Vega, J., A., Jimenez, E., Rigolot, E. (2008): Fire resistance of European pines. In: Forest Ecology and Management, 256, 246-255. Doi: 10.1016/j.foreco.2008.04.032

France-Presse, A. (2023): Greece Wildfire Declared Largest Ever Recorded in EU. The Guardian. URL: https://www.theguardian.com/world/2023/aug/29/greece-wildfire-declared-largest-ever-recorded-in-eu

Freudenschuß, A., Markart, G., Scheidl, C., Schadauer, K. (Hrsg.) (2021): Schutzwald in Österreich - Wissensstand und Forschungsbedarf. Bundesforschungszentrum für Wald, Wien: 80 S., ISBN 978-3-903-258419

Fritz, E. (2013): ÖBf – Forstbetrieb Oberinntal: Die Bedeutung der Fichte aus Sicht der Praxis. In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 30-31. ISSN: 1815-3895.

Genries, A., Finsinger, W., Asnong, H., Bergeron, Y., Carcaillet, C., Garneau, M., Ly, C., Ali, A. (2012): Local versus regional processes: Can soil characteristics overcome climate and fire regimes by modifying vegetation trajectories? In: Journal of Quaternary Science. Doi: 10.1002/jqs.2560.

Genries, A., Mercier, L., Lavoie, M., Muller, S., Radakovitch, O., Carcaillet, C. (2009): The effect of fire frequency on local cembra pine populations. In: Ecology. 90(2). 476-486. Doi: 10.1890/07-1740.1.

Geosphere Austria (2023): Klimakarte 1971 – 2000. URL: https://data.hub.geosphere.at/dataset/klimakarten

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M. (2014): 21st century climate change in the European Alps—A review. In: Science of The Total Environment, 493, 1138–1151. Doi:10.1016/j.scitotenv.2013.07.050

Gossow, H., Hafellner, R., Arndt, N. (2007): More forest fires in the Austrian Alps – a real coming danger? In: Managing Alpine Future. 2.

Groisman, P., Sherstyukov, B., Razuvaev, V., Knight, R., Enloe, J., Stroumentova, N., Whitfield, P., Førland, E., Hanssen-Bauer, I., Tuomenvirta, H., Aleksandersson, H., Mescherskaya, A., Karl, T.,R. (2007): Potential forest fire danger over Northern Eurasia: Changes during the 20 TH century. In: Global and Planetary Change. 56. 371-386. Doi: 10.1016/j.gloplacha.2006.07.029.

Grootemaat, S., Wright, I., Bodegom, P., Cornelissen, J., Cornwell, W. (2015): Burn or rot: Leaf traits explain why flammability and decomposability are decoupled across species. In: Functional Ecology. 29. 1486-1497. Doi: 10.1111/1365-2435.12449.

Gumming, S., G. (2001):Forest type and wildfire in the Alberta boreal mixedwood: What does fires burn? In: Ecological Applications. 11(1). 97-110.

Gustafson, E., Zollner, P., Sturtevant, B., He, H., Mladenoff, D. (2004): Influence of forest management alternatives and land type on susceptibility to fire in northern Wisconsin, USA. In: Landscape Ecology. 19. 327-341. Doi: 10.1023/B:LAND.0000030431.12912.7f.

Guyette, R., P., Dey, D., C. (2000): Human, Topography, and Wildland Fire: The Ingredients for Long-term Patterns in Ecosystems. Proceedings: Workshop on Fire, People, and the Central Hardwoods Landscape. GTR-NE-274. 2000. 29-35

Habegger, B. (2010): Factsheet: Bewertung von Risiken (ETH Zurich). Center for Security Studies (CSS), ETH Zürich. https://www.research-collection.ethz.ch/handle/20.500.11850/39096 Doi: https://doi.org/10.3929/ethz-a-006577363

Hawkes, B., Beck, J. (1999): A Wildfire Threat Rating System. In: Fire management. 59(2). 25-30.

Hengst, G., E., Dawson, J., O. (1994): Bark properties and fire resistance of selected tree species from central hardwood region of North America. In: Canadian Journal of Forest Research. 24(4): 688-696. https://doi.org/10.1139/x94-092

Héon, J., Arseneault, D., Parisien, M., A., (2014): Resistance of the boreal forest to high burn rates. In: Proceedings of the National Academy of Sciences. 111. 13888-13893. Doi: 10.1073/pnas.1409316111.

Hoch, G. (2013): Fichte – Brotbaum auch für Schädlinge? In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 13-15. ISSN: 1815-3895.

Holden, Z., Jolly, W., M. (2011): Modeling topographic influences on fuel moisture and fire danger in complex terrain to improve wildland fire management decision support. In: Forest Ecology and Management. 262. 2133-2141. 10.1016/j.foreco.2011.08.002.

Illera, P., Fernandez, A., Delgado, J., A. (1995): Temporal evolution of the NDVI as an indicator of forest fire danger. In Intenational journal remote sensing, 17(6), 1093-1105.

Jacobo, J., Peck, D. (2023): Record-Breaking Wildfires Occurred in Northern Hemisphere in 2023. ABC News. URL: https://abcnews.go.com/US/record-breaking-wildfires-occurred-northern-hemisphere-2023-new/story?id=103169036

Jenkins, M., Hebertson, E., Page, W., Jorgensen, C. (2008): Bark beetles, fuels, fires and implications for forest management in the Intermountain West. Forest Ecology and Management. 254. 16-34. Doi: 10.1016/j.foreco.2007.09.045.

Kaltenbrunner, A. (2010): Waldbrandprävention im Kanton Graubünden. In Schweizerische Zeitschrift für Forstwesen. 161(11), 460-464. Doi: 10.3188/szf.2010.0460.

Keeley, J. (2009): Fire intensity, fire severity and burn severity: A brief review and suggested usage. In: International Journal of Wildland Fire. 18. 116-126. Doi: 10.1071/WF07049.

Kilian, W., Müller, F., Starlinger, F. (1994): Die forstlichen Wuchsgebiete Österreichs. Eine Naturraum Gliederung nach waldökologischen Gesichtspunkten. In: FBVA-Berichte 82. ISSN: 0374-9037.

Kreye, J., Varner, J., Kobziar, L. (2020): Long-Duration Soil Heating Resulting from Forest Floor Duff Smoldering in Longleaf Pine Ecosystems. In: Forest Science. 66(3). 1-13. Doi: 10.1093/forsci/fxz089.

Lachat, T., Brang, P., Bolliger, M., Bollmann, K., Brändli, U., Bütler, R., Herrmann, S., Schneider, O., Wermelinger, B. (2019): Totholz im Wald: Entstehung, Bedeutung und Förderung. 2. Überarbeitete Auflage Merkblatt für die Praxis. 52. ISSN: 1422-2876.

Land Tirol (2020): Digitales Geländemodell. Land Tirol - data.tirol.gv.at. URL: https://data-tiris.opendata.arcgis.com/maps/fd330c925ce44e2ea44b3e1086d72a1b/explore?location=47.198266%2C11.554400%2C9.61

Land Tirol (2023): Verkehrswege. Land Tirol - data.tirol.gv.at. URL: https://data-tiris.opendata.arcgis.com/datasets/a3b8885df1d44c45bd7c1afe87cfecaa_0/explore

Land Tirol (2023): Gebäude. Land Tirol - data.tirol.gv.at. URL: https://data-tiris.opendata.arcgis.com/datasets/9fa2f10f991c46739d51e77dbbd39534_0/explore

Leblon, B., Alexander, M., Chen, J., White, S. (2001): Monitoring fire danger of northern boreal forests with NOAA-AVHRR NDVI images. In: International Journal of Remote Sensing, 22(14), 2839-2846. Doi: 10.1080/01431160121183

Ledermann, T., Kindermann, G. (2013): Modell für die künftige Bewirtschaftung der Fichte. In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 16-19. ISSN: 1815-3895.

Leitgeb, E., Englsich, M., Herzberger, E., Starlinger, F., (2013): Fichte und Standort – Ist die Fichte besser als Ihr Ruf? In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 7-9. ISSN: 1815-3895.

Lexer, M., J., Seidl, R. (2007): Der österreichische Wald im Klimawandel – Auswirkungen auf die Waldbewirtschaftung. In: Ländlicher Raum. Online-Fachzeitschrift des Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft. 1 – 14.

Lexer, M.J., 2001. Simulation der potentiellen natürlichen Vegetation für Österreichs Wälder. Vergleich von statischen und dynamischen Modellkonzepten. In: Forstliche Schriftenreihe, 16, Universität für Bodenkultur Wien. 166 p.

Lexer, M.J., Hönninger, K., 2001. A modified 3D-patch model for spatially explicit simulation of vegetation composition in heterogeneous landscapes. In: Forest Ecology and Management, 144, 43-65.

Lexer, M.J., Hönninger, K., Scheifinger, H., Matulla, C., Groll, N., Kromp-Kolb, H., Schadauer, K., Starlinger, F., Englisch, M., 2002. The sensitivity of Austrian forests to scenarios of climatic change: A large-scale risk assessment based on a modified gap model and forest inventory data. In: Forest Ecology and Management,162, 53-72.

Leys, B., Carcaillet, C. (2016): Subalpine fires: the roles of vegetation, climate and, ultimately, land uses. In: Climatic Change. 135. 683–697. Doi: 10.1007/s10584-016-1594-4.

Leys, B., Carcaillet, C., Blarquez, O., Lami, A., Musazzi, S., Trevisan, R. (2014): Resistance of mixed subalpine forest to fire frequency changes: The ecological function of dwarf pine (*Pinus mugo* ssp. mugo). In: Quaternary Science Reviews. 90. 60–68. Doi: 10.1016/j.quascirev.2014.02.023.

Lillis, M., Bianco, P., Loreto, F. (2009): The influence of leaf water content and isoprenoids on flammability of some Mediterranean woody species. In: International Journal of Wildland Fire. 18. 203-212. Doi:10.1071/WF07075.

Lindner, M., Fitzgerald, J., Zimmermann, N., Reyer, C., Delzon, S., van der Maaten, E., Schelhaas, M., Lasch, P., Eggers, J., van der Maaten-Theunissen, M., Suckow, F., Psomas, A., Poulter, B., Hanewinkel, M. (2014): Climate Change and European Forests: What do we know, what are the uncertainties, and what are the implications for forest management? In: Journal of Environmental Management. 146. 69-83. Doi: 10.1016/j.jenvman.2014.07.030.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M., Marchetti, M. (2010): Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. In: Forest Ecology and Management. 259. 698-709. Doi: 10.1016/j.foreco.2009.09.023.

Linn, R., Winterkamp, J., Edminster, C., Colman, J., J., Smith, W., S. (2007): Coupled influences of topography and wind on wildland fire behaviour. In: International journal of wildland fire, 16, 183-195. Doi: 10.1071/WF06078.

Liu, Y., Goodrick, S., heilman, W. (2014): Wildland fire emissions, carbon, and climate: Wildfire-climate interactions. In: Forest Ecology and Management, 317, p.80-96.

Lorz, C., Fürst, C., Galić, Z., Matijašič, D., Podrazky, V., Potočić, N., Simončič, P., Strauch, M., Vacik, H., Makeschin, F. (2010): GIS-based Probability Assessment of Natural Hazards in Forested Landscapes of Central and South-Eastern Europe. In: Environmental management. 46. 920-930. Doi: 10.1007/s00267-010-9508-0.

Malin, H. (2013): Stand Montafon – Forstfonds: Die Fichte aus Sicht eines Praktikers. In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 27-29. ISSN: 1815-3895.

Maringer, J., Conedera, M., Ascoli, D., Schmatz, D., Wohlgemuth, T. (2016): Resilience of European beech forests (*Fagus sylvatica* L.) after fire in a global change context. In: International Journal of Wildland Fire. 25. 699–710. Doi: 10.1071/WF15127.

Marlon, J., Bartlein, P., Walsh, M., Harrison, S., Brown, K., Edwards, M., Higuera, P., Power, M., Anderson, R., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F., Lavoie, M., Long, C., Minckley, T., Richard, P., Scott, A., Whitlock, C. (2009): Wildfire responses to abrupt climate change in North America. In: Proceedings of the National Academy of Sciences of the United States of America. 106. 2519-24. 10.1073/pnas.0808212106.

Martínez-Fernández, J., Vega-Garcia, C., Chuvieco, E. (2008): Human-caused wildfire risk rating for prevention planning in Spain. In: Journal of environmental management. 90. 1241-1252. Doi: 10.1016/j.jenvman.2008.07.005.

Meneses-Tovar, C., L.. (2011). NDVI as indicator of degradation. In: Unasylva 238, 62, 39-46.

Moris, J., V., Vacchiano, G., Ravetto Enri, S., Lonati, M., Motta, R., Ascoli, D. (2017): Widerstandsfähigkeit von Lärchenwäldern (*Larix decidua* Mill.) gegenüber Waldbränden in den Westalpen. In: Neue Wälder, 48, 663–683 (2017). Doi: 10.1007/s11056-017-9591-7

Mößmer, E., M (2008): Wald im Klimastress. Fakten – Folgen – Strategien. Stiftung Wald in Not. Band 16. 1. Auflage, 36 S.

Müller, M & Vilà Vilardell, L., Vacik, H., Mayer, C., Mayr, S., Carrega, P., Duche, Y., Lahaye, S., Böttcher, F., Maier, H., Schunk, C., Zimmermann, L., Ascoli, D., Cotterchio, A., Fiorucci, P., Gottero, F., Pirone, S., Rizzolo, R., Vacchiano, G., Sautter, M.(2020a). Forest fires in the Alps - State of knowledge, future challenges and options for an integrated fire management - White Paper for policy makers. Doi: 10.13140/RG.2.2.15609.42081.

Müller, M., M. (2023): Sehr geringe Waldbrandgefahr. Waldbrand-Blog Österreich. URL: https://fireblog.boku.ac.at/2023/08/04/sehr-geringe-waldbrandgefahr-9/

Müller, M., M., Vacik, H. (2017). Characteristics of lightnings igniting forest fires in Austria. In: Agricultural and Forest Meteorology, 240-241, 26–34. doi:10.1016/j.agrformet.2017.03.020

Müller, M., M., Vacik, H. (2019): AFFRI 2. Austrian Forest Fire Reasearch Initiative II. Österreichische Forschungsinitiative Waldbrand 2. Endbericht 2019. Institut für Waldbau, Department für Wald- und Bodenwissenschaften. Universität für Bodenkultur Wien.

Müller, M., M., Vacik, H., Diendorfer, G., Arpaci, A., Formayer, H., Gossow, H. (2012): Analysis of lightning-induced forest fires in Austria. In: Theoretical and Applied Climatology, 111(1-2), 183–193. doi:10.1007/s00704-012-0653-7

Müller, M., Vacik, H., Valese, E. (2015): Anomalies of the Austrian Forest Fire Regime in Comparison with Other Alpine Countries: A Research Note. In: Forests, 6(12), 903–913. doi:10.3390/f6040903

Müller, M., Vilà Vilardell, L., Vacik, H. (2020b): Towards an integrated forest fire danger assessment system for the European Alps. In: Ecological Informatics. 60. 101151. Doi: 10.1016/j.ecoinf.2020.101151.

Neumann, M., Hauk, E., Starlinger, F. (2013): Fichte – ökologisches Desaster oder Highlight der Diversität? In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 20-22. ISSN: 1815-3895.

Neumann, M., Vilà Vilardell, L., Müller, M., Vacik, H. (2022): Fuel loads and fuel structure in Austrian coniferous forests. In: International Journal of Wildland Fire, 31(7), 693-707. Doi: 10.1071/WF21161.

Osvaldova, L., M., Castellanos, J., R., S. (2019): Burning rate of selected hardwood tree species. In: Acta facultatis xylologiae zvolen, 61(2): 91−97, 20189. Doi: 10.17423/afx.2019.61.2.09

Pezzatti, G., Angelis, A., Conedera, M. (2016): Potenzielle Entwicklung der Waldbrandgefahr im Klimawandel. In: Auswirkungen des Klimawandels auf den Wald.

Pickenpack, L. (2013): Fichte ist Brotbaum für die wertschöpfungskette Forst und Holz. In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 23-24. ISSN: 1815-3895.

Pradhan, B., Suliman, M., D., H., Awang, M. (2007). Forest fire susceptibility and risk mapping using remote sensing and geographical information systems (GIS). In: Disaster Prevention and Management, 16, 344-352. Doi: 10.1108/09653560710758297.

Renn, O. (2008): Concepts of Risk: An Interdisciplinary Review Part 1: Disciplinary Risk Concepts. GAIA - Ecological Perspectives for Science and Society, 17, 50–66. Doi: 10.14512/gaia.17.1.13.
43-65.

Riyadi, M., Setiawan, Y., Taufik, M., Tonoto, P. (2022): Mapping of Potential Hazard Areas for Forest and Land Fire based on GIS in Kepulauan Meranti Regency, Riau. In: IOP Conference Series: Earth and Environmental Science. 1030. 012014. Doi: 10.1088/1755-1315/1030/1/012014.

Santoni, P., A., Balbi, J., H. (1998): Modelling of two-dimensional flame spread across a sloping fuel bed. In: Fire Safety Journal, 31, 201-225.

Sass, O., Haas, F., Schimmer, C., Heel, M., Bremer, M., Stöger, F. and Wetzel, K.-F. (2012): Impact of forest fires on geomorphic processes in the Tyrolean Limestone Alps. In: Geografiska Annaler: Series A, Physical Geography, 94, 117–133. Doi:10.1111/j.1468-0459.2012.00452.x

Schüler, S., Grabner, M., Karanitsch-Ackerl, S., Fluch, S., Jandl, R., Geburek, T., Konrad, H (2013): Fichte – fit für den Klimawandel? In: Die Fichte – Brotbaum oder Problemkind. BFW-Praxisinformation, 31, 10-12. ISSN: 1815-3895.

Schumacher, S., Bugmann, H. (2006): The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. In: Global Change Biology. 12. 1435 - 1450. Doi: 10.1111/j.1365-2486.2006.01188.x.

Schuster, R., Stüwe, K. (2022): Geological and Tectonic Setting of Austria. In: Embleton-Hamann, C. (eds) Landscapes and Landforms of Austria. World Geomorphological Landscapes. Springer, Cham. Doi: 10.1007/978-3-030-92815-5_1

Seidl, R., Rammer, W., Lexer, M., J. (2011): Adaptation options to reduce climate change vulnerability of sustainable forest management in the Austrian Alps. In: Canadian Journal of Forest Research, 41(4), 694–706. doi:10.1139/x10-235

Steixner, C. (2017): IMM. Innsbruck Mountain Museum. Institut für Architektur und Entwerfen. Fakultät für Architektur und Raumplanung. Technische Universität Wien. Wien.

Stephens, S., Agee, J., Fulé, P., North, M., Romme, W., Swetnam, T., Turner, M. (2013): Managing Forests and Fire in Changing Climates. In: Science. 342. 41-42. Doi: 10.1126/science.1240294.

Stillman, D. (2023). Canada's Wildfire Smoke Is More Dangerous Than Ever, and Climate Change Is to Blame. The Washington Post. URL: https://www.washingtonpost.com/weather/2023/09/13/canada-wildfire-smoke-climate-change/

Theobald, D., Romme, W. (2007): Expansion of the US wildland–urban interface. In: Landscape and Urban Planning. 83. 340-354. Doi: 10.1016/j.landurbplan.2007.06.002.

Tuominen, J., Lipping, T., Kuosmanen, V., Haapanen, R. (2009): Remote sensing of forest health. In: Geoscience and Remote Sensing. 30-52. Doi: 10.5772/8283.

Vacik, H., Arndt, N., Arpaci, A., Koch, V., Müller, M., Gossow, H. (2011): Charakterisierung von Waldbränden in Österreich. In: Austrian journal of forest science, 128(1): 1-32.

Valderrama-Landeros, L., Flores-de-Santiago, F., Kovacs, J., M., Flores-Verdugo, F. (2018): An assessment of commonly employed satellite-based remote sensors for mapping mangrove species in Mexico using an NDVI-based classification scheme. In: Environmental Monitoring and Assessment, 190(23). doi:10.1007/s10661-017-6399-z

Vallejo, V., R., Arianoutsou, M., Moreira,, F. (2012): Fire Ecology and Post-Fire Restoration Approaches in Southern European Forest Types. In: Post-Fire Management and Restoration of Southern European Forests, Managing Forest Ecosystems, 24, 93-119. Doi: 10.1007/978-94-007-2208-8_5

Venevsky, S., Thonicke, K., Sitch, S., Cramer, W. (2002): Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study. In: Global Change Biology. 8. 984-998. Doi: 10.1046/j.1365-2486.2002.00528.x.

Waldbrand – Datenbank Österreich (2023): Acess to the forest fire data for Austria. URL: https://fire.boku.ac.at/firedb/de/

Wang, J., Sammis, T., Gutschick, V., Gebremichael, M., Dennis, S., Harrison, R. (2010): Review of Satellite Remote Sensing Use in Forest Health Studies. In: The Open Geography Journal. 3. 28-42. Doi: 10.2174/1874923201003010028.

Wassermann, S. (2015): Das qualitative Experteninterview. In: Niederberger, M., Wassermann, S. (Hrsg.) (2015): Methoden der Experten- und Stakeholdereinbindung in der sozialwissenschaftlichen Forschung. Springer. Wiesbaden. Doi:10.1007/978-3-658-01687-6_4,

Wastl, C., Schunk, C., Leuchner, M., Pezzatti, G., Menzel, A. (2012): Recent climate change: Long-term trends in meteorological forest fire danger in the Alps. In: Agricultural and Forest Meteorology. 162-163. 1-13. Doi: 10.1016/j.agrformet.2012.04.001.

Watts, A., Kobziar, L. (2013): Smoldering Combustion and Ground Fires: Ecological Effects and Multi-Scale Significance. In: Fire Ecology. 9(1), 124-132. Doi: 10.4996/fireecology.0901124.

Weibel, P., Elkin, C., Reineking, B., Conedera, M., Bugmann, H. (2010): Waldbrandmodellierung - Möglichkeiten und Grenzen. In: Schweizerische Zeitschrift für Forstwesen. 161. 433-441. Doi: 10.3188/szf.2010.0433.

Wick, L., Moehl, A. (2006): The mid-Holocene extinction of silver fir (*Abies alba*) in the Southern Alps: A consequence of forest fires? Palaeobotanical records and forest simulations. In: Vegetation History and Archaeobotany. 15. 435-444. Doi: 10.1007/s00334-006-0051-0.

Wohlgemuth, T., Conedera, M., Kupferschmid Alblsettl, A., Moser, B., Usbeck, T., Brang, P., Dobbertln, M. (2008): Effekte des Klimawandels auf Windwurf, Waldbrand und Walddynamik im Schweizer Wald. In: Schweizerische Zeitschrift für Forstwesen, 159(10), 336-343. Doi: 10.3188/szf.2008.0336

Xanthopoulos, G., Calfapietra, C., Fernandes, P. (2012): Fire Hazard and Flammability of European Forest Types. In: Post-Fire Management and Restoration of Southern European 93 Forests, Managing Forest Ecosystems, 24, 79-92 DOI: 10.1007/978-94-007-2208-8_4.

Yananto, A., Prayoga, M., B., R., Harsoyo, B. (2017): Forest and Land Fire Vulnerability Mapping Based on Land Physical Parameters in Sumatera and Kalimantan Region of Indonesia. In: Journal of applied geospatial information, 1(2), 75-81. Doi: 10.30871/jagi.v1i2.521

Zhang, X., Wu, S., Yan, X., Chen, Z. (2016): A global classification of vegetation based on NDVI, rainfall and temperature. In: International Journal of Climatology. Doi: 10.1002/joc.4847

Zumbrunnen, T., Bugmann, H., Conedera, M., Bürgi, M. (2009): Linking Forest Fire Regimes and Climate—A Historical Analysis in a Dry Inner Alpine Valley. In: Ecosystems 12, 73–86. Doi: https://doi.org/10.1007/s10021-008-9207-3

Zumbrunnen, T., Pezzatti, G., Menéndez, P., Bugmann, H., Brgi, M., Conedera, M. (2011): Weather and human impacts on forest fires: 100 years of fire history in two climatic regions of Switzerland (Online First). In: Forest Ecology and Management. 261. 2188-2199. Doi: 10.1016/j.foreco.2010.10.009.

Appendix

1. Interview

Nils Scheffler: Also ich schreibe gerade meine Masterarbeit über das Thema „Waldbrände in Tirol“ und ich befasse mich hauptsächlich mich mit dem Gebiet Innsbruck und Innsbruck Land und mein Hauptuntersuchungsgebiet ist die Nordkette. Das Ziel der Arbeit ist zu untersuchen, ob meine Hypothese, dass durch ein verändertes Waldmanagement und verändertes Risikomanagement in Bezug auf Waldbrand die Waldbrandgefahr in den nächsten Jahren durch den Klimawandel gleich gehalten werden kann. Das heißt, dass wir auch mit höheren Temperaturen und mit verstärkten Trockenperioden, durch ein verändertes Management die Waldbrandgefahr niedriger halten können.

Andreas Friedl: Und das Management in welcher Richtung?

Nils Scheffler: Das heißt verändertes Einsatzbild der der Feuerwehr. Und da bin ich ja gerade da, um darüber was zu lernen und ein verändertes Waldmanagement würde bedeuten…

Stefan Löffler: Bepflanzung ändern!

Nils Scheffler: Genau eine andere Bepflanzung. Das heißt nicht mehr nur Fichten - Kulturen in Reihen, das ist ja nur ein monetärer Aspekt, sondern…

Stefan Löffler: Mischwälder!

Nils Scheffler: Genau, Mischwälder, vor allem weil die ein deutlich geringeres Brandrisiko haben als zum Beispiel die Fichtenmonokulturen und dann auch noch was man macht mit Totholz, abgestorbenen Bäumen, die ganze Streu, die auf dem Untergrund liegt, wie befasst man sich damit genau?

Andreas Friedl: Also Richtung Forstwirtschaft, oder?

Nils Scheffler: Genau. Der forstwirtschaftliche Aspekt und dann natürlich das Management des Waldbrandrisikos von der Seite der Feuerwehr aus. Also das ist meine Hypothese, deshalb bin ich jetzt erst mal da, um einen Einblick zu bekommen, weil ich habe nur den wissenschaftlichen Einblick auf das Waldbrandrisiko, aber ich kenne mich überhaupt nicht aus mit wie die Feuerwehr dort fungiert, agiert und wie Sie auch das Thema überhaupt einschätzen, also wie groß Sie das Risiko einschätzen und auch das zukünftige Risiko und was für Schritte eigentlich unternommen werden. Erstens in Prävention und dann auch, wenn ein Waldbrand ausgebrochen ist, ob überhaupt die Möglichkeiten bestehen, wie jetzt angenommen in den USA mit so einem großen Waldbrandmanagement überhaupt umzugehen, also, wenn man einen Waldbrand hat, von mehreren 1000 Hektar oder sowas, das ist jetzt überdimensioniert, aber einfach nur mal so, ob die Berufsfeuerwehr Innsbruck sowas handeln könnte und wie sie da vorgeht. Das sind meine Fragen und da hätte ich, also ich habe einen Fragebogen vorbereitet.

Nils Scheffler: Am Anfang würde ich gerne erstmal ihre Einschätzung hören, welche Bereiche von ihrer Meinung aus sehr gefährdet sind, welche weniger gefährdet werden, welche Bereiche gut erreichbar sind, entweder mit Helikopter, Löschflugzeugen oder auch mit Fahrzeugen, Einsatzfahrzeugen oder einfach nur Personal erreichbar sind und welche Bereiche nicht erreichbar sind.

Stefan Löffler: Tirol ist jetzt nicht vergleichbar mit Amerika oder Portugal oder Griechenland. Unsere Topographie ist immer steil bergauf. Mit Flugzeugen nicht machbar. Das ist bei uns immer nur auf Helikopter aufgebaut. Das ist jetzt über Jahrzehnte sehr gut aufgestaffelt worden. Also von den Löschgeräten und Equipment sind wir international auf top-Stand. Da kann man eigentlich gar nicht mehr viel verändern.

Stefan Löffler: Was ich noch zum Forst sagen möchte, wir sind nicht die Fachleute wegen Bepflanzungen oder so, Tirol eigentlich, ob Monokultur hin oder her wir haben sehr viel Fichte stehen das mag sein, aber wir sind im Vergleich zum Rest Österreich immer noch besser aufgestellt bezüglich Monokulturen. Wenn man an der Nordkette schaut oder auch im Süden wir haben sehr viel Mischwald, weil die Waldbesitzer eben schon vor 30 Jahren umgedacht haben, denn wir brauchen wieder ein Mischwald. Der Käferbefall in den Monokulturen ist schon viel besser geworden. Sowas dauert natürlich, das geht nicht in 10 Jahren. Da reden wir von Zeiträumen von 50 bis 60 vielleicht sogar 100 Jahren ist das wieder Urwald ist so wie wir uns früher mal gekannt hat. Temperaturmäßig ja Klimawandel haben wir alle nicht im Griff. Wobei der Forst sicher schon umdenkt, weil die Fichte mag die hohen Temperaturen nicht die wächst dementsprechend dann auch schlechter jetzt kommen natürlich die Waldbesitzer her und sagen wir möchten trotzdem einen Ertrag haben die Schwenken dann natürlich auch auf andere Bäume um.

Stefan Löffler: Wir haben rund 70% Fichte und auch Föhre stehen. Und die Föhre ist so ein Baum der so einen Waldbrand eigentlich ganz gut weggesteckt. Bei einem Brand vor einiger Zeit, wo ein starker Bewuchs von Föhren herrschte, hat die Hälfte überlebt. Aber das hat eine Woche gebrannt. Das ist wirklich ein robuster Baum. Wie gesagt Tirol ist auf dem besten Weg und andere Bundesländer beneiden unser Wald, weil wir Buche und Laubbäume fördern durch das haben wir auch dementsprechend wenig Käferbefall. Wir haben schon auch Käferbefall aber dementsprechend wenig im Gegensatz zu anderen Bundesländern.

Andreas Friedl: Jede Feuerwehr weiß eigentlich, wo ihre Problembereiche sind. Wenn man sich Innsbruck anschaut, und haben einige Waldbrände bis zu 10 Tage. (Zeigt auf Rauschbrunnen und Zirler Bahnstrecke) Das ist in den letzten 30,40 Jahren der Bereich gewesen, wo es am meisten Brände gehabt hat. Alles, was von da in Richtung Westen ist das für uns exponierte und gefährliche Gebiet.

Auf der Strecke der Mittenwalder Bahn ist die Hauptursache die Bahn. Alles, was auf der südlichen Seite ist, also Patscherkofel kannst du vergessen.

Stefan Löffler: Das gefährlichste Gebiet ist eigentlich da, wo die Bahn ist, da gibt es immer funken da haben wir jetzt eigentlich die aktivsten Brände gehabt. Also der Zug ist bei uns ein Problem. [Am Patscherkofel] ist es immer Schatten seitig da bleibt der Boden feucht genug durch das, dass die Sonneneinstrahlung erst am Abend kommt.

Andreas Friedl: Das Ziel sollte sein, dass man am Ende wie bei Lawinenwarnstufen auch Warnstufen für Waldbrand hat. Das ist meines Erachtens für die örtliche Feuerwehr nicht relevant, weil die wissen genau was gefährlich ist: das ist im Frühjahr wenn der Schnee weg ist bis im Oktober wenn es weiß wird. In Südlagen, wenn es im April schon 30 Grad hat, dann wird's gefährlich. Ob sich dann auf die Waldbrandgefahr eine andere Baumart irgendwie auswirkt, das weiß ich jetzt nicht.

Andreas Friedl: Im Vergleich zu Frankreich, wo tausende Hektar draufgehen, haben wir ja nur kleine Brände. Auch der Zeitpunkt der Branderkennung ist ein sehr früher, auch weil die Bevölkerung meist direkt daneben ist. In bestimmten Wetterlagen wie Föhn, ist so ein Brand nicht händelbar.

Stefan Löffler: Die Feuerwehr ist nie im roten Bereich, sie ist immer im schwarzen Bereich. Sonst würde man sich definitiv in Gefahrenzonen begeben. Die Helikopter probieren immer zu unterstützen und die Flanken einzugrenzen.

Nils Scheffler: Gibt es noch Wünsche in Bezug auf Equipment, Personal oder Ausbildungsmöglichkeiten?

Stefan Löffler: Der österreichische Staat hat einen Waldbrandfond und sehr viel Geld ausgegeben, es ist sehr viel Gerätschaft und Material gekommen. Von dem her sind wir eigentlich auf Top-Stand, auch international von den Gerätschaften her.

Nils Scheffler: Im Gebiet Nordkette welche Bereiche würden sie denn einschätzen sind nicht wirklich gefährdet?

Andreas Friedel: Alles, was ab da [zeigt auf Rauschbrunnen] Richtung Osten geht. In den letzten Jahren im Bereich Seegrube, Arzler Alm weiß ich keinen Brand. Hat vielleicht auch etwas mit der Lage zu tun, ist vielleicht nicht so exponiert und auch, was mit der Bewaldung mag sein da ist alles vielleicht dichter und feuchter vom Boden her. Ich weiß da keinen einzigen Einsatz in den letzten 30 Jahren.

Nils Scheffler: Welche Gebiete sind für Sie nicht erreichbar? Sind die Waldwege nutzbar für Einsatzfahrzeuge?

Andreas Friedl: Grundsätzlich schon. Aber in der Vergangenheit hat es nie da gebrannt, wo die Waldwege sind. Brände sind fast immer nur zu Fuß oder mit dem Hubschrauber erreichbar.

Stefan Löffler: Ja das ist allgemein das exponiert Gebiete, wo es schwer zugänglich ist auch mit Fahrzeugen. Mit dem Feuerwehrauto können wir bis auf die Seegrube.

Nils Scheffler: Wie viele Hubschrauber sind denn einsatzbereit?

Andreas Friedl: Also Einsatz bereit für den Waldbrand gibt es defacto gar kein Hubschrauber. Laufen tut des, dass der jeweilige Einsatzleiter über die landeswarnzentralen Hubschrauber anfordert. Es gibt ja im Endeffekt einmal das Bundesheer und private Betreiber die Hubschrauber stellen. In Innsbruck geht das schnell und je nach Typ können die Lasten von 400-500 Liter transportieren. Manche privaten gehen bis über 1000 Kilo Last. Es wird natürlich für jede Minute Geld verlangt. Wir in Tirol sind in der glücklichen Lage, dass das Netz ein Verhältnis mäßig dichtes ist. Vor allem in den Zeiten, wo es brennt, da sind wir im Frühjahr und im Herbst da haben sie keine Bauarbeiten. Da hast du in kürzester Zeit viele Hubschrauber. Wir reden da von hunderten von tausenden Euro für so einen Einsatz. Es gibt aber einfach keine Waldbrandbekämpfung ohne Hubschrauber.

Nils Scheffler: Wie viele Einsätze haben Sie denn so im Jahr?

Andreas Friedl: Dieses Jahr (2022) war Garnichts. Es war dieses Jahr in Tirol verhältnismäßig wenig, ich glaube, dass es letztes Jahr mehr war. Wie gesagt, das hängt in erster Linie vom Wetter ab.

Stefan Löffler: Wenn nach dem Winter ein gebiet durch Schadenslage austrocknet, dann ist das auch erstmal gefährdet. Weil es einfach trockener wird, weil sie einfach kaputt sind die Bäume.

Andreas Friedl: Aber grundsätzlich ist ja die Tendenz, dass es eher Richtung mehr Waldbrände geht. Weil es einfach trockener wird.

Nils Scheffler: Wie viele Personen sind hier als Feuerwehrmänner oder -frauen beschäftigt?

Andreas Friedl: Wir sind 26 Männer und Frauen, die jeden Tag im Dienst sind.

Nils Scheffler: Gibt es Schulungen zum Waldbrand und wie oft werden diese durchgeführt?

Andreas Friedl: Ja, einmal im Jahr. Da geht's aber weniger Richtung Taktik, weil das eigentlich Standardtaktik ist. Da geht es eher um gerätetechnische Geschichten. Im Endeffekt ist das [Waldbrandbekämpfung] ein Nebengeschäft, weil einen Waldbrand umgraben ist eh keine riesen Geschichte. Es ist viel Arbeit, im steilen Gelände gefährliche Arbeit aber jetzt da eine Spezialgeschichte draus zu machen ist einfach nicht so wichtig

Nils Scheffler: Wie lange dauern solche Schulungen?

Andreas Friedl: Die Flughelfer Schulung ist eine drei Tages Ausbildung. Kommunikation mit Hubschraubern und Boden. Man hat einmal diese drei Tage und dann alle paar Monate Wiederholungen mit der ganzen Mannschaft.

Nils Scheffler: Werden irgendwelche Vorwarnsysteme in Bezug auf Waldbrand von Ihnen genutzt?

Andreas Friedl: Nein. Es gibt diese Seite Waldbrand.at. Da gibt's auch eine Homepage. Das war ja der Hintergedanke. Aber noch einmal. Ich weiß, wann es bei uns gefährlich ist. Da nutzt mir diese Homepage Garnichts. Auf ganzes Bundesland gesehen wird dies vielleicht eine sinnvolle Sache sein auch vielleicht in Bezug auf Neubauprojekte kann ich mir das vorstellen, dass sowas vielleicht sinnvoll wäre. Sonst als Feuerwehr kann ich mir das ganz schlecht vorstellen.

Nils Scheffler: Wie sehen sie das Verhältnis mit anderen Akteuren wie Waldbesitzer, Politik oder dies Stadt in Bezug auf Zusammenarbeit bezüglich Waldbrände?

Andreas Friedl: Gut. Es ist wichtig, dass im Einsatzgeschehen die ganzen handelnden Personen in der Einsatzleitung sind. Wenn es da brennt, dann weiß ich ja nicht wo fängt der Bundesforst an und wo sind private Forste. Deshalb ist wichtig, dass der Forst in dem Fall in der Einsatzleitung drin sind, die auch die Örtlichkeiten kennen.

Nils Scheffler: Gibt es irgendetwas, was den Einsatz erleichtern und zur Verbesserung der Waldbrandbekämpfung beitragen würde?

Andreas Friedl: Also wir haben eine Geländepraxis, die die letzten Jahrzehnte sich bewährt hat. Das heißt Leute schnell vor Ort bringen, das ist mein Lerneffekt aus den letzten Jahrzehnten, mit massiv Hubschraubereinsatz zu arbeiten. Früher hat man immer gelernt, kein Hubschrauber, weil es Geld kostet, sondern Bundesherr und Polizei, weil die nichts kosten. Bundesheer dauert mindestens mal einen Tag, dann kommen sie. Die Kostengeschichte hat sich in den letzten Jahren verbessert, deshalb kann ich mir da eigentlich nichts wünsche, weil es kostenmäßig kein Thema mehr ist. Die Erkenntnis ist einfach, dass man in der Erstphase ganz massiv arbeiten musst, weil wenn du das Feuer nicht am ersten Tag hast, dann hast du sein Problem. Wir haben eine gute Ausbildung und auch Ausrüstung alles, was wir wollen.

Andreas Friedl: Das Gebiet was wir hier so haben, ist ja kein riesen Gebiet und haben wir verhältnismäßig viele Waldbrände.

Andreas Friedl: Das Hauptproblem im Gelände ist, du hast kein Wasser, kein Bach, Garnichts. Da musst du das Wasser alles hochfliegen. Du kannst das aktiv hochfliegen, vorausgesetzt ich habe eine Punktabwurf. Vor Jahrzehnten hat man das Konzept entwickelt, dass man Faltbehälter aufstellt, das sind 15.000 Liter Behälter, die gibt es auch in 3000 Liter varianten. Die werden mit dem Hubschrauber auf den Berg geflogen, du musst noch einen Platz finden, der eben ist, der Behälter wird dann mit dem Hubschrauber befüllt. Dann ganz einfach kommt ein Saugschlauch und eine Pumpe darein die saugt das Wasser dann zu den Strahlern. So funktioniert die Waldbrandbekämpfung im Gelände. Damit kann man punktgenau löschen. Das harte beim Waldbrand ist ja nicht nur Löschen, sondern du musst auch Graben. Solche Bodenfeuer wie oberhalb der Kranebitterklamm können auch noch nach 10 Tagen wieder entflammen.

Nils Scheffler: Was ist ihrer Meinung nach der häufigste Grund für die Entstehung von Waldbränden?

Andreas Friedl: Brandursache ist der Mensch. Mensch und Blitzschlag. Ob das Landwirte sein die was verbrenne. Glas ist fast unmöglich. Eine erste Linie der Mensch, Zigaretten, Feuer machen und nicht löschen und Blitzschlag. Sonst weiß man die Ursache oft nicht. In Abrams waren es zwei Jugendliche, die haben sich danach auch gemeldet. Es ist sonst ganz schwer nachzuvollziehen ob jetzt jemand eine Zigarette weggeworfen hat. Das ist fas unmöglich.

Andreas Friedl: Es wird der einzige richtige weg sein, dass man sagt man kommt so weit wie bei Lawinen, wo es ja Lawinenwarnstufen gibt, dass es bei den Leuten ins Bewusstsein kommt, okay Waldbrandstufe 5, und vielleicht der Raucher nicht mehr raucht. Ob das so funktioniert, sei so dahingestellt. Aber bei lawinenstufe 4 oder 5 weiß jeder das ist gefährlich und gehen schon nicht mehr ins Gelände. Bei waldbrandstufe 4 oder 5 das die Leute nichtmehr auf den Berg gehen und rauchen, das kann ich mir nicht vorstellen. Aber das wär ja das Ziel. Was es ja gibt, sind Infos über die Medien. Akute Waldbrandgefahr, aufpassen! Ob das aber auch bei den Leuten ankommt ist die Frage.

Andreas Friedl: Auch wenn die Sommer der letzten Jahren trocken waren, wir haben ja immer regen gehabt. Hat vielleicht schon gelangt.

Andreas Friedl: Es kommt darauf an, wie die Leute drauf reagieren. Bei Lawinenstufe 4 gehe ich nicht mehr ins Gelände. Bei Waldbrandgefährdung 4 oder 5, dass dort jetzt niemand mehr spazieren geht und raucht das glaube ich nicht.

Nils Scheffler: Wie schätzen sie die jetzige Waldbrandgefährdung auf einer Skala von 1 sehr gering bis 10 sehr hoch, auf dieses Jahr bezogen auf den Raum Innsbruck ein?

Andreas Friedl: 5. Übers Jahr gesehen.

Nils Scheffler: Wie schätzen sie die zukünftige Waldbrandgefährdung auf einer Skala von 1 sehr gering bis 10 sehr hoch bezogen auf den Raum Innsbruck ein?

Andreas Friedl: Grundsätzlich soll es ja trockener werden, wo bei man das ja nicht unbedingt sagen kann, wobei wenn es trockener wird, es auch gefährlicher wird. Ich glaube dieses Jahr (2022) ist eine Fünf, also ein normales Jahr. Ich glaube das es eher so Richtung 6 und 7 gehen wird. Das es einfach gefährlicher wird. Dieses Jahr war ein normaler Sommer, es hart aber mal Wochen gegeben, wo es gefährlicher war. Im März war es ja mal so warm und der Mai war ja so feucht. Der April war sicher gefährlicher.

Nils Scheffler: Führt eine verstärkte touristische Nutzung an der Nordkette ihrer Meinung nach zu einer höheren Waldbrandgefahr?

Andreas Friedl: Eher nicht. In dem Bereich, das wo es gebrannt hat, waren Touristen eher weniger unterwegs. Da sind ehre einheimische unterwegs, denn das kennt keiner. Wo gehen die Touristen hin? Seegrube! Der Großteil der Touristen geht ja nicht zu Fuß, sondern fährt mit der Gondel hoch.

Nils Scheffler: Welche Art von Waldbestand haten sie für am gefährdetsten in Bezug auf Brände?

Stefan Löffler: Das ist der Nadelwald. Alles, was mit Nadeln zu tun hat, ist gefährdet. Sie sind luftdurchlässiger und oft dichter. Hat trockenen Untergrund. Der Nadelbaum ist gefährdeter als der Laubbaum.

Nils Scheffler: Wie schätzen sie das öffentliche Bewusstsein bezüglich der Waldrandgefahr ein. Wieder auf einer Skala von 1 bis 5?

Andreas Friedl: 2. Seien wir mal nicht zu negativ.

Nils Scheffler: Glaube sie eine Veränderung des Waldbestandes würde eine Verringerung der Waldbrandgefahr mit sich bringen?

Andreas Friedl: Vielleicht. Wenn es viel Laubbaum wäre. Wenn man sich das Gelände mal anschaut mit großen offenen Flächen und es dichte wachsen würde dann vielleicht. Aber ob das realistisch ist, weiß ich nicht. Vor allem wie weit Laubbäume dort oben wachsen können.

End of formal interview. A short personal conversation was continued, but with no informational value to the master thesis.

Eidesstattliche Erklärung

Ich erkläre hiermit an Eides statt durch meine eigenhändige Unterschrift, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe. Alle Stellen, die wörtlich oder inhaltlich den angegebenen Quellen entnommen wurden, sind als solche kenntlich gemacht.

Die vorliegende Arbeit wurde bisher in gleicher oder ähnlicher Form noch nicht als Magister-/Master-/Diplomarbeit/Dissertation eingereicht.

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