Characterisation of the ignition factors of forest fires in Styria

Master thesis submitted by

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Affidavit

I hereby declare that I am the sole author of this work; no assistance other than that permitted has been used and all quotes and concepts taken from unpublished sources, published literature or the internet in wording or in basic content have been identified by footnotes or with precise source citations.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

August 2019

Matouš Hořejší

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List of abbreviations

A	diameter of burned area
AD	anno Domini
AFFRI	Austrian Forest Fire Research Initiative
ALP FFIRS	Alpine Forest Fire Warning System
ALDIS	Austrian Lightning Detection and Information System
ANOVA	Analysis of Variance
B	Buffer zone
BGLD	Burgenland
BMLFUW	Federal Ministry of Agriculture and Forestry, Environment and Water
(BMNT)	Management – currently Federal Ministry for Sustainability and Tourism
BUI	Buildup Index
CFFDRS	Canadian Forest Fire Danger Rating System
DBH	Diameter at breast height
DC	Drought Code
DMC	Duff Moisture Code
FFMC	Fine Fuel Moisture Code
FIRIA Change	Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate
FWI	Fire Weather Index
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
ISI	Initial Spread Index
K	Carinthia
LMI	Lightning Map Index
LLS	Lightning Location System
NOE	Lower Austria
OOE	Upper Austria
R	R - programming language for statistical computing
R	Radius of fire occurrence

rh	Relative humidity
SBG	Salzburg
STMK	Styria
T	Tirol
VBG	Vorarlberg
Vfm	Growing stock [m^3]
W	Vienna
w	Wind speed
ZAMG	Central Institute for Meteorology and Geodynamics

Abstract

Austria is dominated by mountains and mostly alpine environments, which implies a highly diverse environment in terms of climate, vegetation and fauna. This results in a wide variety of sites with different levels of susceptibility and predisposition to forest fire. Several research initiatives have been launched in Austria to study fire danger rating, fire behavior modeling and fire management. The Austrian Forest Fire Research Initiative (AFFRI) identified forest fire “hot spots” depending on vegetation, climate and socio-economic conditions. Styria is one of the provinces of Austria with a high abundance of forest fire events. 20% of all forest fires in Austria occurring during the last 50 years have been in Styria, which makes proper fire management important.

The objectives of this thesis are to analyze the behavior and the ignition factors of forest fires from the years 1957 – 2016. A digital elevation model, a forest map with forest inventory data and a set of climatic data containing information about precipitation, temperature and speed of wind will be used to analyze the spatial distribution of forest fires and provide a characterization of the fire events according to seasonality, cause of ignition, size and impact of vegetation.

To characterize ignition factors of wildfires, 3 pilot areas will be selected in three different climatic zones. In each of these three regions 3 different groups of forest fires will be chosen. The first group represents wildfires caused by natural agents, the second and third group show artificial forest fires based on diverse conditions of ignitions (high or low human activity). The pilot areas will help to understand the influence of different factors on forest fire ignition, behavior and occurrence. The risk of thunderstorms igniting forest fires is mainly influence by topography, especially elevation and terrain steepness and secondly by forest stand data, representing the share of coniferous tree species and canopy closure.

Abstract (deutsch)

Ein großer Teil Österreichs ist von alpiner Landschaft geprägt. Dies bringt eine reiche Vielfalt an Flora und Fauna sowie unterschiedlichste klimatische Bedingungen mit sich. Die Prädisposition der Wälder für das Auftreten von Waldbränden zeigt dabei eine ebenso große Bandbreite. In diversen Forschungsarbeiten wurde die Brandgefahr in Österreich evaluiert, das Verhalten von Feuern modelliert und versucht Bewirtschaftungsansätze für die Prävention zu finden. Im Rahmen der österreichischen Waldbrandinitiative (AFFRI) sind besonders durch Waldbrand gefährdete Gebiete auf Grund von morphologischen, klimatischen und sozioökonomischen Merkmalen identifiziert worden. Fast ein Viertel aller Waldbrände Österreichs ereignet sich in der Steiermark. Ein umfangreiches Waldbrandmanagement ist deshalb unerlässlich.

Ziel dieser Arbeit ist die Analyse des Auftretens und der Ursachen der Waldbrände in den Jahren 1957 bis 2016. Um die räumlich-zeitlich Verteilung der Waldbrände, deren Brandursache, Größe und Einfluss auf die Vegetation zu analysieren werden klimatologische Daten (Niederschlag, Temperatur, Windgeschwindigkeiten), Waldinventurdaten, Fernerkundungsdaten und ein digitales Geländemodell herangezogen. Um die Faktoren für das Auftreten von Waldbränden zu untersuchen, wurden 3 Pilotgebiete in 3 klimatisch unterschiedlich ausgeprägten Zonen verwendet. Innerhalb dieser Gebiete wurden 3 Kategorien von Waldbränden unterschieden. Brände, die durch natürliche Ereignisse hervorgerufen wurden, sowie Waldbrände welche in Regionen mit geringer und mit hoher menschlicher Aktivität auftreten. Es zeigte sich generell, dass die Charakteristik der Vegetation einen geringen Einfluss auf das Auftreten von Bränden hat. Bei natürlich ausgelösten Bränden sind neben dem Nadelholzanteil und dem Kronenschluss hauptsächlich topographische Merkmale maßgeblich für das Auftreten.

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1. Introduction

1.1. Problem statement

"The protection of life, property, and forest resources requires increasingly more effective forest fire management. A well-funded fire protection program is fundamental to insuring that investments in intensive forest management reach fruition" (Stocks et al. 1989)

"Understanding the environmental and human determinants of forest fire ignitions is crucial for landscape management." (Reineking et al. 2010)

Forest fires on the European continent are usually associated with Mediterranean countries such as Greece, Italy, Spain or Portugal, where they damage millions of hectares of forest land every year (Wastl et al. 2012; Giglio et al. 2006), but they can also deeply affect Central European forests and Alpine regions (Stocks et al. 1989). Slopes exposed to the south in the Alps are affected by forest fires almost every single year. Forest fires bigger than 0,1 ha burned 68 835 ha of forest land and occurred in 7646 cases around the Alps in the period of 2000-2009 (Valese et al. 2011). The temperature has risen about 0,7 degrees Celsius since the beginning of the 20th century, and it will increase by 0,8 – 3,5°C by 2100 AD, depending on different scenarios (IPCC 2007). A higher temperature will increase fuel dryness, therefore it can be assumed that the fire risk will rise and hence the number of fires will increase. This effect will become more severe in those regions where precipitation levels decrease (Moriondo et al. 2006).

Effect of forest fires is much larger in mountains regions than in lowlands because of the vulnerability of the ecosystem. Forests in mountainous areas are characterized by steep terrain - which helps the fire to spread faster (Schunk et al. 2013) - as well as relatively open forest canopies to the timberline, which leads to the faster drying of fuel by wind and sunshine, more severe fire behavior and difficult fire-fighter operations (Schunk et al. 2013). The growth of bark beetle outbreaks in the future (Seidl and Rammer 2017) will likewise probably increase the vulnerability of mountainous forests to a wildfire, because of the availability of appropriate fuel and influence on fire behavior (Hicke et al. 2012).

We also have to consider that most of the mountain forests have to fulfill a protective function, and that forest fires increase the risk of secondary destructive elements e.g. debris flows, rock fall and avalanches and especially erosion (Ryu et al. 2017; Vacik and Gossow 2011). Forests with a protective function size make up around 21% of the whole forest area in Austria, that is around 830 000 hectares. Most of the forests with a protection function are situated between 1300 and 2100 meters above sea level (BFW 2010a, 2016), the area where we can find a considerable number of late summer fires.

Besides the huge differences in topography in the Alpine region, the Alps also show a large temporal variability of wildfires. The Southern Alps regions (e.g. France, Italy) become liable to wildfires mainly in winter and early spring between December and April. The main fire season in the north of the Alps can be defined between April and December (Reinhard et al. 2005b).

Styria, the green heart of Austria, is the province of Austria with the biggest relative size of forest area. Forests cover 61,4% of land in this province, which represent more than one million forested hectares. Protection forests are spread out on 172 000 hectares that total more than 17% of the whole forest area (BFW 2010a). Styria offers a unique variance of diverse ecosystems from lowland *Quercetum petraeae – cerris* forests on the southeast of the province to high alpine areas as Dachsteinplateau, where *Rhododendro ferruginei-Pinetum prostratae* phytocoenosis take a place (Kilian et al. 1994).

1.2. Objectives

The objective of this master thesis is to provide comprehensive information about the forest fire situation in the Austrian province of Styria and to analyze wildfires which occurred there. The collection of forest fire records extends to half of the 20th Century, providing the possibility to chart the long-term trend in seasonality, number and size of forest fires over the last 60 years. The focus of this work will be directed to the cause of ignition. To be able to characterize patterns, which are characteristic for different causes of ignition, three groups of forest fires will be analyzed according to the cause of the ignition. The first group will be characterized by forest fires which were caused naturally and ignited by lightning during thunderstorms. The second group of fires will represent artificial forest fires caused in areas with high human activity and the third group shows events caused by humans in districts with low human activity. The analyses are directed by the meteorological situation which preceded the fire ignition and took place afterwards, the forest stand parameters, and topography. For such an analysis, records of wildfires from the Austrian Forest Fire Databases which took place between the years 2000 and 2016 will be used.

The following objectives have been formulated:

- To characterize the forest fire situation in Styria
- To analyze forest fires regarding the cause of ignition, and topographical and forest stand parameters.
- To create a model, which will indicate probability of forest fire ignition by natural agents.

2. Overview

2.1.Situation and regime of forest fires in Austria

The key factors of fire propagation (weather, fuel, terrain) vary in the Alps as well as in Austria (Valese et al. 2011) and can change locally and/or on year to year basis as well as during a year (Böhm et al. 2001). Geographically the Alps are a transition area between the Mediterranean, the Atlantic, a Eurasian zone, which has an influence on landscape structure, climate and forest composition. These factors affect also local spatial ecology and demography. Mostly we can consider Austrian forests as coniferous dominated forest. Two important gradients drive local climate, distance from the sea and altitude. Besides we have to consider microclimatic differences which are generally associated with slope aspect. Only 2% of the wildfires and 0,5% burned area which happened in the Alps took a place in Austria (Valese et al. 2011).

In the last 20 years we could see a higher focus of research to the topic wildfire in the Alps. Especially after two intensive fire years in 2003 and 2007 wildfires become an issue in Austria as well (Gossow et al. 2007). This interest based on the growing number of forest fire events. The years 2011, 2012, 2015 and 2017 (see figure no. 1 and 2 below) were the worst since the database has been established (Müller 2018). Fire activity doesn't have changed just due to climatic change (Moriondo et al. 2006), but also because of the change in land use and forest stand conditions – for example in a unification of forest stands and increase of fuel loads (Zumbrunnen et al. 2012).

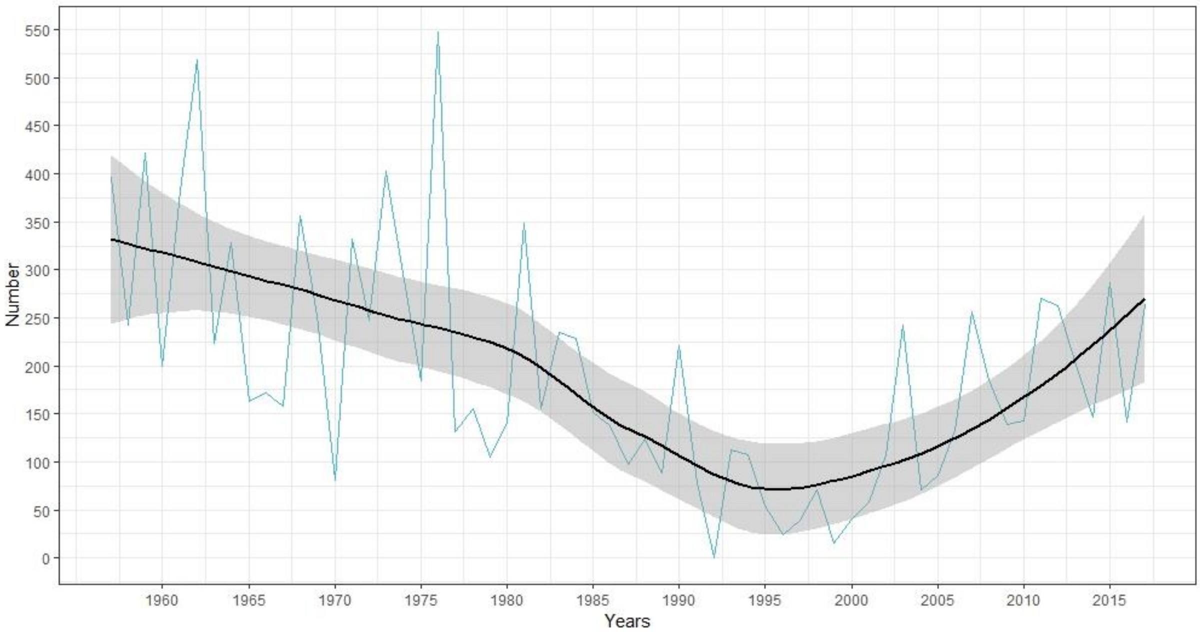

Figure 1: Number of forest fires in Austria 1957 to 2017 [n = 11760](Waldbrand-Datenbank Österreich 2018; BMNT 1992)

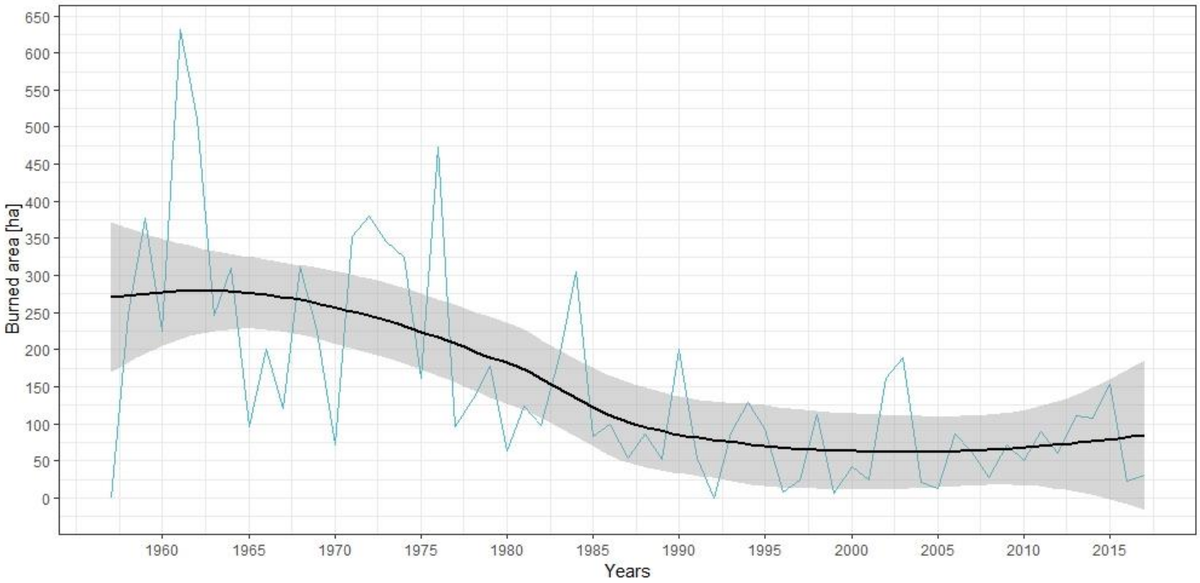

Figure 2: Area effected by forest fires per year in Austria 1957 to 2017 [n = 11760](Waldbrand-Datenbank Österreich 2018; BMNT 1992)

2.2. Forest Fire Database in Austria

A database of wildfires for Austria has been established recently within projects related to the Austrian Forest Fire Research Initiative (AFFRI) and the Alpine Space project Alp-FFIRS (Alpine Forest Fire waRning System) (Vacik et al. 2011). Alp-FFIRS was launched in September 2009 to monitor and reduce forest fire hazard in Alpine region area and it led to a homogenization of data collection. It was for the first time possible to share data about forest fire through Alpine countries and regions (Valese et al. 2011).

The former wildfire statistics covered a time period between 1953 to 1991 and were provided by Federal Ministry of Sustainability and Tourism (Bundesministerium für Nachhaltigkeit und Tourismus or BMNT). Data from this database are not part of the new (current) wildfire database, because information about location and date were missing (Vacik et al. 2011). This database includes information about the number of fires and burned area for each province. Also, the database contains information about the type of wildfire, age class of forest stand and cause of a fire. Unfortunately, not for each year complete information is available.

The new (current) wildfire database is online accessible under the link: http://fire.boku.ac.at/firedb/. The database has been established under projects AFFRI (Austrian Forest Fire Research Initiative), ALP FFIRS (Alpine Forest Fire Warning System) and FIRIA (Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate Change) since 2008 (Institut für Waldbau 2018). The oldest record in the database is from the year 1540 and so far, it contains more than 6000 wildfire records. The database has been coherent since 1993 and includes most of the larger forest fires. Since 2003 it has registered all relevant fires (Müller 2018).

Different ways were used to establish the wildfire database and to investigate previous fire events. On one side information were extracted from public available platforms as www.wax.at and www.feuerwerh-news.at. The second way was by directly addressing to fire brigades and municipalities all over Austria. Due this research it has been possible to record 1170 fires between 1993 and 2009. Records in the database have incorporated information for each wildfire (e.g. date and time of ignition, time of notification, duration of the fire, location and elevation, size of area damaged, buffer zone, cause of fire, tree species, vegetation type, level of reliability) since 1993 (Vacik et al. 2011).

2.3. Temporal distribution of fires in Austria

Austrian fire season has generally two peaks during a year. The first (spring) one peak comes on the end of the March, beginning of April. Summer peak occurs usually in July and August (Gossow et al. 2007; Vacik et al. 2011; Müller et al. 2015).

Spring fires are seldom caused by natural agents and are predominantly caused by human activities. Forest accumulate a large amount of dry fuel during winter months. This situation together with rising temperatures in spring months cause an increasing probability of fire ignition. Also, an occurrence of warm and strong "Foehn" winds can influence locally vulnerability to wildfires (Müller et al. 2013).

Summer fires are usually associated with high temperatures, long periods without precipitation and low air humidity, which cause a drying out of fuels. Causes for fire ignition in the summer months are quite balanced and vary between years, but in general it' s about 60% for artificially caused forest fires, 40% of wildfires are caused during thunderstorm due lightning (Müller et al. 2013).

In 21 fire seasons between the years 1993 – 2013 in average 23 hectares of forest land were burned down in spring by 57 fires respectively 22 hectares in summer months by 39 wildfires (Müller et al. 2015). Figure 3 shows the shift in temporal occurrence of forest fires over the last 50 years. Most of the wildfires happened in springtime until the beginning of 1980s. It is possible to see an increase of summer fires since that time. Summer forest fires pose more than half of the share after the year 2000.

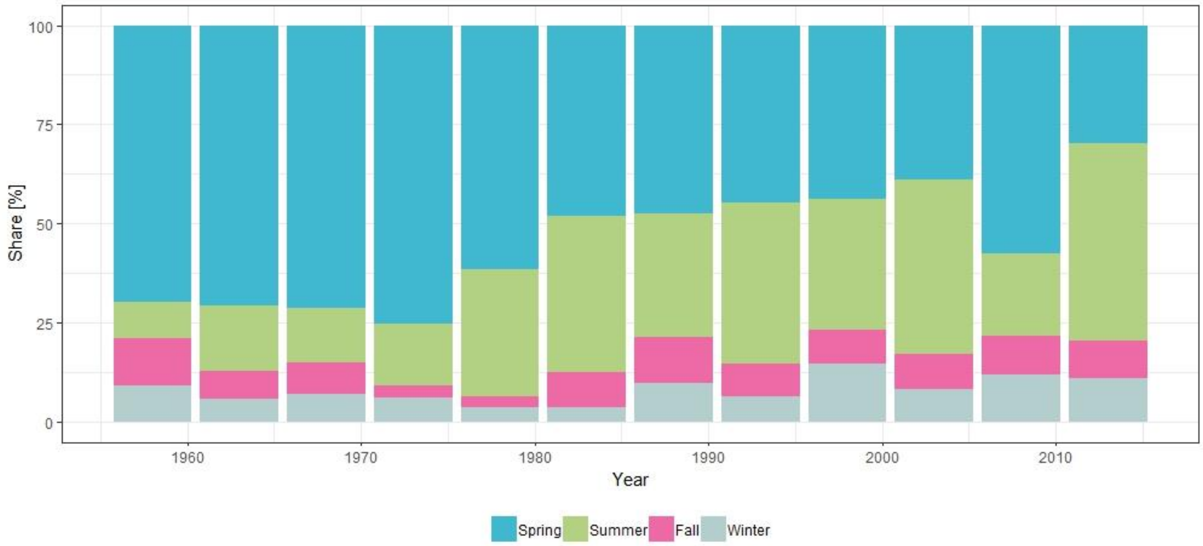

Figure 3: Number of forest fires by season - sum of five years [n = 11760] (Waldbrand-Datenbank Österreich 2018; BMNT 1992)

2.4.Causes of Ignition

Two agents can be identified, which lead to wildfire ignition in Austria. The first one is natural, it compromises mostly lightning. The second group of fires is anthropogenically caused, which are connected to human activity (Arndt et al. 2013; Vacik et al. 2011). Predominant causes of wildfires in most parts of the world are human activity (e.g. Mediterranean region 85% (Martínez et al. 2009) – 95%, South Asia (90%), South America (85%), Northeast Asia (80%) (IPCC 2007)). In Austria the share of artificial fires is bit smaller, especially in some parts of the country (e.g. Carinthia), due hummocky landscape and high number of thunderstorms in summer months (Vacik and Gossow 2011). Around 15% of forest fires are ignited by lightning on year to year basis, up to 40% in the summer months, cf. Figure 4. (Müller et al. 2013) – in the summer months of the year 2017 it happened for the first time that lightning caused more than 50% forest fires in Austrian ‘s forests (Müller 2018).

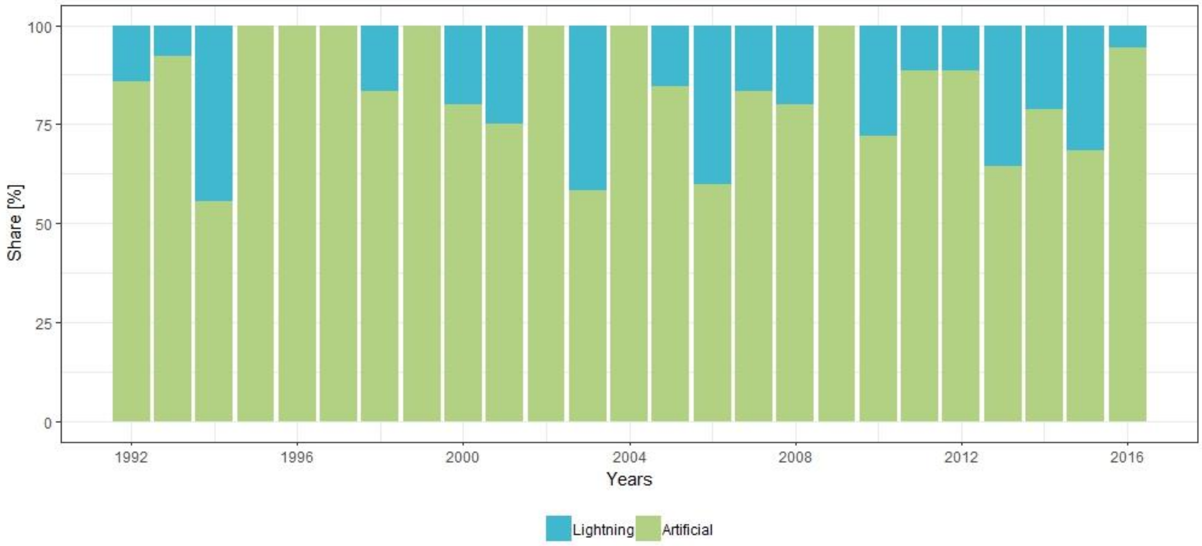

Figure 4: Cause of ignition during a year [n = 3463](Waldbrand-Datenbank Österreich 2018)

2.5.Spatial distribution of fires in Austria

Austria has a wide variability in wildfire occurrence in sense of spatial distribution and the difference between the most prone areas and less vulnerable province is more than a factor of 10. An overview of the years 1993 – 2017 is given in Table 1. Most of the fires happened in province Lower Austria (853), followed by Tirol (669), Carinthia (586) Styria (568), Upper Austria (285), Salzburg (107) and Vorarlberg (72). The lowest amount of records is from the city of Vienna (50), which has also the smallest forested area.

Table 1: Basic indicators about forest and fires in the provinces (1993 – 2017) [n = 3463](Waldbrand-Datenbank Österreich 2018)

	BGLD	K	NOE	OOE	SBG	STMK	T	VBG	W
Forest cover (%)	33,9	61,2	40,0	41,6	52,5	61,4	41,2	37,4	21,5
Area (km^2)	3692	9538	19186	11980	7156	16401	12640	2601	415
Forest area (km^2)	1251,59	5837,26	7674,40	4983,68	3756,90	10070,21	5207,68	972,77	89,23
No. of fires	107	586	853	285	158	568	669	72	50
No. of fires/year	4,46	24,42	35,54	11,88	6,58	23,67	27,88	3,00	2,08
n/100 km^2 1*	8,55	10,04	11,11	5,72	4,21	5,64	12,85	7,40	56,04
n/100 km^2/year 2*	0,36	0,42	0,46	0,24	0,18	0,24	0,54	0,31	2,33
m^2/1 km^2 3*	461,41	579,05	815,88	174,35	173,81	266,05	540,45	413,62	2257,56
m^2/1 km^2/year 4*	19,23	24,13	33,99	7,26	7,24	11,09	22,52	17,23	94,07

BGLD – Burgenland, K – Carinthia, NOE – Lower Austria, OOE - Upper Austria, SBG – Salzburg, STMK – Styria, T – Tirol, VBG – Vorarlberg, W – Vienna

1 - Number of fires per 100 km^2, 2* number of fires per 100 km2 per year, 3* burned forest land per 1 km2, 4* burned forest land per 1km per year.*

The biggest density of forest fires has the city of Vienna, where $2{,}33x10^{-4}$ ha^{-1} wildfires occur every single year. Tirol has $5{,}4x10^{-5}$ ha^{-1} forest fires and 0,22 m^2ha^{-1} burned area per year. Lower Austria is on the second place with a relative size of forest fires with 0,33 m^2ha^{-1}

burned forest land and $4,6x10^{-5}ha^{-1}$ forest fires a year. The lowest relative number of forest fires is in the province of Salzburg with $1,8x10^{-5}ha^{-1}$ forest fires a year, which is less than 13 times compared to the city of Vienna. Fires burn relatively small areas in the province Upper Austria and Salzburg. In both, forests are damaged on 0,07 $m^2ha^{-1}h$, that is 13,4 times smaller than in Vienna.

Large spatial variability can be found in the causes of wildfire ignition – see Table 2. The biggest share of fires ignited during thunderstorms by lightning has the province of Salzburg (22,15%) and Tirol (22,12%), followed by Styria and Carinthia, where every fifth forest fire is caused by lightning. The smallest share of natural forest fires is recorded in Burgenland with less than one percent, a small role plays lightning as a fire trigger in the city of Vienna (4,00%) and in Vorarlberg (5,56%) also.

Table 2: Number and share of forest fires classified by cause of ignition in the province from 1993 to 2017 [n = 3463](Waldbrand-Datenbank Österreich 2018)

	BGLD	K	NOE	OOE	SBG	STMK	T	VBG	W
Lightning	1	113	92	44	35	116	148	4	2
Artificial	106	473	761	241	123	452	521	68	48
Total	107	586	853	285	158	568	669	72	50
Share (%)	0,93	19,28	10,79	15,44	22,15	20,42	22,12	5,56	4,00

BGLD – Burgenland, K – Carinthia, NOE – Lower Austria, OOE – Upper Austria, SBG – Salzburg, STMK – Styria, T – Tirol, VBG – Vorarlberg, W – Vienna

3. Material and Methods

3.1. Site Description

3.1.1. Styria

Das grüne Herz Österreichs *(The green heart of Austria)* is a touristic motto from the early '70s (Kleine Zeitung 2012), which really characterizes the province of Styria well, because it has the highest share of forest cover (61,4% of province) from all provinces of Austria (Statistik Austria 2018; BFW 2010a). Forests cover 1 006 000 hectares of Styria (BFW 2010a; Zuschnitt 2013).

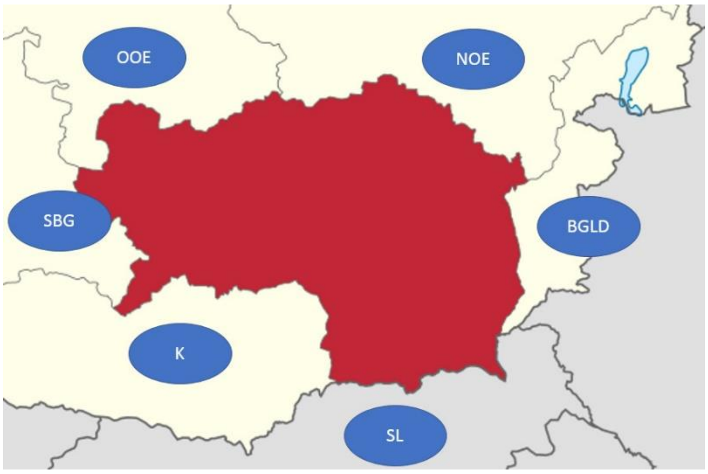

Figure 5: Map of Styria (wikipedia.org)18.4.2018

The average stock is 354 m^3 per hectare. The annual yield is 8,2 m^3 per hectare and the average amount harvested is 7,4 m^3 per hectare (BFW 2010a).

Styria spreads out on the southeast of Austria as the second largest out of nine Austrian provinces, covering 16 401 km^2 (Statistik Austria 2018). Styria borders Austrian provinces Upper Austria (*Oberösterreich*) and Lower Austria (*Niederösterreich)* to the north, province Burgenland (*Burgenland*) to the east, province Salzburg (*Salzburg)* to the west, province Carinthia (*Kärnten*) and Slovenia (*Republika Slovenija*) to the south – cf. Figure 5. The highest point of Styria is Hohe Dachstein with 2995 m and the lowest one is on the Slovenian borders close to Bad Radkersburg with 199 m. Styria is predominantly a mountainous province, the Alps are covering close to 70% of the country (Strunz 2017).

3.1.2. Species composition

More than two-thirds of the trees species, which grow in Styria are Norway Spruces *(Picea abies 70,5%)*, second highest share between conifers has European Larch *(Larix decidua 5,5%)*, with the same share of 2,8% on third place take a place Silver Fir *(Abies alba)* and Scots Pine *(Pinus sylvestris)***.** Swiss Stone Pine *(Pinus cembra)* has a share of 0,2% (BFW 2010b).

Deciduous trees cover 18,2% of Styrian forests – hardwood 13% and softwood 5,2%. The highest share of hardwood has European beech *(Fagus sylvatica 6,2%)* followed by European ash *(Fraxinus excelsior 1,5%)* and by trees of the genus maple (*Acer)* with 1,4%. European hornbeam *(Carpinus betulus)* have 1% share and trees of the genus *Quercus* - oak trees (0,9%). Negligible shares have elms *(Ulmus),* sweet chestnuts *(Castanea sativa),* black locust *(Robinia pseudoacaia)*, Sorbus and prunus *(Sorbus et Prunus) (BFW 2010b).*

European white birch *(Betula pendula)* has with 1,5% the highest share between the softwood species. Second is grey alder (*Alnus incana)* with the same share as birch, third is black alder *(Alnus glutinosa)* which has 1% share between all trees in Styria. Trees in genus *Tilia* take a share of 0,6%. Negligible shares have poplar *(Populus)* and willows *(Salix)* *(BFW 2010b)*

3.1.3. Climate and forest vegetation types

Kilian et al. (1994) have defined forest ecoregions of Austria in the publication: „Die forstlichen Wuchsgebiete Österreichs – Eine Naturraumgliederung nach waldökologischen Gesichtspunkten".

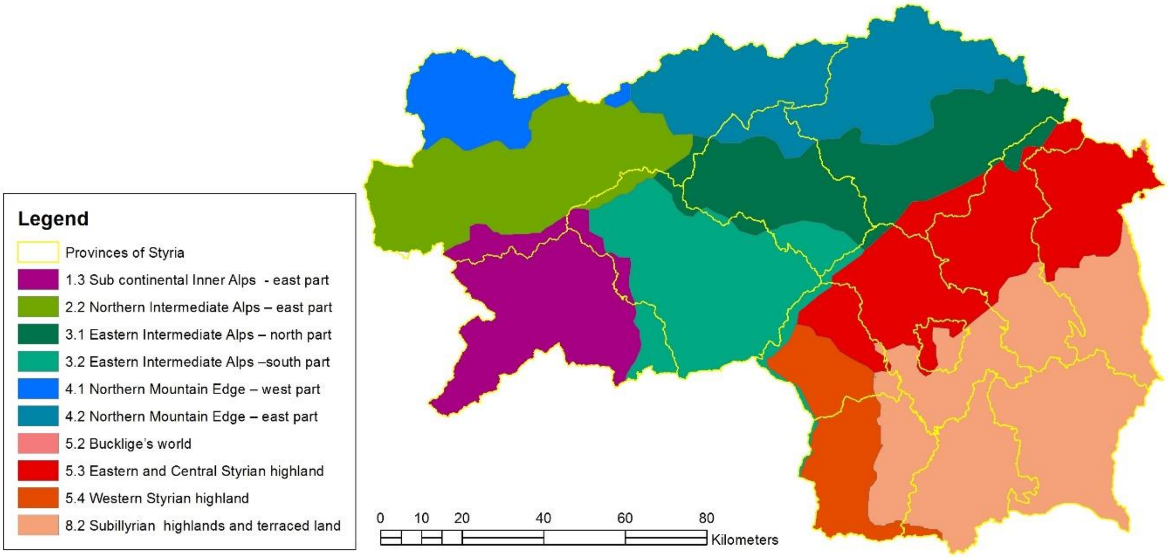

Figure 6: Extract of the Ecoregions of Styria (Kilian et al. 1994)

Styria has large ecological variability and it is divided into six ecoregions, which further divides to 10 sub-regions (cf. Figure): Subcontinental Inner Alps - east part (*1.3 Subkontinentale Innenalpen - Ostteil*), Northern Intermediate Alps – east part (*2.2 Nördliche Zwischenalpen – Ostteil)*, Eastern Intermediate Alps – North and South part *(3.1 & 3.2 Östlichen Zwischenalpen Nord- & Südteil)*, Northern Mountain Edge – west and east part *(4.1 & 4.2 Nördliche Randalpen – West- & Ostteil)*, Mountain Hills (5.2 Bucklige Welt), Eastern and Central Styrian highland (5.3 Ost- und Mittelsteierisches Bergland), Western Styrian highland *(5.4 Weststeieriches Bergland)*, Subillyrian highlands and terraced land *(8.2 Subillyrisches Hügel- und Terassenland)* (Kilian et al. 1994).

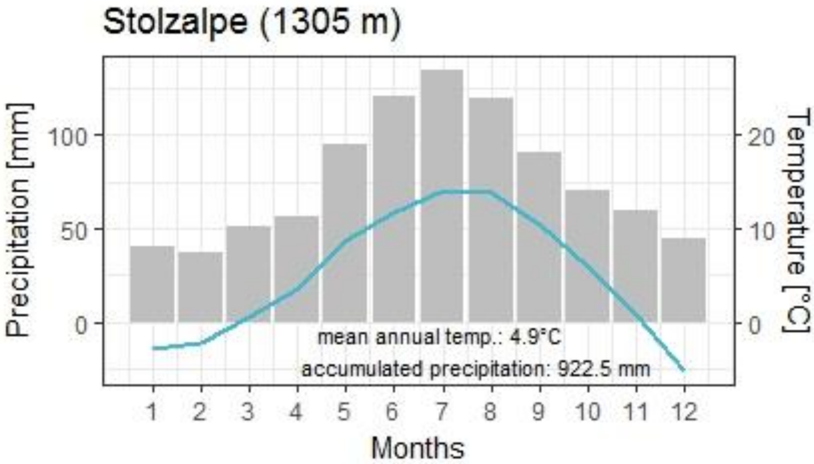

Figure 7: Climate Chart Eco Region 1.3 (ZAMG 2002)

Continental and cold winter weather with regular occurrence of winter inversion is characteristic for the southwest part of Styria, which is part of 1.3 Subcontinental Inner Alps – east part (1.3). The highest precipitation takes place during the summer months, the minimum is between January and March. Average annual precipitation is around 1000 mm (cf. Figure 7).

Luzola-Silver Fir-Spruce (*Luzola nemorosae – Piceetum*) biocenosis occur especially on poor silicate stands in sub montane and high montane part, on richer soils dominate Oxalis – Silver Fir – Spruce forests (*Galio rotundifolii – Piceetum*), we can find a mixture of Beech trees in border parts of the altitude zone.

Parts which are regularly flooded or destroyed by avalanches are dominated by Alnus Incana forests (*Alnetum incanae*), on fresh moist steep hillsides grows Maple-Elm-Asch communities (e.g. *Carici pendulae – Aceretum, Ulmo – Aceretum*).

Spruce forest with an admixture of Larch (*Larici-Piceetum*) trees dominate in a lower part of a subalpine zone, in upper parts communities of Larch and Swiss pine (*Larici-Pinetum-cembrae*) grows (Kilian et al. 1994).

Transition climate with winter inversions is a typical sign for the sub eco region Northern Intermediate Alps – east part (2.2). Kalkalpen forms a natural border and reduces precipitations, which are kept under 1000 mm in the valley bottom (e.g. Schladming 740 m, 992 mm). Amount of annual precipitation increases with elevation slightly, in montane zone values reach between 1000 – 1500 mm, in subalpine it can be over 1500 mm (e.g. Obertauern: 1740 m, 1536 mm). The precipitation maximum comes in the summer months, the second peak in winter is fractional (cf. Figure 8).

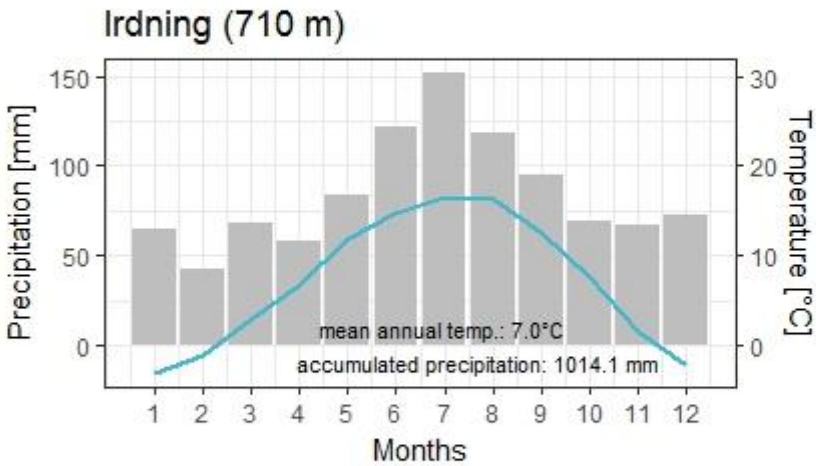

Figure 8: Climate Chart Eco Region 2.2 (ZAMG 2002)

Sub montane and montane altitude zones of Northern Intermediate Alps are typical for Spruce – Silver fir forests, at positively influenced places (nutrition or higher temperature) with an admixture of beech trees and in higher elevation with a rare occurrence of Swiss pine (Dachsteinplateau). Pure spruce stands grow especially in deep frost valleys. Rarely is possible to find communities of pine (*e.g. Erico-Pinetum sylvestris*) – mainly on steep slopes exposed to the sun. Places under continue disturbance pressure by avalanches or mudflows are typical for Maple – Elm - Asch (*e.g. Carici pendulae*) biocenosis or with a domination of grey alder (*Alnetum incanae*).

The lower subalpine grade is characteristic by spruce forest with an additive of larch. Higher subalpine zones are dominated by Larch-swiss pine communities (e.g. Larici-Pinetum cembrae, Laricetum deciduae) on unfavorable places with by dwarf mountain pine (e.g. Rhododendron ferrugineum-Pinetum prostratae) (Kilian et al. 1994).

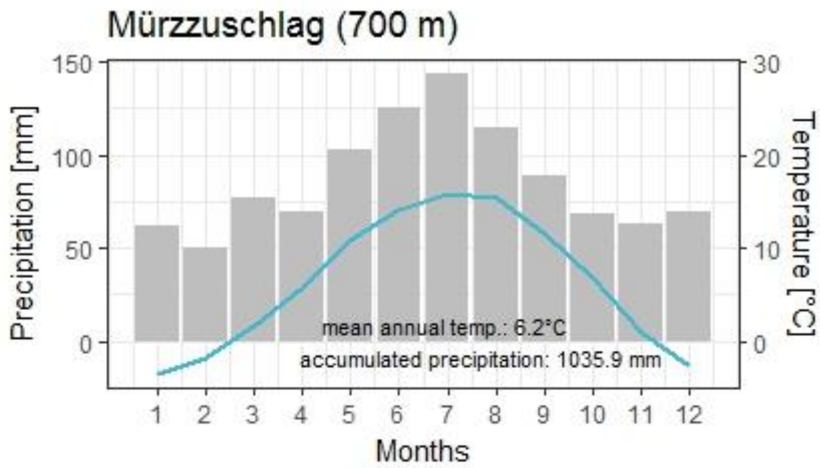

Figure 9: Climate Chart Eco Region 3.1 (ZAMG 2002)

Southeast edge of the Alpine range is formed by Eastern Intermediate Alps, which is parallel to Northern Intermediate Alps, but it is warmer and drier with a lower cover by snow. East part of Eastern Intermediate Alps (3.1) has higher horizontal precipitation variability as Northern Intermediate Alps, Valley bottoms received annually between 750 – 800 mm of rain, in high montane and the subalpine altitudinal zone between 1250 mm – 1500 mm. The most copious rainy month arrives in July (cf. Figure 9).

Most of the forests are formed by a mixture of spruce – silver fir as main species with an admixture of larch and/or beech. In the lower montane zone is possible to find fragments of oak-pine forests (*Deschampsio flexuosae – Quercetum*), also a mixture with maple and beech is not sporadic especially in the middle part of a montane zone. Places with a higher occurrence of disturbance agents are occupied by grey alder *(Alnetum incanae*).

Pure spruce stands or with admixture larch grow in a lower subalpine zone, in higher elevations grow dwarf mountain pine cover or communities dominated by a green elder (*Alnetum viridis*) (Kilian et al. 1994).

West part of Eastern Intermediate Alps (3.2) reflecting almost borders of Murtal region compare to east part weather is bit milder (cf. Figure 10). A climate of valley bottoms (e.g. Murtal, Friesach) show strong central alpine characteristics and south exposed slopes are influenced by South "stau" phenomes. Precipitations in valleys lay between 800 - 1000 mm, in high montane and subalpine zone exceed 1250 mm. The rainiest season is July and August.

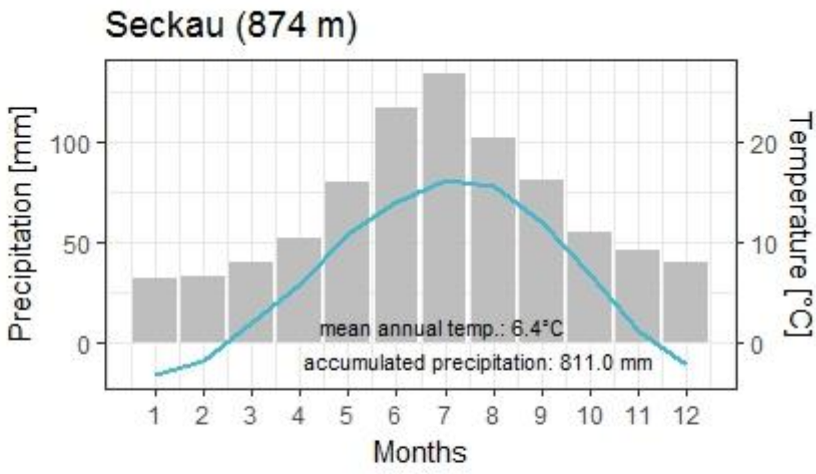

Figure 10: Climate Chart Eco Region 3.2 (ZAMG 2002)

Most of the sub montane and montane forests form spruce – silver fir forests (on silicate soils *Luzola nemorosum - Piceetum*, on rich soils *Galio rotundifolii – Piceetum*, on soils rich on carbon *Adenostylo glabrae – Abietetum*). Locally on sunny steep slopes grows pure pine communities (*Vaccinio vitis -idaeae-Pinetum, Erico – Pinetum sylvestris*) or with admixture. Communities of grey elder form in avalanche tracks.

Cover by larch and spruce can be found in a lower alpine zone, at higher one mostly dwarf mountain pine communities, locally also a mixture of larch and Swiss pine. Green elder cover is formed on places with high accumulation of snow (avalanche tracks and deposition areas) (Kilian et al. 1994) .

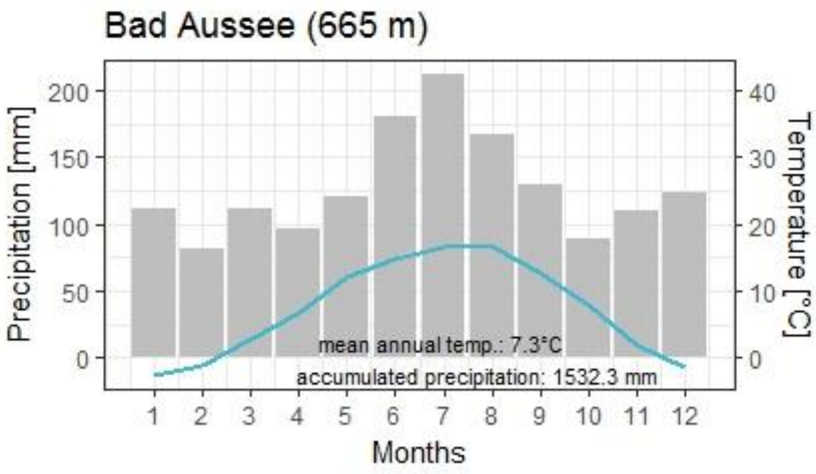

Figure 11: Climate Chart Eco Region 4.1 (ZAMG 2002)

Northern Mountain Edge is characterized by cold, humid, central European climate with plentiful and steady rain (cf. Figure 11). West part of this mountain edge (4.1) is much more humid than Intermediate Alps due Northwest "stau" phenomena (*Schnürlregen).* Annual precipitation reaches high variability thought region and depends on the slope expositions and west-east direction, in valley bottom lays between 1100 – 2200 mm, in high montane and the subalpine zone between 1300 – 2500 mm. Summer months are rich for rain, springs and autumns are drier.

Trees of European Hornbeam (*Galio sylvatici – Carpinetum*) dominate warm to slopes of the Alps in lower montane elevation zone in Northern Mountain Edge ecoregion. Beech stands with admixture Silver Fir (not so often Maple, Asch or Spruce) grow on flysch pseudogley soils. Communities of spruce, silver fir and beech form together with whorled Solomon's-seal (*Polygonatum verticillatum*) characteristic biocenosis in the middle and upper part of a montane zone. On the sunny side of steep grow pine communities (*Erico – Pinetum sylvestris*), on dark side dwarf mountain pine with Hairy Rhododendron (*e.g. Rhododendro hirsuti – Pinetum montane*).

Spruce forests with larch dominate lower subalpine forests. On places, there can be found a pure stand of larch (*Laricetum deciduae*). Dwarf mountain pine communities grow mostly in an upper subalpine zone, locally is possible to find cover by larch and Swiss pine (*Pinetum cembrae*) or green elder *(Alnetum Viridis*)(Kilian et al. 1994) .

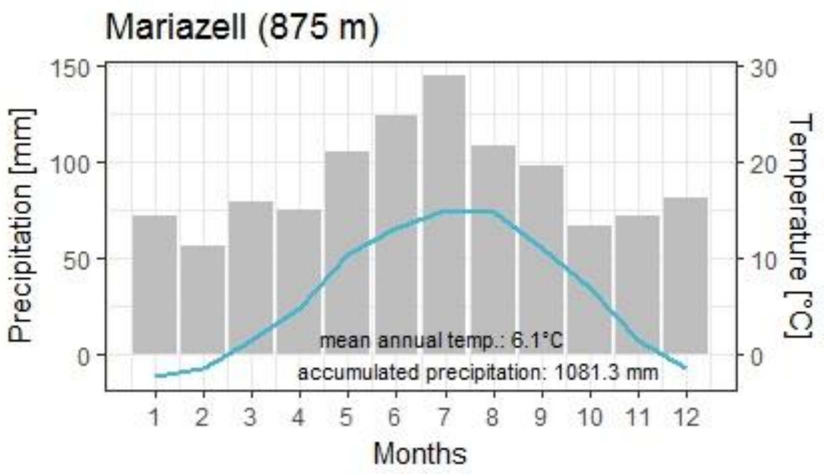

Figure 12: Climate Chart Eco Region 4.2 (ZAMG 2002)

Humid, but not so much as in west part, "stau" climate dominate in East part of Northern Mountain Edge (4.2). Precipitation is between 1000 mm and 1700 mm in lower montane parts and in a valley bottom, in higher montane and subalpine zone are between 1100 and 1900 mm, on exposed location can reach up to 2200 mm. Precipitations reach two peaks during the season, first one in winter months, the second one in July (cf. Figure 12).

This sub ecoregion represents the ecological optimum for spruce-silver, fir-beech forest cover in lower montane zone. The higher zone is dominated by a mixture of spruce and silver fir. Pine forests have better conditions for grow on dolomite than in sub ecoregion 4.1. Steep warm slopes offer good conditions for growth to European oak – European hornbeam communities (*Galio sylvatici – Carpinetum).* We can find common lime as a dominant species (*Cynancho – Tilietum*) in forests on drier calcic stands.

Spruce forests grow in a lower subalpine zone. Dwarf mountain pine cover is possible to find in a higher subalpine zone, locally larch in shaded places. Avalanche tracks are formed by green elder communities(Kilian et al. 1994) .

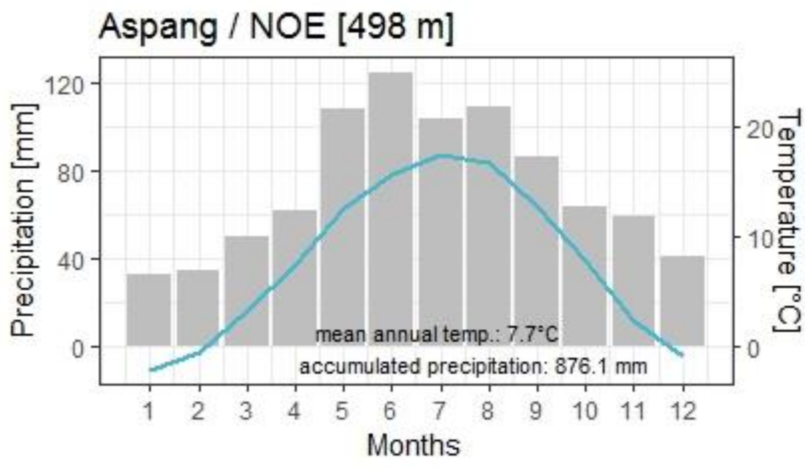

Figure 13:Climate Chart Eco Region 5.2 (ZAMG 2002)

Bucklige's world (5.2) is characterized by Illyrian weather (influenced from east south of Europe e.g. from Slovenia, Hungary etc.). Bucklige 's world becomes just with a very small part of Styria in Schäffern's municipality and covering negligible part of the province - approximately 510 hectares of Styria. Annual precipitation is strongly heterogeneous with a summer peak in June and July and relatively dry spring and fall season (cf. Figure 13). Low land receives between 700 – 1000 mm precipitation, high montane part up to 1250 mm.

Oak – European hornbeam forests dominate in a lower montane zone. A mixture of Pine and Oak (*Deschampsio flexuosae – Quercetum*) form forest cover on acid soils. Locally grow Black pine or mixture of Silver fir – Beech with an admixture of Oak, Sweet Chestnut or Pine. Spruce – Silver fir – Beech forest prefers middle parts of the montane zone. Upper parts dominate Spruce – Silver fir. Lower sub alpine represents optimum for the spruce forest with larch individuals (*Larici – Piceetum*)(Kilian et al. 1994) .

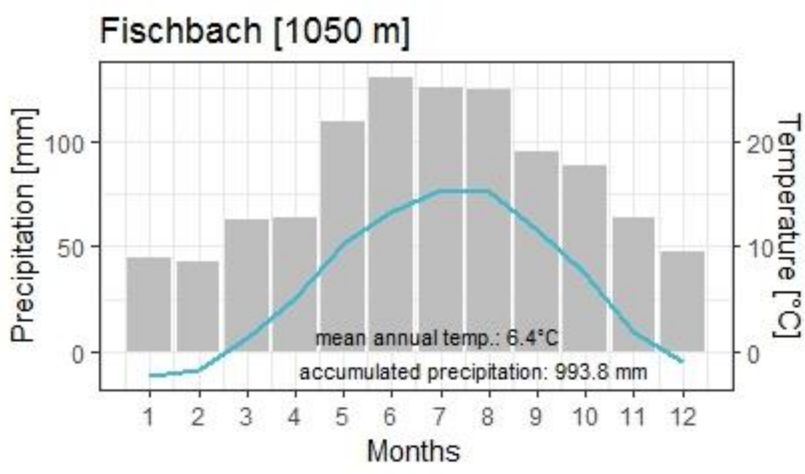

Figure 14: Climate Chart Eco Region 5.3 (ZAMG 2002)

Eastern and Central Styrian highland (5.3) is quite a humid sub ecoregion with a high frequency of summer thunderstorms. Precipitation has a significant west-east gradient, where the east parts on the borders with Burgenland are the driest. Bottom of valleys with sub montane zones received annually between 700 – 1000 mm of rain, higher parts of highlands exceed 1100 mm of precipitation. Climate is less continental than in sub ecoregion 5.2, thus vegetation period is in the same altitude longer. Most of the precipitation comes in summer (cf. Figure 14).

In a Lower montane zone, south exposed slopes are formed by Oak – European Hornbeam cover with an additive of beech (*e.g. Asperulo odoratae – Carpinum*), on acid slopes prevail composition of Oak and Pine (*Deschampsio flexuosae – Quercetum*). Locally on calcic soil (e.g. around the city of Graz) occurrence of downy oak forests (*Geranio sanguinei –*

Quercetum pubescentis). Areas around rivers, which are regularly flooded, form covers of white willow (*Salicetum albae*) and grey alder (*Alnetum incanae*). A lower montane zone is occupied by mixed forests, where beech species dominates with an admixture of Silver – Fir, Pinus, Sweet Chestnut or Oaks. Stand with moist climate are suitable for a deciduous forest of Maple, Common Ash and Elm (*e.g. Arunco-Aceretum or Scolopendrio – Fraxinetum*). On the opposite side, common lime communities (*Cynancho - Tilietum*) prefer drier stands.

Conifer forest can be found in a higher montane zone, especially Spruce – Silver Fir cover is predominant with an addition of Larch, Maple and Beech.

Lower subalpine zone forms spruce forests on calcium (*e.g. Adenostylo glabrae-Piceetum, Adenostylo alliariae-Abietetum*) or with an addition of larch on silicate soils (*Larici – Piceetum*). An upper subalpine zone is rare and it is represented by dwarf mountain pine (Kilian et al. 1994).

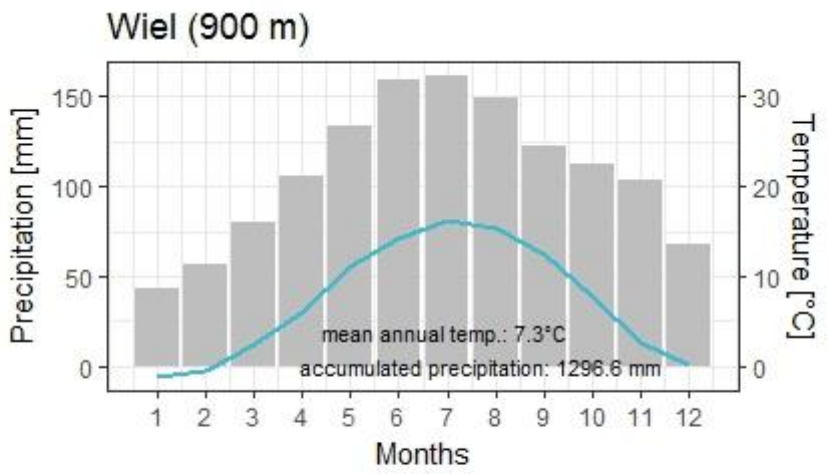

Figure 15: Climate Chart Eco Region 5.4 (ZAMG 2002)

Western Styrian highland (5.4) is clearly influenced by Subillyrian weather, especially slopes with southeast aspect receive more precipitation than stands in Eastern and Central Styrian Highlands. Sub and low montane regions have annually between 900 – 1100 mm of precipitation (e.g. Deutschlandsberg: 410 m, 1081 mm). Stand in high and subalpine zone reaches up to 1500 mm on year to year base. Allocation of precipitation arrives by Mediterranean influence, rainy spring and autumn months are characteristic for western highlands with a low-key peak in summer months. Summer rain is accompanied by thunderstorms (cf. Figure 15).

Beech forests with an admixture of Silver Fir, Pine, Sweet Chestnut and Oak form a lower montane zone. Oak and European Hornbeam mixture (*Asperulo odoratae – Carpinetum*) grows on sunny rich soil slopes, acid slopes are occupied by Oaks and Pine (*Deschampsio flexuosae – Quercetum*). Deciduous forests composed of Maple, Asch, Elm and Common Lime (*e.g. Arunco – Aceretum*) grow on moist stands. Upper parts of a montane zone are comprised of Spruce- Silver Fir forests with an additive of Beech, Larch, Maple.

Lower subalpine zone predominantly forms Spruce with a small number of Larch individuals. Dwarf Mountain Pine and Green Alder occupy upper subalpine zone (Kilian et al. 1994).

Subillyrian highlands and terraced land (8.2) has characteristic low-land Subillyrian climate with annual precipitation between 700 – 1000 mm, which vary from southwest (e.g. Stainz: 340 m, 937 mm, Leibnitz: 275 m, 922 mm) to northeast (e.g. Hagensdorf-Luising: 200 m, 706 mm, Gerersdorf bei Güssing: 280 m, 735 mm). Summer months are the richest for precipitation. On the south and west, we can find the second maximum in autumn months (cf. Graph 16).

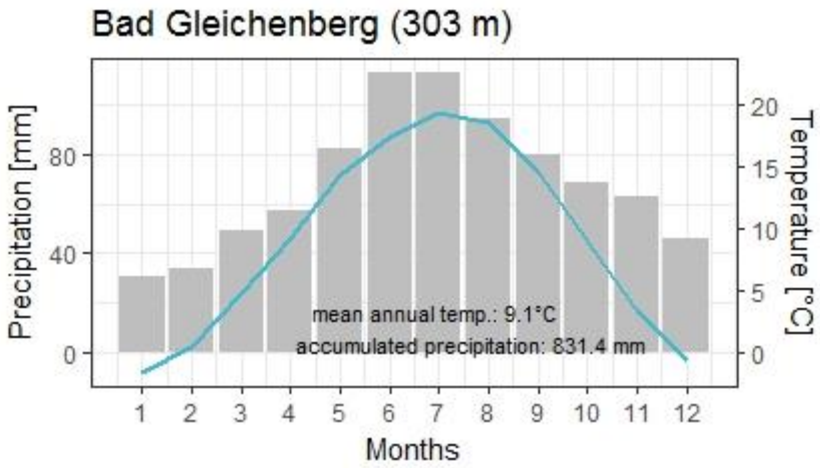

Figure 16: Climate Chart Eco Region 8.2 (ZAMG 2002)

Sub ecoregion 8.2. is the only one in Styria with Colline altitude zone, which is approximately between 200 – 300 meters above sea level. Oaks and European Hornbeam communities (*Asperulo odoratae – Carpinetum*) are common, with Ash and European Oak admixture (*Fraxino pannonicae – Carpinetum*). Pine – Oak forests grow on a stand with strong acid soil.

A lower montane zone is suitable for Beech forests with Silver Fir, Sweet Chestnut, Pine individuals (*Luzulo nemorosae - Fagetum*).

Typical riparian forests are formed in valleys around rivers. These forests are formed predominantly by White Willow (*Salicetum albae*) with an addition of Silver Poplar, Grey Alder, Black Alder. European White Elm, European Oak and Ash can be found in hardwood riparian woods. Carr forms with Black Alder (*Carici elongatae – Alnetum glutinosae*) develop in areas which are subject of frequent flood events (Kilian et al. 1994).

3.2.Source of data

3.2.1. Cartographic materials

Most of the forest stand parameters are extracted from maps provided by the Styrian government office (Land Steiermark - Amt der Steiermärkischen Landesregierung, A17 Landes- und Regionalentwicklung Referat Statistik und Geoinformation). These data layers contain information about canopy cover, share of conifer species, growing stock, the height of dominant trees, DBH, horizontal structure (number of layers).

Valuable cartographic information provide public server also: (Offene Daten Österreichs 2018) (https://www.data.gv.at), which provide access to open data from Austria. The digital elevation model and the laser scan data layer are retrieved from there. These two layers were used to calculate steepness of slopes.

3.2.2. Human activity map

Considerable number of international studies confirmed that distance of forest fires to touristic trails, settlements, road and land used to agriculture or forestry purposes indicate significant predisposition to fire ignition (Arndt et al. 2013; Catry, F., X. et al. 2009; Martínez et al. 2009). The map showing the fire danger classification on municipality level for Austria is based on the data collected over 17 years between 1993 and 2009 by (Arndt et al. 2013). More than 50 social-economics parameters were analyzed and final model with fire significant variables was developed: touristic activities are described by length of hiking trails to total municipality area, agriculture activities are covered for number of agriculture holdings with pasture land, significant influence on fire ignition from forestry sectors shows the number of forestry operations and length of the forest roads in the municipality area, last variable which was used in the model is length of the railroads in the municipality area (Arndt et al. 2013).

The fire ignition risk map for Austria was used in this work to decide, which forest fires occurred in the areas with low or high human activity.

3.2.3. Fire records

Current Austrian forest fire database has been established by Institute of Silviculture at the University of Natural Resources and Life Sciences in Vienna as a part of the Austrian Forest Fire Research Initiative (AFFRI) and the Alpine Space project Alp-FFIRS (Alpine Forest Fire waRning System) in the year 2009 (Vacik et al. 2011).

779 records of wildfires have been recorded since the beginning of 20th century for the province Styria. For most of the analysis records from 1.1. 1992 to 31.12 2016, were used in total 517 fire records. Unfortunately the quality of the records varies and for that reason it wasn´t possible to work with all datasets for each analyzes and some of the calculations were done with a limited number of records (e.g. lightning risk map is based on 17 forest fires caused by lightning and 51 records of fires caused by human activity, due to the need for a high spatial accuracy).

For long-term analysis a combination of the old database provided by BMNT and new (current) forest fire database was used. These data provide an overview about number and size of fires on quartal (partly on monthly) basis over 60 years long period (1957 – 2016).

3.2.4. Meteorological data

Ignition of forest fires is a result of the interaction of ecological factors (e.g. occurrence of a suitable fuel, forest structure, topography and weather) and social – economic factors. The probability of ignition of forest fires is connected to the dryness of the vegetation (Arpaci et al. 2013). Two meteorological datasets provided by Central Institute for Meteorology and Geodynamics (Zentralanstalt für Meteorologie und Geodynamik - ZAMG) were used for assessing the fuel moisture conditions.

The first dataset contains data from 8 meteorological stations, which represent the sub ecoregions (cf. Figure 17). The east part of the subcontinental Inner Alps and south part of Eastern Intermediate Alps are characterized by the meteorological station in Zeltweg, which is 679 meters above sea level. The meteorological station Irding – Gumpenstein lays in altitude 679 meters and represents sub ecoregion 2.2 Northern Intermediate Alps – east part. North part of Eastern Intermediate Alps is covered by two meteorological stations. Bruck an der Mur is possible to find on the west of this sub ecoregion in altitude 484 meters above sea level and Mürzzuschlag on the east at an altitude of 709 meters. On the very Northwest of province lays the city of Bad Aussee (743 m) in the eastern part of Northern Mountain Edge. Meteorological station in Mariazell in altitude 864 meters was the source of them for the east part of Northern Mountain Edge. The highest located meteorological station is on the top of the mountain Schöckl at 1439 meters and represents three sub ecoregions (Bucklige´s world, Eastern and Central Styrian highland, and Western Styrian highland). On another side of altitude scale is possible to find the lowest meteorological station, the station on the airport of Graz in altitude of 340 meters. This meteorological station was selected to represent the weather data for sub ecoregion 8.2 – Subillyrian highlands and terraced land on the south-east of Styria.

For these meteorological stations information about minimal, maximal and average air temperature at 2 meters above ground level have been collected, the sum of daily precipitation at 7 a.m., wind speed data represent an average value of 3 measurements during a day - Wind speed= *(w7+w14+w19)/3*, relative humidity is also represented as average of three measurements during a day Relative humidity *= (rh7+rh14+rh19)/3.* All the data were collected between 1. January 1992 and 31. December 2016.

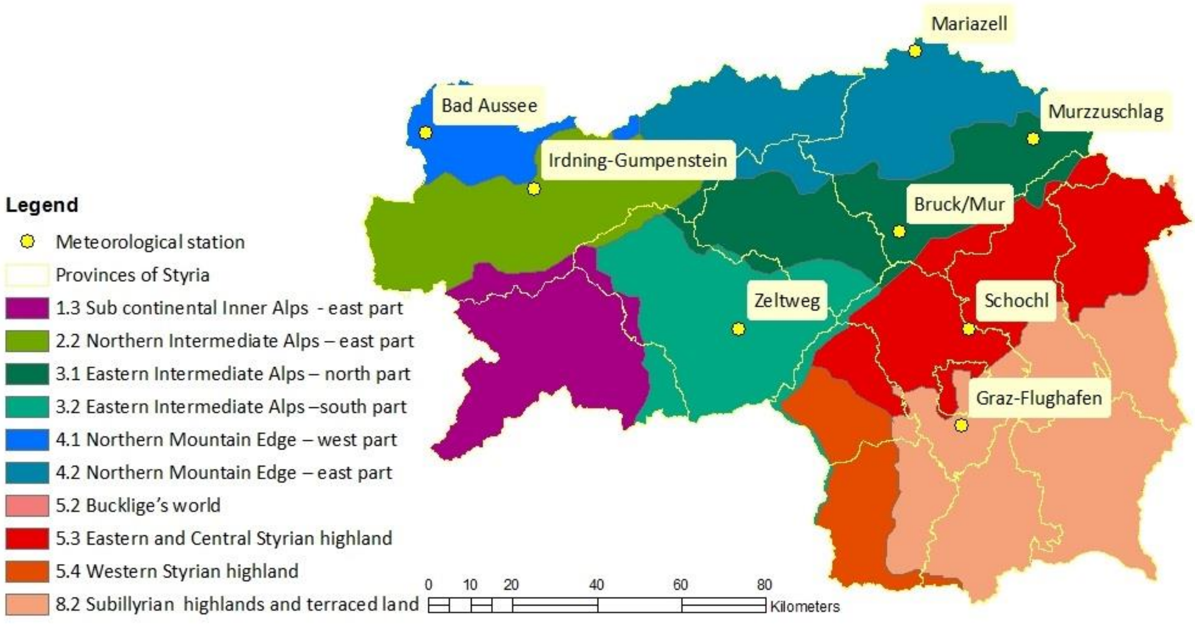

Figure 17: Position of meteorological stations (ZAMG 2002) according to the ecoregions (Kilian et al. 1994)

3.3.Forest fire danger classification

Research on the forest fire danger and danger classification has a long tradition (Stocks et al. 1989). Forest fire danger is defined by Canadian Committee on Forest Fire Management as "a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, the rate of spread, the difficulty of control, and fire impact" (Stocks et al. 1989).

During systematic evaluations and integrating the individual and combined factors, which are connected to fire danger, it is possible to derive a fire danger rating (cf. Figure 19). Fire danger rating systems represent qualitative and/or numerical indexes of fire potential, which can support fire management activities (Groot 1987; Stocks et al. 1989).

Central Institute for Meteorology and Geodynamics (ZAMG - Zentralanstalt für Meteorologie und Geodynamik) is providing a forest fire danger rating in Austria, that system has worked already for a while and produce on daily basis fire danger forecast for the whole country. Austrian forest fire danger rating is based on the Canadian Fire Weather Index, input values are daily temperature, relative humidity, wind speed and precipitation (Arpaci et al. 2013).

3.3.1. Canadian Forest Fire Weather Index

Canadian Forest Fire Danger Rating System (CFFWI) incorporate 6 components – 3 Fuel Moisture Codes: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC), 2 Fire Behavior Indexes: Initial Spread Index (ISI), Buildup Index (BUI). The Fire Weather Index (FWI) is comprised of all previous mentioned components. FWI is based solely on daily values of dry-bulb temperature, relative humidity, wind speed at 10 meters above ground and cumulated precipitation records in last 24 hours at noon local standard time (Stocks et al. 1989). For a deeper analysis in this work FFMC, ISI, BUI and the FWI indexes and codes were used mostly (cf. Figure 19).

Three moisture codes show actual fuel moisture for different scales, which react with different rates and time-lags on the amount of precipitation and estimate the net effect of daily drying and wetting phase. For example, FFMC index reacts promptly to rain, thus if after a few dry days there is a storm, FFMC raises up, but DMC or DC rates stay low (Groot 1987; Alexander and Groot 1988; Stocks et al. 1989).

3.3.2. Fine Fuel Moisture Code

FFMC code represents moisture content of the top layer, which contains mostly litter and other cured fine fuels as needles, moose etc. This organic layer is usually 1-2cm deep and has around 5 tons per hectare in the forest of Canada (cf. Figure 18). FFMC code strongly depends on actual weather conditions, has a huge surface area to volume ratio and a short-term memory which reflects weather situation over last three days (Groot 1987).

Most of the fires begin and spread in fine fuels, because of that the FFMC code is used to indicate the probability to ignition. FFMC values vary from 0 to 99, whereas 0 represent the lowest probability to ignition and 99 the highest. Generally, fires begin to ignite close to values of 70, crucial for boreal forest are values between 86-89, which represent a high risk of ignition, the FFMC value 96 is the highest theoretical value (Groot 1987; Stocks et al. 1989).

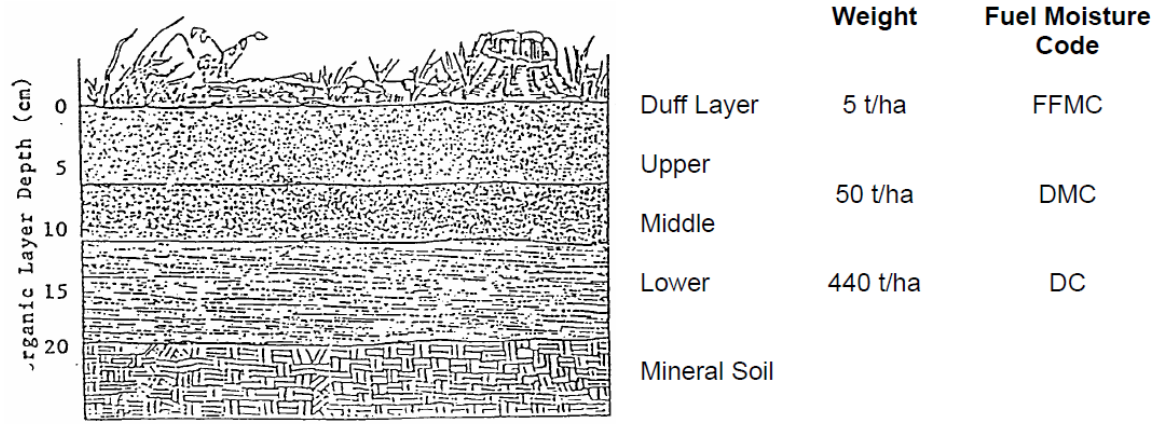

Figure 18 - Representation of forest floor fuels by Fuel Moisture Codes of the FWI System (Groot 1987)

3.3.3. Duff Moisture Code

DMC shows moisture content in moderate deep organic layers, approximately in 5 – 10 cm depth of the soil layer. DMC fuels are located bellow forest surface, because of that there is a longer reaction to actual weather conditions and a slower drying of particles, also it is not anymore affected by wind. Effect of rain, temperature and relative humidity is calculated for a 12 days period. DMC is often used for the prediction of fires caused by lightning because strikes usually initiate fires in duff layer (Groot 1987).

3.3.4. Drought Code

DC represents moisture value in a compact deep organic layer, approximately in 10 – 20 cm depth of the forest surface layer. DC fuels react really slowly to actual weather conditions with 52 days time-lag. DC is affected just by rain and temperature and highly important are precipitations during winter months (Groot 1987).

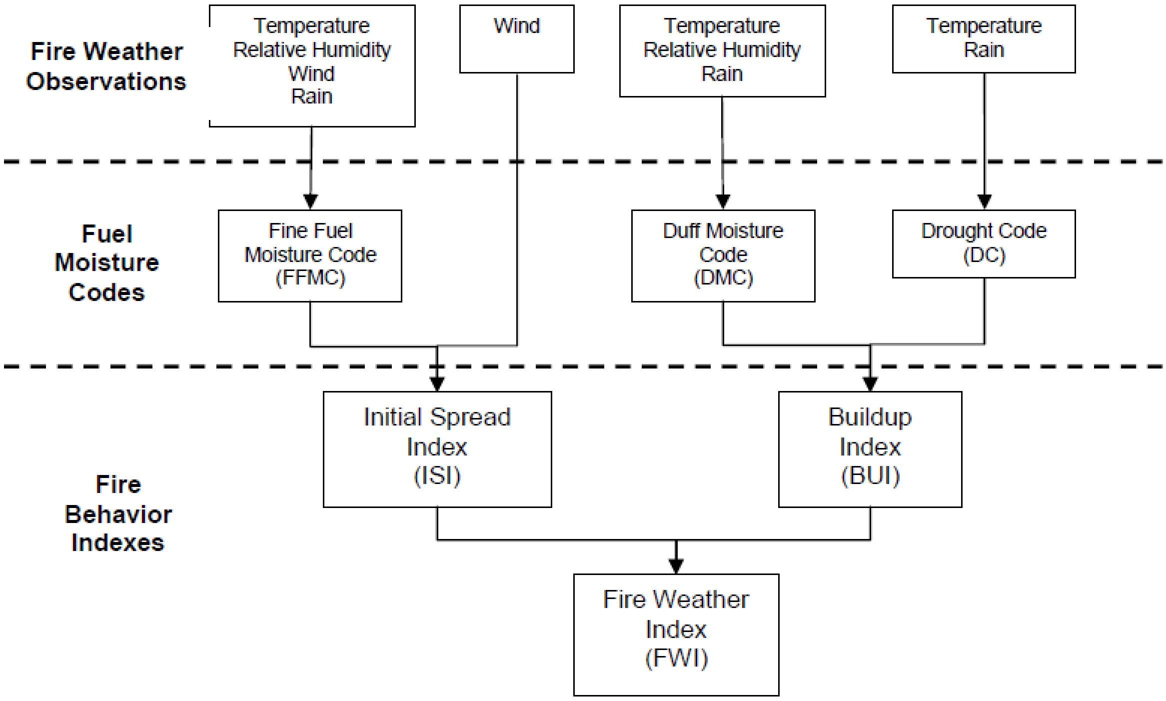

Figure 19 - Structure of the Canadian Forest Fire Weather Index (FWI) System (Groot 1987)

3.3.5. Initial Spread Index

The ISI is a combination of fine fuel moisture by the FFMC and the wind speed, designating the rate of fire spread. When wind speed reaches 13 km/h then ISI values will double (Groot 1987; Stocks et al. 1989).

3.3.6. Buildup index

BUI shows amount of available fuel by a combination of DMC and DC values. DMC code is more important and has a bigger weight in the BUI formula and zero values of DMC results zero values of BUI as well (Groot 1987; Stocks et al. 1989).

3.3.7. Fire Weather Index

FWI indicate a relative measure of potential frontal fire intensity in a standard fuel complex on level terrain (Groot 1987; Stocks et al. 1989). Frontal fire intensity is "the rate of heat energy release per unit time per unit length of fire front". FWI is helpful for decision making of fire suppression requirements, but to get correct values of all codes and indexes local, very accurate and correct weather information are needed (Alexander and Groot 1988).

3.3.8. Calculation of FWI

A relation between recorded wildfire events in Styria, and indexes from the Canadian Forest Fire Weather Index is analyzed. The hypothesis was tested, if there is a coherence between wildfire ignition and Fuel Moisture Codes (FFMC, DMC, DC) and Fire Weather Index (FWI) in Styria. The second question related to Canadian forest fire weather index if there is a connection between the size of wildfire and magnitude of Fire Behavior Indexes (BUI and ISI) in Styria.

The calculation of the Fuel Moisture Codes and Fire Behavior Indexes for all fire records required information about the location and in which ecological (sub)-region (*Wuchsgebiete*) the wildfire occurred. The forest fire records were matched with ecological regions map in ArcGIS (ArcMap 10.5). This additional information was necessary for FWI calculations because it indicates the most appropriate meteorological stations (Figure 17 on the page 19) for weather data input.

Calculations of Forest Weather Indexes were made by "CFFDRS" package in version 1.7.6 by Xianli Wang group, which was released at 5th April 2017 for statistical software R for all of the meteorological stations. As input data from all meteorological stations were used daily average temperature, sum of precipitation in last 24 hours, daily mean air humidity, daily average speed of the wind (cf. figure 20).

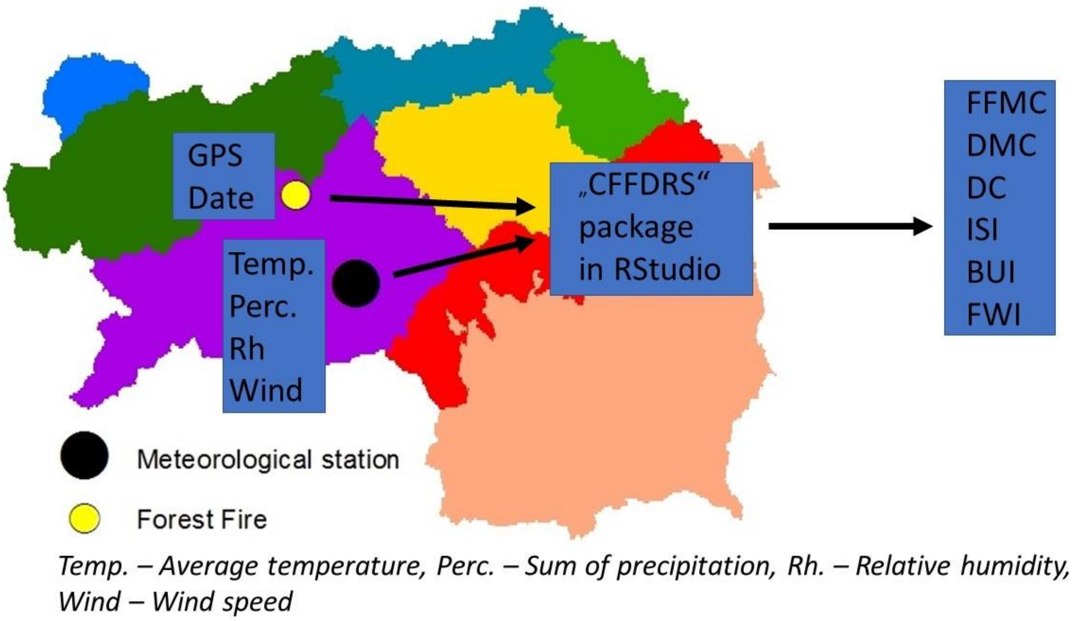

Figure 20: Diagram of FWI calculations

Forest fire records and calculated FWI results were matched in R Studio. Each of 517 fire records was assigned to one of eight FWI date frames, this step was based on the location of forest fire and meteorological station, and date of the event. In this step every forest fire record received the information about the FFMC, DMC, DC, ISI, BUI and FWI values for a period of twenty-eight days before the fire until eleven days after the fire event.

3.3.9. Lightning map

The creation of the lightning map was based on the hypothesis, that it´s possible to find trends in stand structure between fire events, which have a different cause of ignition. Input data with information about the rate of human activity was adapted from Arndt and her work "Modeling human-caused forest fire ignition for assessing forest fire danger in Austria". We defined 3 groups of wildfires for this part of the analysis: forest fires caused by lightning, forest fires caused by humans in areas with high human activity and in areas with low human activity.

Selection of forest fire records for this part was based on these criteria's: event had happened after the year 2000 – to have still reasonable old information about stand structure, cause of ignition is known (fire was caused by lightning or it was artificial), buffer zone is under or equal 1000 meters (buffer zone represent spatial accuracy) and burned area was bigger than 1 m^2 – cf. Table 3.

Table 3: Basic information about selected fires in specified groups [n=70] (Waldbrand-Datenbank Österreich 2016)

	Number	Buffer (m)		Sea Level (m)		Burned Area (m^2)	
		Min	Max	Min	Max	Min	Max
Lightning	19	100	1000	432	1739	1	10000
Human Low	25	30	1000	317	1737	10	10000
Human High	26	30	1000	401	1163	10	10000

Selected Fires were projected in ArcMap. Around each fire a circle “buffer” with variable radius *R* was created by geoprocessing tool “Buffer”.

$$R = B + \sqrt{\frac{A}{\pi}}$$

“B” is representing the size of the original buffer (*puffer_m*) from Austrian forest fire database, which means the area where the occurrence of event was expected. “A” is diameter of burned area by wildfire (cf. figure 21).

Each of the forest fire record with the buffer zone R was used as a template for a cut in forest stand data layers. The zonal statistic was used in this step. The zonal statistic calculated the mean value of stand parameters inside of the buffer zone R.

Forest stand data were extracted from 7 layers. List of them is bellow (cf. Table 4)

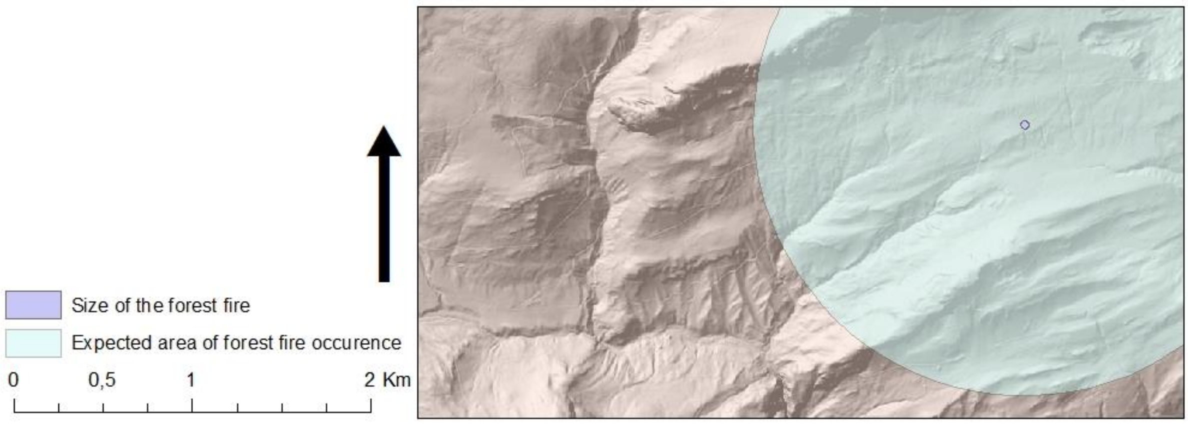

Figure 21: Illustration of expected area of forest fire (B - Buffer) and size of the forest fire (A)

Table 4: List of layers which were used for forest stand analysis

Name (eng.)	Original name	Source	Code	Value	Resolution
Share of Confer spp	Waldatlas - Baumartenverteilung Nadelwald in [%]	Amt	1	0 - 25 %	3 m
			2	25 - 75 %	
			3	75 - 100 %	
Canopy Cover	Waldatlas - Deckungsgrad [%]	Amt	1	0 - 10 %	3 m
			2	10 - 30 %	
			3	30 - 60 %	
			4	60 - 100 %	
Development	Waldatlas - Entwicklungsstufen der Bäume	Amt	1	Jugend	3 m
			2	Stangenholz	
			3	Baumholz	
			4	Baumholz	
			5	Starkholz	
			6	NA	
Volume	Waldatlas - Holzvolumen [vfm/ha]	Amt	1	0 - 50 m^3	3 m
			2	50 - 100 m^3	
			3	100 - 150 m^3	
			4	150 - 200 m^3	
			5	200 - 250 m^3	
			6	250 - 300 m^3	
			7	300 - 350 m^3	
			8	350 - 400 m^3	
			9	400 - 450 m^3	
			10	450 - 500 m^3	
Height	Waldatlas - Oberhöhe (Baumhöhe) [m]	Amt	1	0 - 5 m	3 m
			2	5 - 10 m	
			3	10 - 15 m	
			4	15 - 20 m	
			5	20 - 25 m	
			6	25 - 30 m	
			7	30 - 35 m	
			8	35 - 40 m	
			9	40 - 45 m	
			10	45 - 50 m	
Horizontal Structure	Waldatlas - Vertikale Bestandsstruktur	Amt	1	1 - schichtig	3 m
			2	2 - schichtig	
			3	mehrschichtig	
Digital Elevation Model	Digitales Geländemodell - 10m - Steiermark	Data.gv		196,102 - 2993,67 m	10 m

Analysis of variance (ANOVA) was used to determinate, which parameters evidence significant differences between defined groups. Parameters, which show significant differences were used as an input data for calculation of LMI (Lightning Map Index) and creation of Lightning map (Map representing probability of wildfire ignition by lightning). Reclassification was used to recalculate entering parameters. Each of the parameter is represented by the values 0 – 3. Zero represents a situation when it is almost any chance of wildfire caused by lightning and 3 means that it is very likely caused by lightning. Raster calculator in ArcGIS, counted for each cell the sum of values from different topographic or forest stand layers. The lightning map was produced with the size of the cells of 200 x 200 m. A higher resolution of the map, wasn´t possible to be produced due to the relatively low spatial accuracy of the forest fire records.

4. Results

4.1. Fire regime in Styria

Styria is not considered as a forest fire prone province of Austria, also it lays with 2,4 * 10^{-5} fires per hectare annually on second position from the end of all provinces (Vacik et al, 2011), but anyway it is possible to find there some fire hotspots (for example area around Kapfenberg or city of Graz) (Arndt et al. 2013) or interesting phenomena like natural forest fires just in the north part of Styria.

The trends in number of wildfires is shown in Figure 22. End of the 1950´s was the period with the highest average number of wildfires, approximately 83 events happened that time per year (data from 1948 – 49). Next decade shows a considerable decrease in records (n = 56,4), the seventies don´t indicate any noticeable change to the previous decade with 50,7 fires per year. Another huge decrease in number of events comes in the 1980s when an average number of forest fires decreased to 25,8 events per year. The lowest number of records happened in the last decade of the second millennium, in the 90s on average just 13 fires per year were recorded. The new millennium brought also a new trend in an annual number of forest fires and since the year 2000 we have seen a steady increase of forest fires, in the first decade it was registered about 17,6 forest fires annually and in second 40,5 (data 2010 – 2017). Last years (2015 & 2017) show the highest number of records (58 and 56) since 1976.

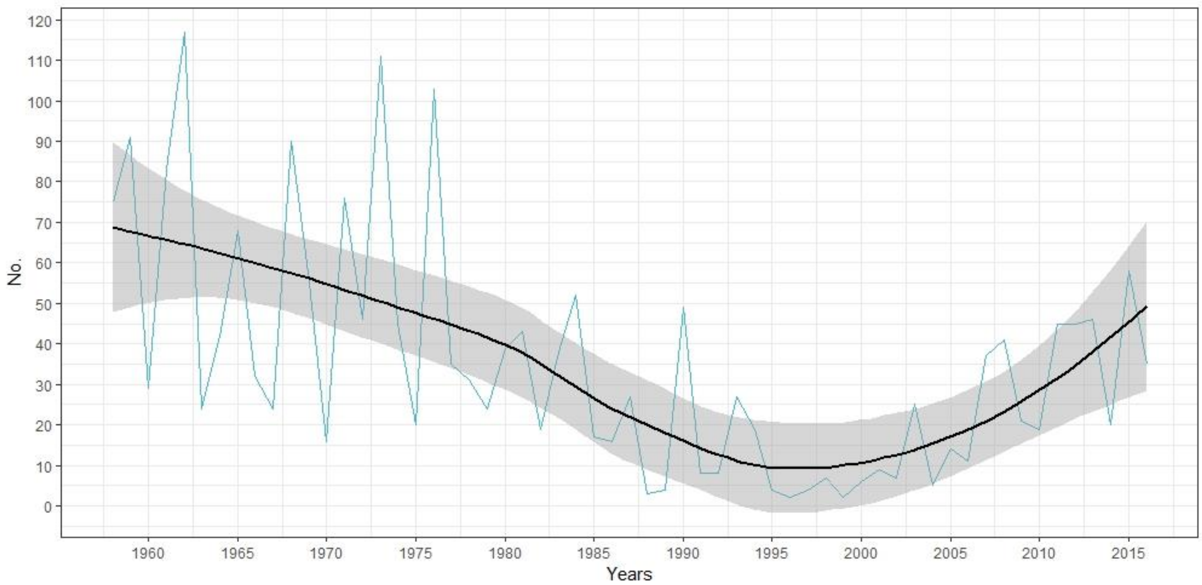

Figure 22: Number of forest fires in Styria [n=2069] (Waldbrand-Datenbank Österreich 2016; BMNT 1992)

A different trend is seen in the graph, which shows the areas affected by forest fires (Figure 23). Average burned forest land decreased from 46,1 hectares annually in the late 1950s over 37,49 and 28,55 hectares in 60s and 70s to 11,29 hectares in 80s. Average burned forest land is in last 4 decades stable, but with a huge year to year variation, in some years just few hundred burned square meters are recorded, but in other years, for example in the year 2003 was more than 60 hectares were affected by wildfires.

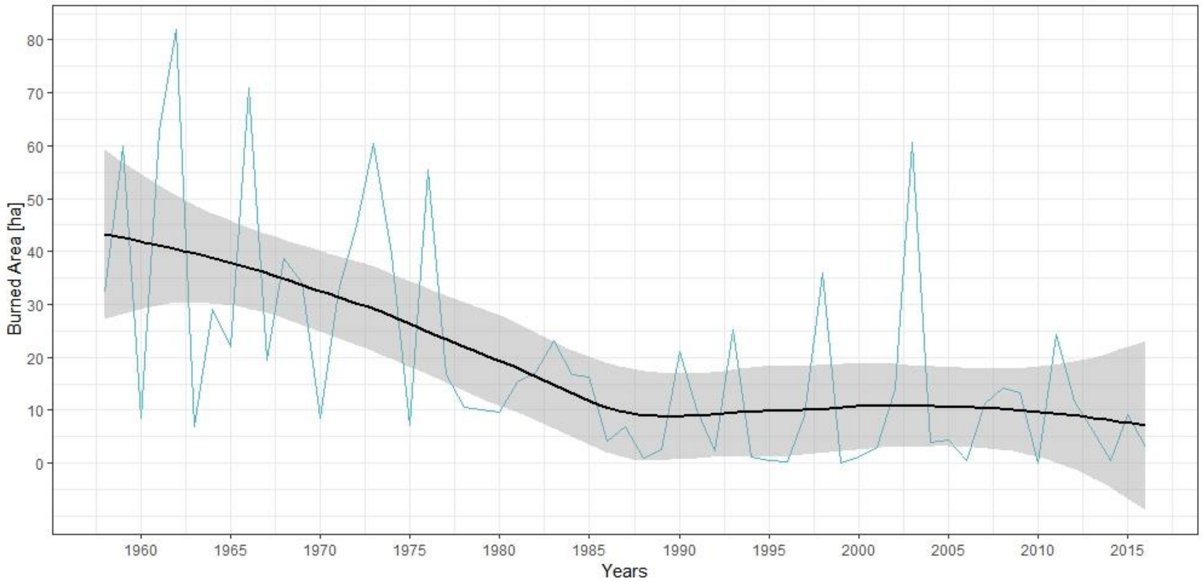

Figure 23: Area Affected by forest fires in Styria [n=2069] (Waldbrand-Datenbank Österreich 2016; BMNT 1992)

4.2.Temporal distribution of wildfires in Styria

Styrian "fire regime" follows the temporal distribution of fires in the whole country and varies on a year to year basis as it is visible in Figure 24. Most of the wildfires occur after winter in spring months, due accumulation of fuel after the winter, which is losing moisture fast during some dry warm days in spring (Müller et al, 2013).

Summertime is a period of thunderstorms, which are the important agent responsible for increasing amount of fires in these months (Müller et al. 2015; Vacik et al. 2011).

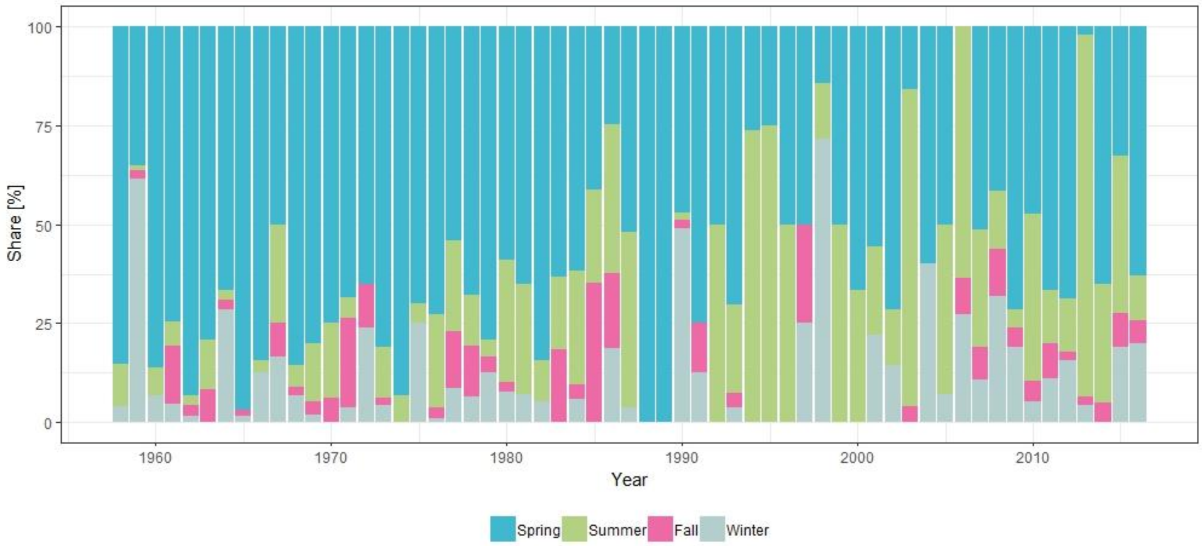

Figure 24: Forest fires by season – single year visualization [n=2069] (Waldbrand-Datenbank Österreich 2016; BMNT 1992)

Data collecting for over 55 years shows a significant change in the temporal distribution of recorded forest fires. The share of fires, which occurred in the spring months is steadily decreasing from 74% at end of the 50s to the present day 35%. On the other hand, it is possible to see a significant increase of a relative number of summertime events from 5% at end of the 50s to current situation with 47% share – cf. Figure 25.

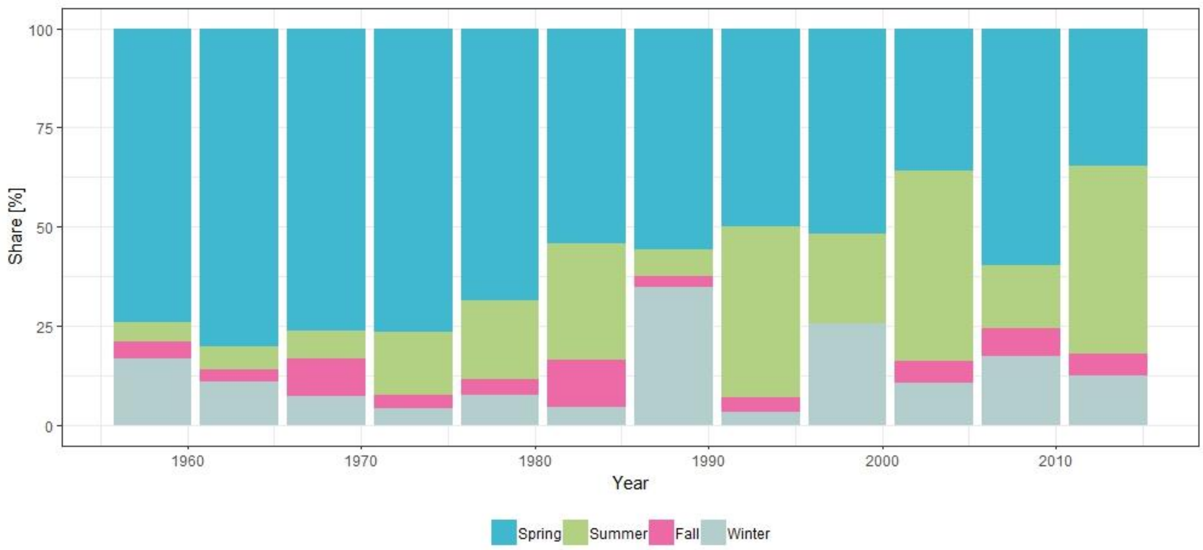

Figure 25: Forest fires by season – 5 years period visualization [n=2069] (Waldbrand-Datenbank Österreich 2016; BMNT 1992)

The number of forest fires during autumn have not meaningfully changed during the reporting period and it was varying between 0% and 12% with the average value of 5,6%. Also, winter have not shown any clear trend over the decades – lowest share of wildfires happened in the first half of the 90s with 4%, the maximum rate was in the second half of the 80s and share was over 34%, the average rate was 11% over the reporting period.

Occurrence of forest fires highly varies between different subregions of the province during a year (cf. Table 5). In the south of Styria (eco region 8.2), forest fire activity begins already in March and it's relatively and absolutely stronger than in the northern part, half of the year forest fires occurred during spring months (March and April – 51,65%). On other hand the northern part of Styria (e.g. eco region 2.2, 4.1, 4.2) evidences small number of spring fires and the main forest fire activity is shifted to the summer month 54,35%, 55,56%, 90% of yearly records. Tables with number of forest fires by cause for each eco region during a year are on the page 68 in Appendix.

Table 5: Number of forest fires during a year in each sub eco region [n=514] (Waldbrand-Datenbank Österreich 2016)

	Sub eco region								
All	22	30	31	32	41	42	53	82	Sum
January	1	1	3	6	0	0	4	11	26
February	1	0	2	3	0	0	7	8	21
March	2	2	4	19	0	0	6	45	78
April	9	2	17	20	1	1	20	49	119
May	4	3	8	7	1	0	4	12	39
June	4	4	10	6	1	1	3	7	36
July	11	1	9	15	1	4	9	11	61
August	10	2	14	19	3	4	12	19	83
September	3	0	5	0	0	0	1	2	11
October	1	1	1	2	0	0	0	2	7
November	0	0	0	2	1	0	1	6	10
December	0	1	3	2	1	0	6	10	23
Sum	46	17	76	101	9	10	73	182	514

4.3.Cause of Ignition

Majority of wildfires in Styria are caused due to carelessness and indifference of visitors or workers in a forest or nearby of forest stands, also it' s possible to find a lot of fires which were caused by a technical failure. In total, almost 80% of fires are caused by anthropogenic reasons. Carelessness (e.g. burning of branches after harvesting or burning wood, which was damaged by bark beetle) is a reason for 12% wildfires. The second most often recorded cause is "leisure" fires with a share of 9% – fires which are caused by squibs, firecrackers or by hot ash from a garden or house fireplace. Little more than 6% of all fires are caused by cigarette smokers. Fourth position holds power lines failures with a share of 5,6%. Arsonists caused 4% of all wildfires in Styria. Due breaks improvement of trains, a cause of ignition by railways has decreased to 3%. Ceremony fires (e.g. Funkenfeuer, Johannisfeuer, Osterfeuer) and camping fires are a reason for 1,4% and 0,8%. For a little bit less than 40% of all fires it wasn't possible to specify the exact cause of a fire.

The Austrian Lightning Detection and Information System (ALDIS) is a lightning location system (LLS) that has located and recorded lightning and thunderstorm activity inside and nearby of Austria with detection efficiency 98% since 1999 (Müller et al. 2013). Using the data of this system allows to determinate that almost 20% of forest fires are caused by lightning, thus they are natural.

Unknown caused of fires remains for 3 records (0,5%) (cf. Figure 26).

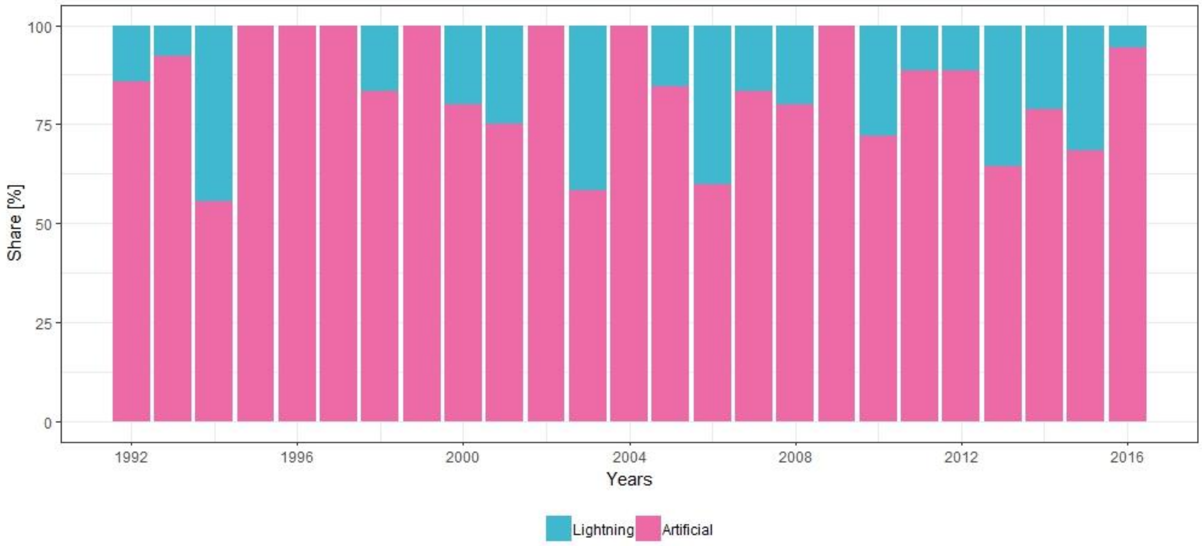

Figure 26: Cause of ignition for every single year 1993 – 2016 [n=514](Waldbrand-Datenbank Österreich 2016)

Cause of ignition is also changing over the time and season. It´s possible to see a new trend, that thunderstorm activity can be considered for a longer period during a year. There were any or a small number of forest fires caused by lightning in May or September in the 90s and the first half of 00s. It is possible to see a change in last 10 years, which shows earlier storm activity. Forest fires caused by lightning occur in April and May also the storm activity remains longer and there are natural forest fires still in September (cf. Figure 27).

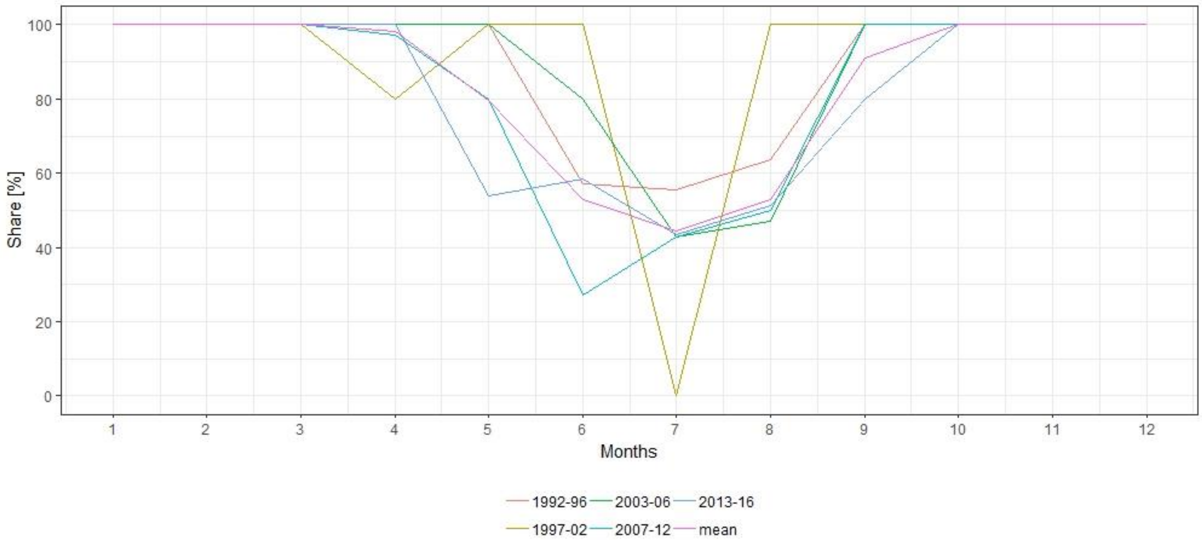

Figure 27: Transformation in cause of ignition 1993 - 2016 [n=514] (Waldbrand-Datenbank Österreich 2016)

Natural forest fires show large seasonality, most of them occur in June, July and August. Lightning caused around 50% of all fires in those months (cf. Figure 28).

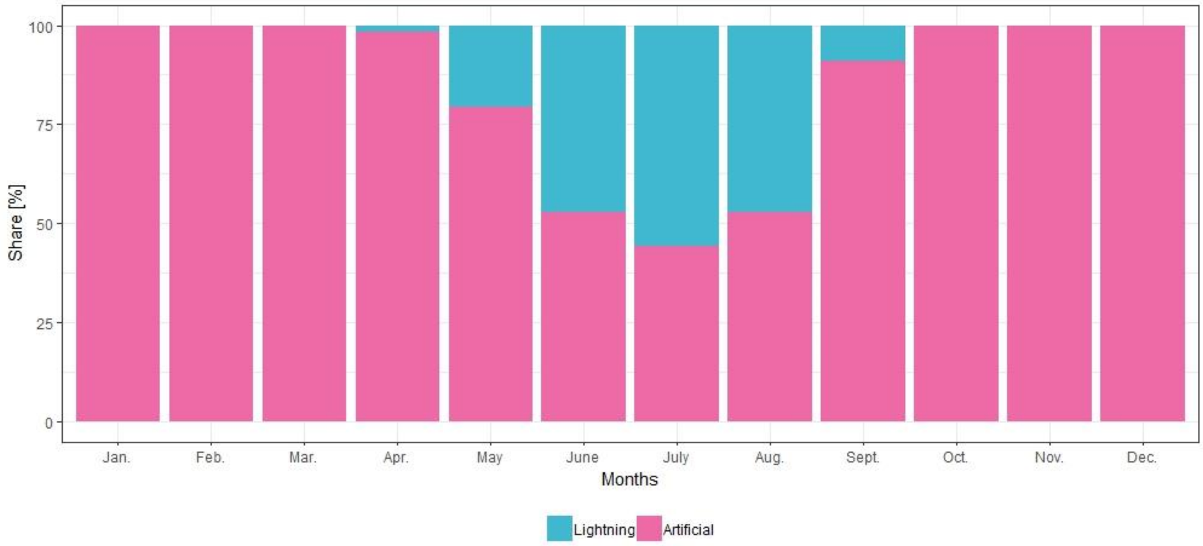

Figure 28: Cause of ignition during a year [n=514] (Waldbrand-Datenbank Österreich 2016)

Styria shows strong spatial dependency on the cause of forest fires ignition. Styrian Prealps can be defined as a natural border between southern part of the province, which is for the most part flat, with the exception of foothills and almost without natural fires and in the northern part of the province share of forest fires caused by lightning in some of the political districts is more than 75% (cf. Figure 29 and Table 6).

Concerning to ecoregions it can be summarized, that the highest share of forest fires caused by lightning happened in eastern part of the Northern Mountain Range ecoregion and in Northern Intermediate Alps (ecoregion code 4.2 and 2.2) with share 50 % and 41,3 %. One-third of the wildfires is naturally caused in North part of Eastern Intermediate Alps (3.1) and a little bit less than one quarter in Eastern and Central Styrian highlands (5.3 – 23,3%) and in the Southern part of Eastern Intermediate Alps (3.2 – 20,8%). The lowest share of thunderstorms on fire ignition is on the south of Styria in ecoregion Subillyrian highlands and terraced land (8.2 – 4,9%) and on the north in ecoregion Northern mountain range - west part (4.1 – 11,1%). Important to notice, that ecoregion 4.1 takes just small part of Styria, with a low number of fire events (n = 9) and most of the ecoregion is located in Salzburg, Tirol and Vorarlberg.

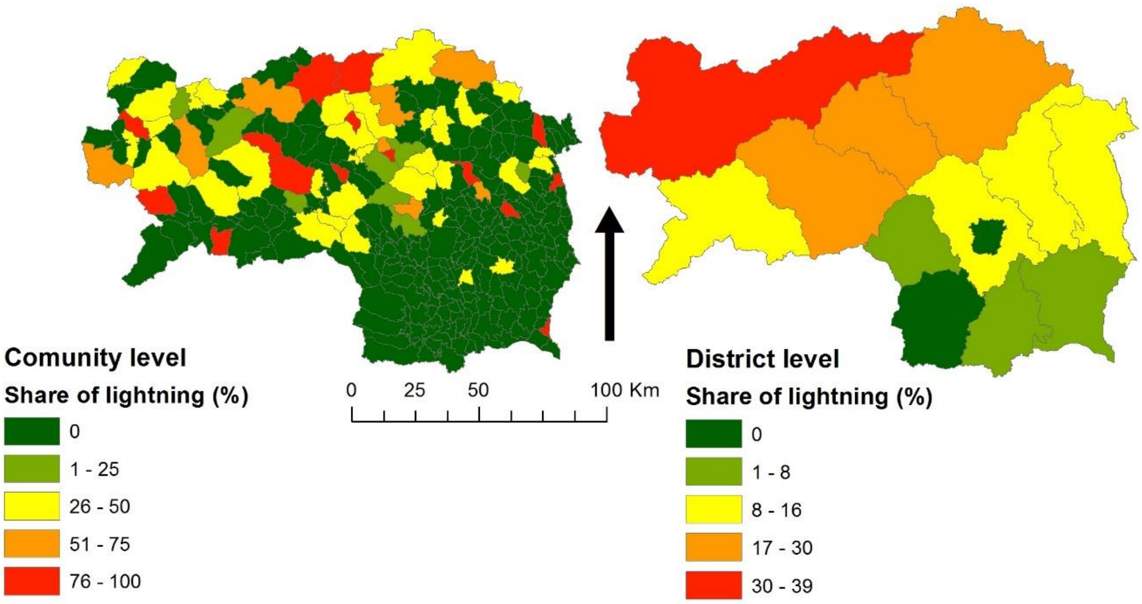

Figure 29: Right cause of ignition by district and by community on the Left [n=514] (Waldbrand-Datenbank Österreich 2016)

4.4.Spatial distribution of fires

Distribution of fires is uneven and varies from $0{,}71*10^{-3}$ fires per km^2 annually in the district of Liezen to suburban of Graz and city of Graz with $2{,}41*10^{-3}$ and $2{,}62*10^{-3}$ (cf. Table 5 and Figure 7). Main fire hotspot can be found in the valley of Mur and Mürz around towns Aichfeld, Leoben, Bruck an der Mur or Mürzzuschlag and the nearby city of Graz.

With regard to the ecoregions it's possible to define the Eastern part of Eastern Intermediate Alps as the region with relatively highest occurrence of forest fires ($1{,}78*10^{-3}$ fires per km^2 annually, n = 95), little bit fewer events happened in Eastern and Central Styrian highlands and Subillyrian highlands and terraced land ($1{,}58*10^{-3}$, n=73 and $1{,}57*10^{-3}$, n=183). A lower number of wildfires is documented in the Southern part of Eastern Intermediate Alps and Northern mountain range - west part (3.2 - $1{,}16*10^{-3}$, n=101 and 4.1 - $1{,}15*10^{-3}$, n=9). The lowest occurrence of wildfires is in the east part Northern Mountain Range ecoregion and in Northern Intermediate Alps (4.2 – $0{,}77*10^{-3}$, n=46 and 2.2 – $0{,}45*10^{-3}$, n=10).

Table 6: Basic indicators by district (1993 - 2016) [n=517] (Waldbrand-Datenbank Österreich 2016; BFW 2009; GBM Graz 2008)

	Area (km^2)	Forest cover (%)	Forest fires (n)	Natural FF (n)	Share of natural fires (%)	Density of FF ($n/100km^2$)	Burned area(m^2) Natural	Artificial
Liezen	3316,8	70,67	57	22	38,6	2,4	32727	288646
Murau	1384,0	57,1	31	5	16,1	3,9	27210	144911
Südoststeiermark	1009,3	37,1	26	2	7,7	6,9	NA	393415
Leibnitz	726,8	41,1	20	1	5,0	6,7	5	360850
Murtal	1675,5	65,1	52	14	26,9	4,8	188100	214420
Weiz	1097,8	54,7	38	5	13,2	6,3	4620	283581
Deutschlandsberg	863,8	57,8	30	0	0,0	6,0	0	71732
Bruck-Mürzzuschlag	2154,6	73,5	79	24	30,4	5,0	78500	8800
Voitsberg	679,1	55,4	25	2	8,0	6,6	50200	108666
Hartberg-Fürstenfeld	1227,6	48,4	46	7	15,2	7,7	160	94465
Leoben	1051,9	76,2	42	12	28,6	5,2	10550	16404
Graz Umgebung	1228,4	52,9	63	10	15,9	9,7	54263	111384
Graz Stadt	127,5	24,39	8	0	0,0	25,7	0	125271
Total	16542,9	61,4	517	104	20,1	5,1	446335	2222545

4.5.Area Burned

The Austrian fire database registered 517 forest fire events over the last 30 years. There are no records about the size of the burned forest for 137 records. Mostly for the period between 2001 – 2010, records are missing for almost 50 % of the events in this time. Less than 15% of records are without information, which indicates the size of the fire after the year 2010.

The fire database contains information about the size of the wildfires for 379 events. These fires had an average size of 7042 m^2, median value = 300 m^2. Most of the forest fires affected an area up to 1 hectare and are labeled as small fires. First size group (1 – 10 m^2) contains 70 records, in the second group (11 – 100 m^2) are 93 fires, the third one (101 – 1000 m^2) has 96 events and the fourth group (1001 – 10 000 m^2) has 78. Forest fires larger than 1 ha occurred rarely, the fire database has only 42 records. The largest fires burned up to 35 ha of forest in Styria (cf. Figure 30).

Large fires which occurred in Styria show similar anomalies compared to rest of the forest fires. In Austria the most significant is artificial cause of ignition. Share of natural forest fires in last 25 years were almost 20%, in the cause of large forest fires was share of lightning as an ignition agent just 2,38%. It should be also noted that there is quite a big difference in FFCM values. The large events have more than 5 points higher FFMC values in the moment of ignition compare to the average of all events (cf. Table 7).

Table 7:Results of Canadian Forest Fire Weather Index (Waldbrand-Datenbank Österreich 2016)

	FFMC	DMC	DC	ISI	BUI	FWI	DSR	ACFF (%)
All	74,21	20,47	142,28	2,17	27,51	4,57	1,06	97,62
10k+	79,38	21,51	111,67	2,32	26,72	4,69	0,62	80,46

All – all the forest fires in Styria (1993 – 2016) n = 515, 10k+ – Forest fires bigger than 1 ha n = 42, FFMC – Fine Fuel Moisture Code, DMC – Duff Moisture Code, DC – Drought Code, ISI – Initial Spread Index, BUI – Buildup Index, FWI – Fire Weather Index, DSR – Daily Severity Rating, ACFF – Artificial caused forest fires

Forest fires bigger than 1 hectare seems to occur more frequently in the spring months, especially in April (42,86%). Relatively small share of large forest fires occurred in the summer months, which is a second peak of forest fires activity in Styria (cf. Table 8 and 9).

Table 8: Occurrence of forest fires by size during a year (Waldbrand-Datenbank Österreich 2016)

	10k+		All	
Month	Number	Share (%)	Number	Share (%)
January	3	7,14	26	5,05
February	4	9,52	20	3,88
March	2	4,76	79	15,34
April	18	42,86	119	23,11
May	4	9,52	40	7,77
June	1	2,38	36	6,99
July	2	4,76	61	11,84
August	4	9,52	83	16,12
September	0	0,00	11	2,14
October	1	2,38	7	1,36
November	2	4,76	10	1,94
December	1	2,38	23	4,47

All – all the forest fires in Styria (1993 – 2016) n = 515, 10k+ – Forest fires bigger than 1 ha n = 42

Table 9: Number of forest fires larger than 1 ha for sub eco region during a year [n=42]

	Sub eco region								
Month	22	30	31	32	41	42	53	82	Sum
January	1	0	1	1	0	0	0	0	3
February	0	0	1	1	0	0	1	1	4
March	0	1	0	0	0	0	1	0	2
April	1	0	2	4	0	1	2	8	18
May	0	1	0	1	0	0	0	2	4
June	0	1	0	0	0	0	0	0	1
July	1	0	0	0	0	0	0	1	2
August	2	0	1	1	0	0	0	0	4
September	0	0	0	0	0	0	0	0	0
October	0	0	0	1	0	0	0	0	1
November	0	0	0	2	0	0	0	0	2
December	0	0	0	0	0	0	1	0	1
Sum	5	3	5	11	0	1	5	12	42

22 - Northern Intermediate Alps – east part, Eastern Intermediate Alps – North (30 - Mürzzuschlag, 31 - Bruck an der Mur) and South part (32), Northern Mountain Edge – west (41) and east (42) part, 53 - Eastern and Central Styrian highland, 82 Subillyrian highlands and terraced land

Eastern and Northern Intermediate Alps indicate bigger probability to occurrence of large forest fires than other parts of Styria (cf. Table 10). On other hand just a little bit more than one quarter of the large forest fires were recorded in the flat and hilly part of south Styria, which is a sub eco region with highest occurrence of forest fires (35,53%).

Table 10: Occurrence of forest fires by size in different sub eco regions of Styria

	10k+		All	
WG	Number	Share (%)	Number	Share (%)
22	5	11,90	46	8,93
30	3	7,14	17	3,30
31	5	11,90	77	14,95
32	11	26,19	101	19,61
41	0	0,00	9	1,75
42	1	2,38	10	1,94
53	5	11,90	72	13,98
82	12	28,57	183	35,53

WG – Sub eco region (Wuchsgebiete), All – all the forest fires in Styria (1993 – 2016) n = 515, 10k+ – Forest fires bigger than 1 ha n = 42, 22 - Northern Intermediate Alps – east part, Eastern Intermediate Alps – North (30 - Mürzzuschlag, 31 - Bruck an der Mur) and South part (32), Northern Mountain Edge – west (41) and east (42)part, 53 - Eastern and Central Styrian highland, 82 Subillyrian highlands and terraced land

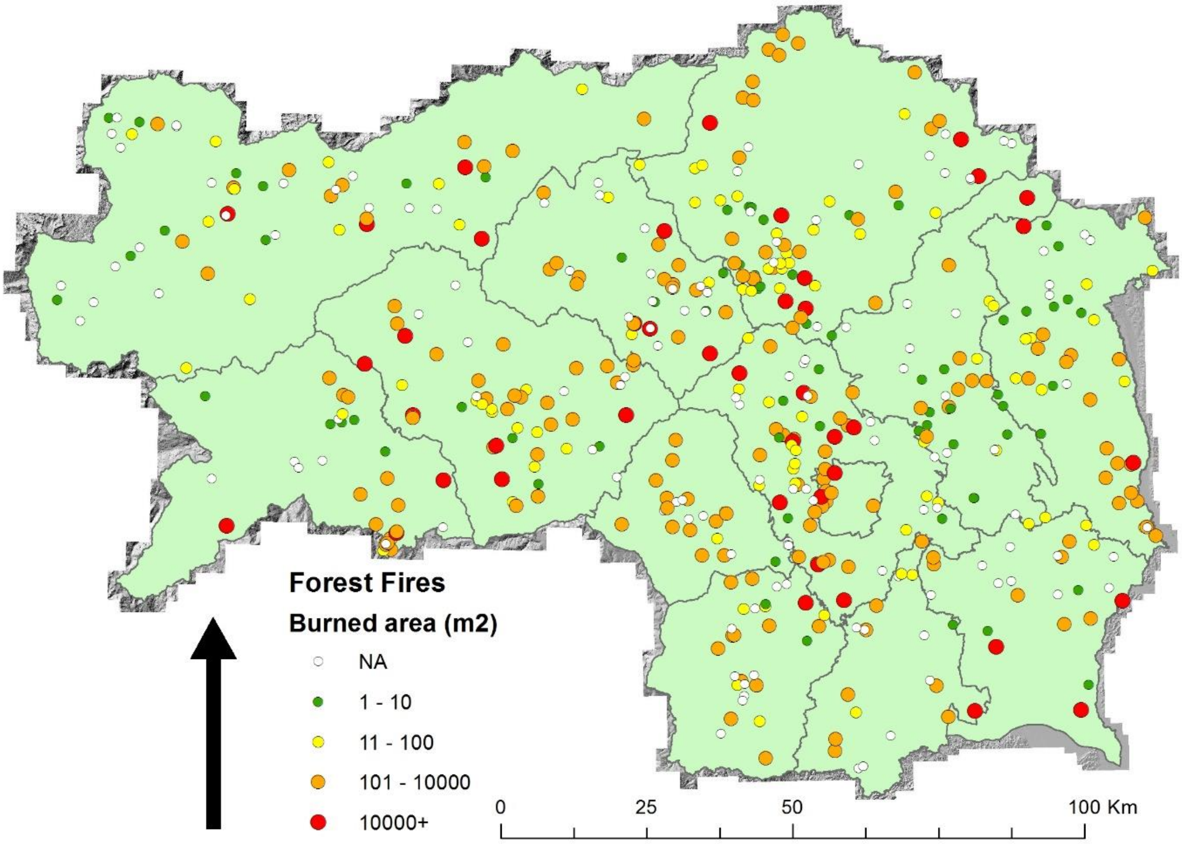

Figure 30: Regional Distribution of Forest Fires in the Province Styria (1993 – 2016) [n=517] (Waldbrand-Datenbank Österreich 2016)

4.6.Topography

Styria spreads out from the lowest elevations to the high alpine zone, this magnitude begins at 199 meters above sea level on the borders with Slovenia and ends at 2995 m on the top of Dachstein massif (Strunz, 2017), fire events occur only on limited part of this scale (236 – 1933 m). A little bit more than one quarter (28,57%) of all forest fires were located on the places with altitudes <500 m. The majority of events occurred in altitude range of 500 – 1000 m, one-sixth (16,41%) between 1000 – 1500 m and the remaining (4,44%) between 1500 – 2000 m. The average altitude of forest fires in Styria is 764 m, median lays at 719 m – cf. Figure 31.

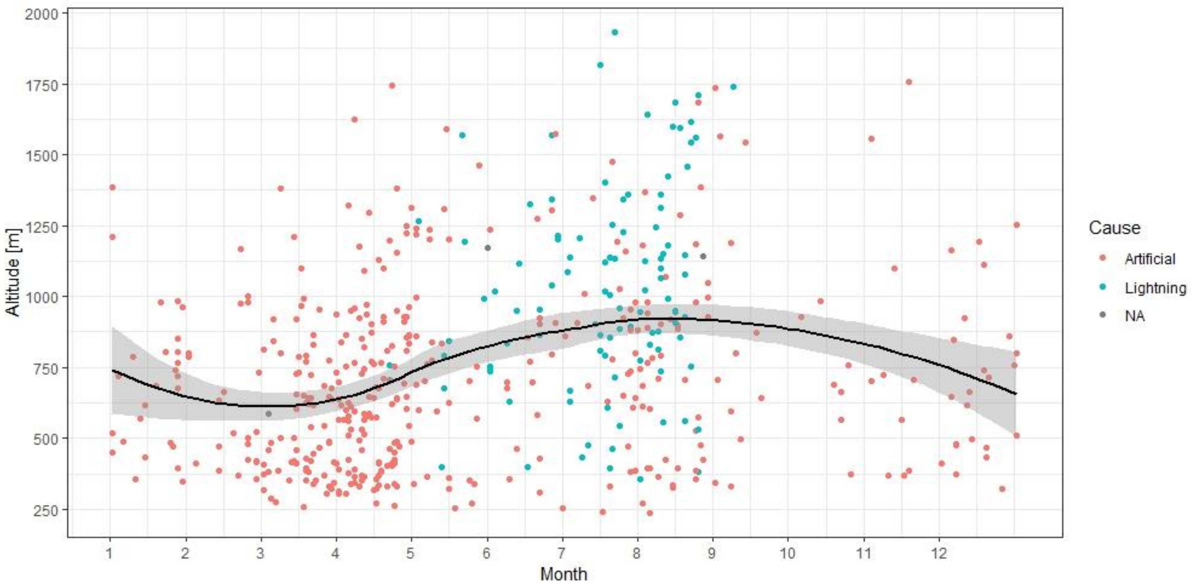

Figure 31: Occurrence of forest fires during a year by elevation [n=517] (Waldbrand-Datenbank Österreich 2016)

The topography plays an import role in the occurrence of the fires during a year. The altitude of events is at the beginning of the year low and slowly increasing during summer months reaching the peak during August/September with an average altitude of 900 meters. The lowest average altitude of forest fires happened in March (578 m). Occurrence of spring fires is horizontally mostly limited to elevation ranges between 300 and 1000 meters. Summer fires are recorded from the whole elevation spectrum from the lowest parts of the province to the subalpine zone.

Also, the cause of the forest fires is closely connected with topography. The average altitude of artificial forest fires is 699 meters and the median value is 652 meters. The mean value of wildfires caused by lightning lays much higher in 1019 meters, median altitude is 993 m. Just around 20 % of all naturally caused forest fires happened under an elevation of 750 meters, but it is possible to locate there more than 60% of artificial forest fires. On the other hand, almost 50 % of the fires caused by lightning occurred on elevation above 1000 meters and there are records, which are noticed nearly in 2000 meters. Artificial forest fires have just a little bit more than 10 % events, which were recorded in altitude above 1000 meters – see bellow in Figure 32.

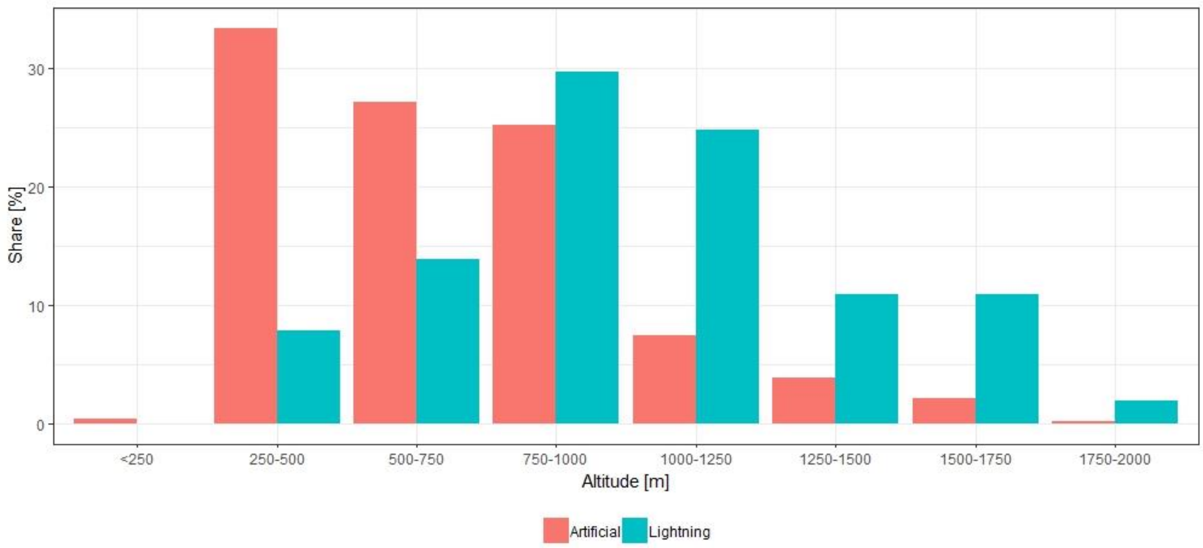

Figure 32: Altitude of forest fires classified by different cause of ignition [n=514] (Waldbrand-Datenbank Österreich 2016)

The predominant tree species in the forest stand, where a forest fire occurred is known for half of the records. This knowledge offered a possibility to match these data with the elevation of forest fire (cf. Figure 33) and the species composition in Styria. The majority (78,19%) of forest fires happened in forest stands, where Norway Spruce dominate. This indicates that forest stands with dominance of Norway Spruce are more often damaged by forest fires, compare to the total share of spruce in Styria (70,50%) (cf. Figure 34). Forest fires in spruce forests show also the biggest range in sense of altitude. The lowest fire occurrence was detected in elevation of 273 m and the highest one is recorded almost above 2000 m. The average altitude of forest fires in spruce forests is 846 m – 80 meters higher than its average value for Styria, the median value is 807 m. Beech forests were a place of wildfire in 19 cases (7,82% of forest fires), which also indicate higher risk of forest fires in beech forest, because beech covers just about 6,20% of the forest land in Styria. The lowest documented fire happened in 317 meters and the highest in 756. The average altitude of events is 480 m, the median is similar and lays in 486 m. In 13 records also pine forest had a forest fire, with a huge altitude range from 343 to 1640 meters. Average elevation of fires in pine forests is 574 meters and median is 662 meters. Pine forests show the highest vulnerability to forest fires from all tree species in Styria. Pine forest grow on 2,80 % of forest land, but 5,35% of all records in the Fire database occurred in pine forests. Low probability of forest fires indicates vegetation constituted by Silver Fir or European Larch. Share of European Larch in Styria is 5,50%, but only in 1,23% of all forest fire records were found in larch forests. Silver Fir covers 2,80% of forest land in Styria and there are no records of forest fires in the database.

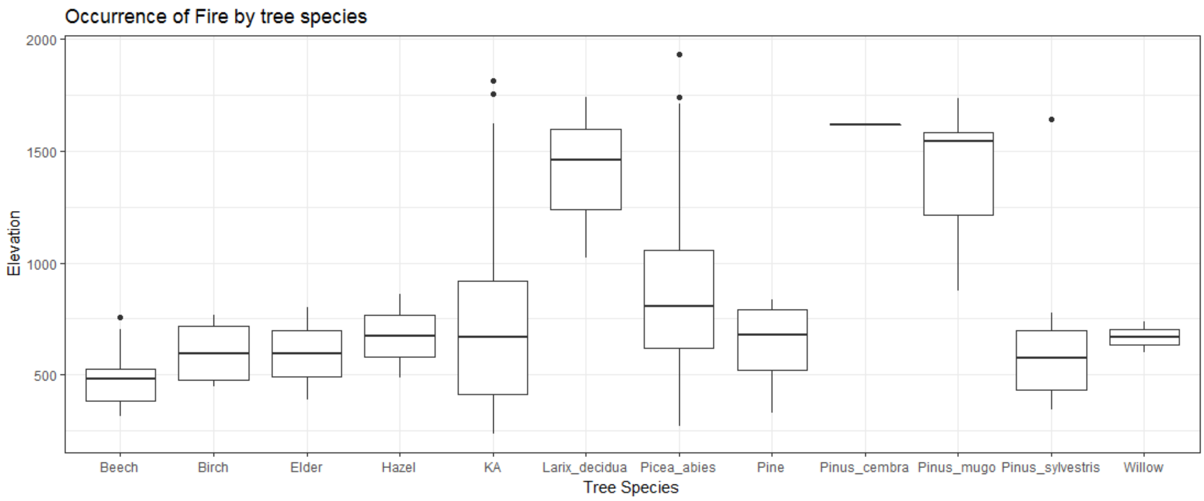

Figure 33: Range of altitude zones of forest fires classify by different tree species [n=243] (Waldbrand-Datenbank Österreich 2016)

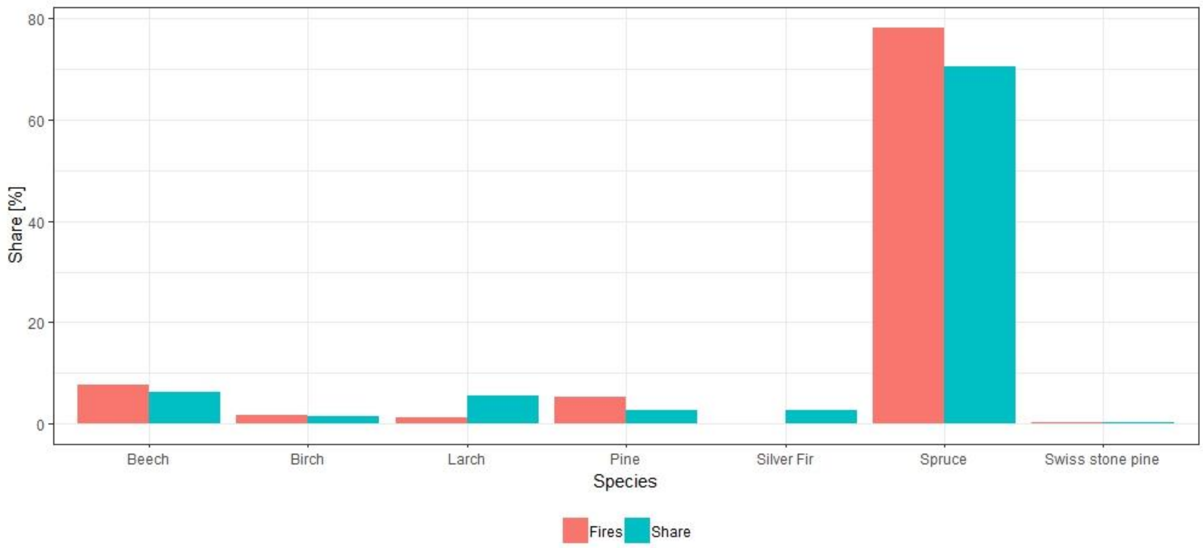

Figure 34: Share of forest fires by tree species and share of tree species in the overall forest area in Styria [n=517] (Waldbrand-Datenbank Österreich 2016; BFW 2010b)

4.7. Canadian Forest Fire Index

The Canadian Forest Fire Index and its subindeces were used in this work to understand the climatic factors behind fire ignition and fire behavior.

4.7.1. Fine Fuel Moisture Index

Fine Fuel Moisture Index was calculated for every wildfire in Styria. Weather input values were from the same sub-ecoregion where the fire happened. Recording of FFMC values begins 28 days before the fire occurred and lasts to the 11th day after the event to have 40 days overview and the possibility to map a trend in FFMC development. The average value 28 days before fire events is $FFMC_{517-28}$ = 65,39 and median value = 78,01. The lowest average values for FFMCs were around city Bad Aussee (ecoregion 4.1 - Northern Mountain Edge – west part) – $FFMC_{BAD-28}$ = 54,19 and city Mürzzuschlag (ecoregion 3.1 - Eastern

Intermediate Alps – north part) – $FFMC_{MUR-28}$ = 52,59. The highest values are on the South of the province, around the city of Graz (ecoregion 8.2 - Subillyrian highlands and terraced land) $FFMC_{GRA-28}$ = 67,49 and on southwest in Eastern Intermediate Alps (3.2) - $FFMC_{ZEL-28}$ = 68,36. In Figure 35 is possible to see the whole trend of average values of FFMC for each meteorological station (ecoregion). Average value of $FFMC_{517}$ varies between 64,09 and 68,33 between Day -28 and Day – 10. Approximately ten days before a wildfire an increase of FFMC value is observed. The highest value of FFMC is possible to observe in timeframe +- 24 hours around ignition of the wildfire, when average $FFMC_{517\ 0}$ reach a value 79,42 and the median value is 84,63. The highest average values are in Northern Mountain Range ecoregion 4.2 $FFMC_{MAR\ 0}$ = 82,99 and around city of Graz (8.2) $FFMC_{GRA\ 0}$ = 79,74. Lowest values reach FFMC code around city of Bad Aussee $FFMC_{BAD\ 0}$ = 68,94 and in neighboring zone ecoregion 2.2 $FFMC_{IRD\ 0}$ = 69,03. After fire is possible to observe dramatic drop of the FFMC values in all meteorological stations. Two days after wildfire average value of $FFMC_{517+2}$ decreased about 5 points to 74,46. Eleven days after wildfire is average value of FFMC approximately similar to pre-fire situation (cf. Figure 35).

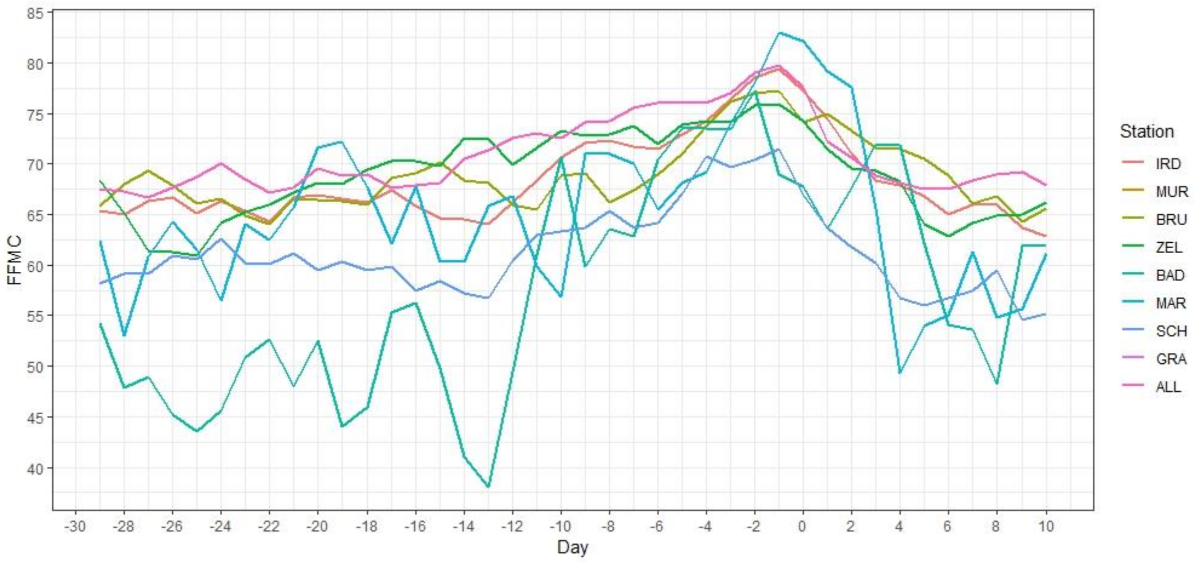

Figure 35:TImeline shows different mean values of FFMC before and after wildfire ignition [n=517] (Waldbrand-Datenbank Österreich 2016; ZAMG 2017)

De Groot in his work: "Interpreting the Canadian forest fire weather index (FWI) system" from 1987 claims, that fires begin to ignite when FFMC values are close to 70, the highest probable value which can be achieved is 96. Janine Oettel defined in her master thesis "Forest Fires and Fuel Characteristics of Tyrol" from 2012 threshold values for FFMC, which was also used in this work. Oettel defined 5 danger levels with 4 thresholds (76, 83, 87, 92) – danger level 1 doesn’t have any lower constrain and danger level 5 is limited by highest theoretical values of FFMC 99 – cf. Table 11.

Table 11:Distribution of forest fires per FFMC in danger levels [n=517]

	Danger Level for FFMC				
	I.	II.	III.	IV.	V.
Range	0 – 76	76 – 83	83 - 87	87 - 92	92 +
Number	106	88	189	133	0
Share	20,54%	17,05%	36,63%	25,78%	0

Interesting values show Figure 36 with the median values of FFMC. Median values of FFMC in 40 days period by meteorological station Graz – Airport, Zeltweg and Bruck an der Mur are stable and show relatively high median. On other hand, median values of FFMC show a huge variability by the meteorological station in Bad Aussee, Mariazell, Mürzzuschlag, Schöckl and in Irding – Gumpenstein.

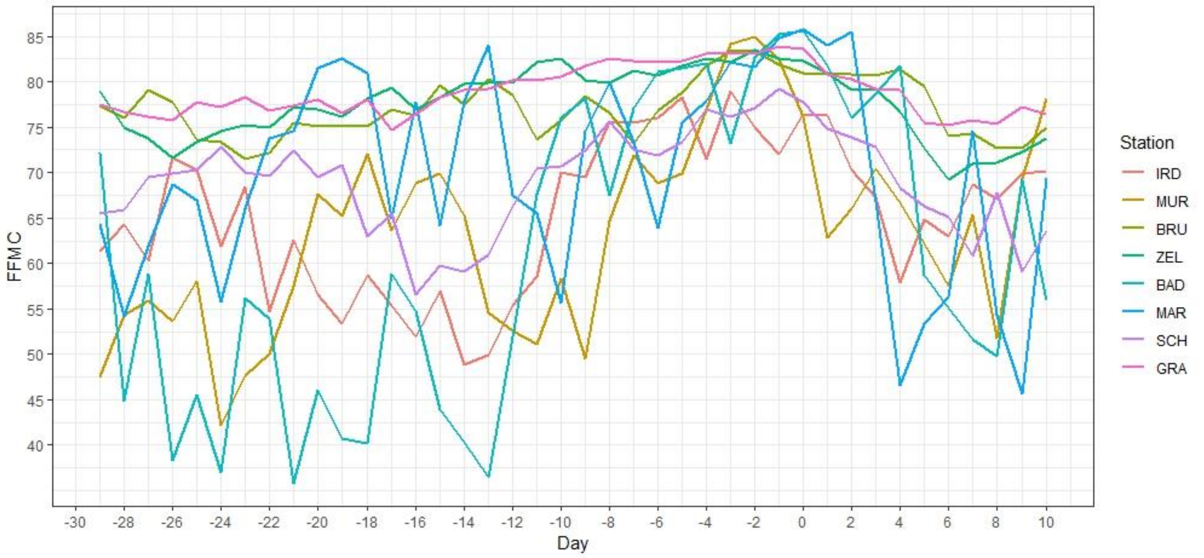

Figure 36: Timeline shows different Median values of FFMC before and after wildfire ignition [n=517] (Waldbrand-Datenbank Österreich 2016; ZAMG 2017)

4.7.2. Fire Behavior Indexes

The Buildup Index (BUI) and Initial Spread Index (ISI) were calculated for each forest fire, which was recorded in the period between years 1992 – 2016. For further analyses it was necessary to use also information about the burned area of each forest fire. 361 records provided the data in the Fire Database.

It was tested which of those indexes is more suitable to predict the size of a forest fire. Buildup Index, a combination of the DMC and the DC that represents the total fuel available to the spreading fire. Initial Spread Index, a combination of wind and the FFMC that represents rate of spread alone without the influence of variable quantities of fuel (van Wagner 1987).

Regression analysis was used to estimate the size of the forest fire based on previous records.

For the Initial Spread Index (ISI) following equation was used:

$$y = 10^{(0,2042x + 2,0925)}$$

Where *Y* express the size of a burned area and *X* value of ISI.

For Buildup Index (BUI) following equation was used:

$$y = 10^{(1,2739x + 23,992)}$$

Where *Y* express the size of a burned area and *X* value of BUI.

For both analyses were calculated a degree of scatter. The analysis of ISI shows much higher coefficient of determination than an analysis of BUI:

ISI: $r^2 = 0,0501$

BUI: $r^2 = 0,0062$

F values of both analyses were compared with the critical value of F, which was set with a degree of freedom in the numerator 1 and 359 as the denominator. Level of uncertainty stayed at the traditional value of 5%, thus, certainty is 95%.

Critical Value F: qf (0,95,1,359) = 3,868.

Calculated values of F:

ISI: F value= 19,270

BUI: F value= 2,229

Value of F_{BUI} is lower than critical value of F, thus we can assume, that it´s not possible to use BUI index in Styria for projecting size of burned area (cf. Figure 38). On other hand, value of F_{ISI} is higher than critical value of F. Initial Spread Index shows a positive correlation with an increasing ISI rate, the burned area increases (cf. Figure 37).

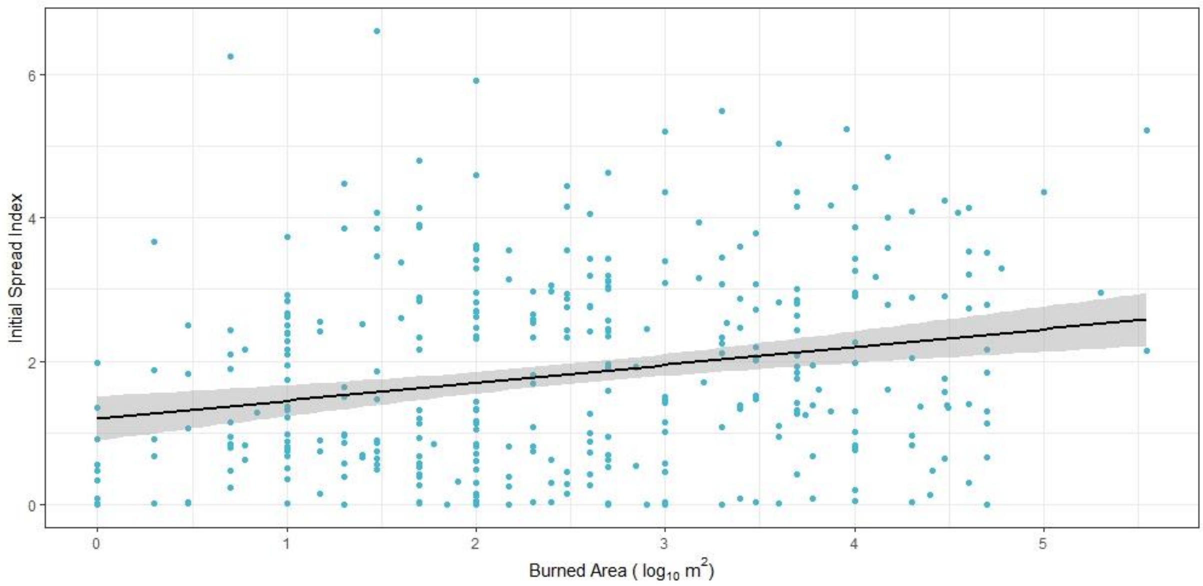

Figure 37: – Influence of ISI on size of burned area [n=361](ZAMG 2017; Waldbrand-Datenbank Österreich 2016)

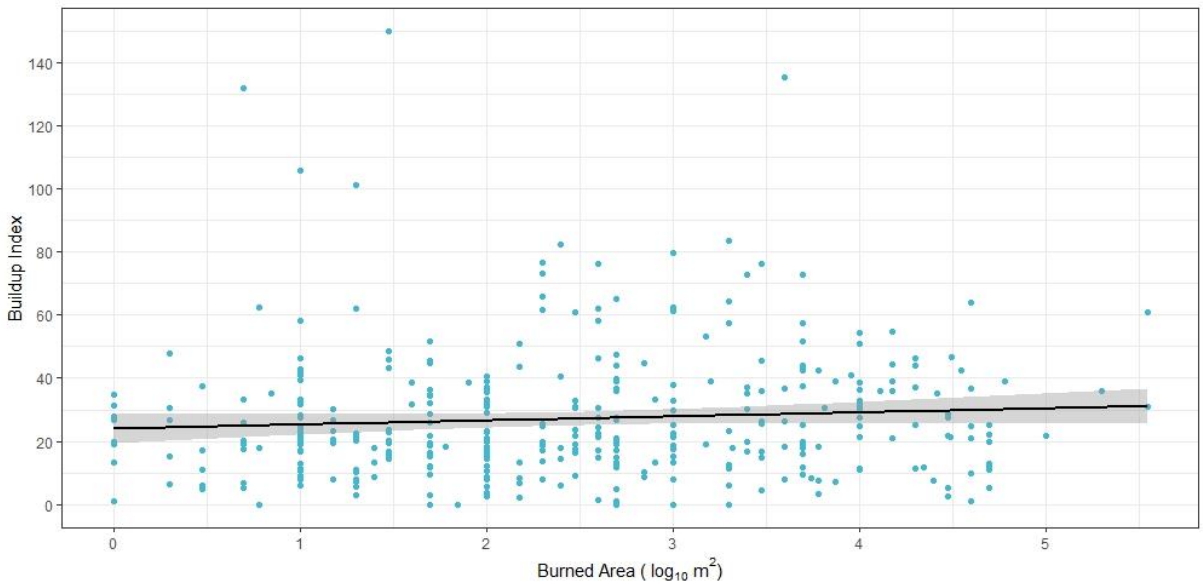

Figure 38: Indicate influence of BUI on size of burned area [n=361](Waldbrand-Datenbank Österreich 2016; ZAMG 2017)

4.8. Detailed comparison of forest fires

The outcomes of 3 groups of forest fires are presented here. Artificial fires were separated into two groups: areas with high human activity (AH) and with low human activity (AL). The third group represents natural forest fires caused by lightning (L).

4.8.1. Topography

It is possible to observe significant differences in the spatial occurrence of forest fires between defined groups. Forest fires in group AH (n=26), occurred in the altitude range between 317 m – 1163 m, average elevation of wildfires in AH group was 589 m and the median value was 541 m. Group of fires, which occurred in areas with lower human activity (n = 25), show a bigger range of values. They begin at 317 meters above sea level, the highest record comes from an altitude of 1737 m. The average altitude of AL is 680 m and the median value is 487 m. Highest mean (936 m) and median values (854 m) have the naturally caused wildfires. The lowest recorded fires happened in 387 m, the highest one was in 1739 m – cf. Figure 39.

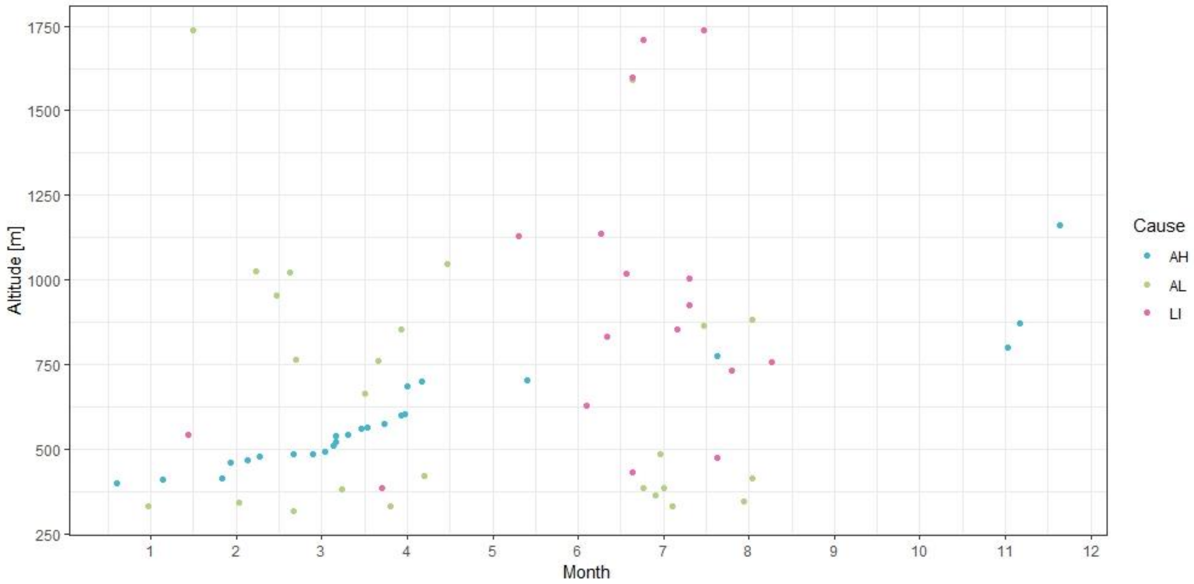

Figure 39: Altitude of forest fires during a year classified by ignition cause (AH, AL or LI) [n=68](Waldbrand-Datenbank Österreich 2016)

Aspect was investigated for all three groups together, thus all fires were considered. Analysis was focus on a number of fires (cf. Figure 40 left) and on the size of a burned area (cf. Figure 40 right) in each of four main cardinal directions. Amount of forest fires was quite similar for each direction. The lowest number of fires was recorded on the slopes, which are oriented south (n = 14) and east with 15 records. Most of the fires occurred on the slope with north facing slope (n = 20), second place took west oriented slopes with 19 records.

On the other hand, burned area by cardinal directions indicates huge differences between them. The lowest area is affected on the north facing slopes, where fires burned 4280 m2 and the average size of wildfire was 214 m2. Area burned by forest fires is quite similar for East (total = 13 480 m2 and average size = 899 m2) and West (total = 15 265 m2 and average size = 803 m2) directions.

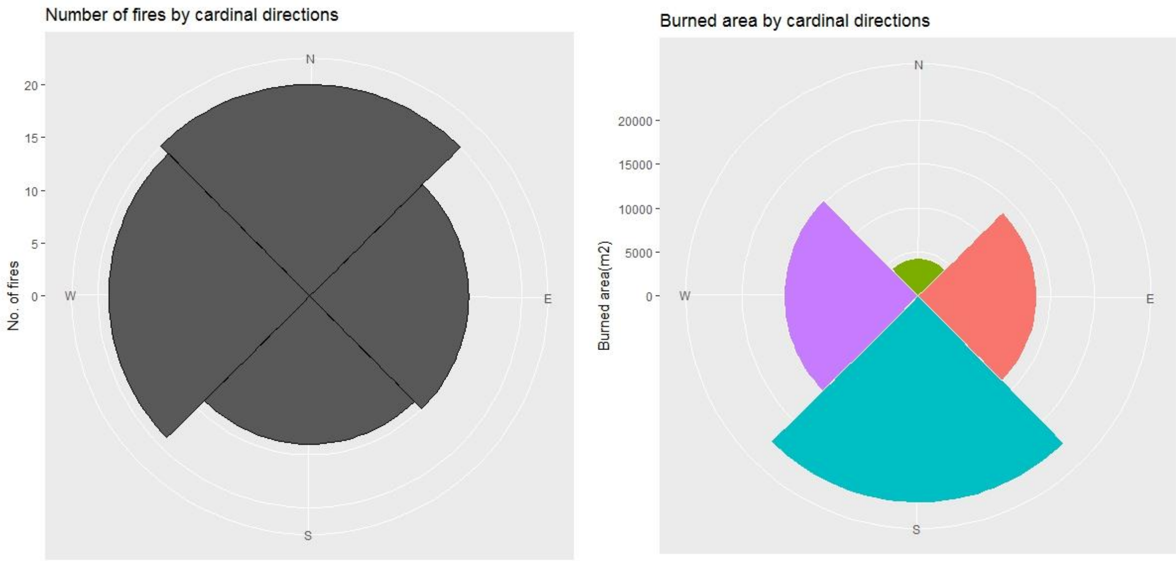

Figure 40: Number of fires by cardinal directions (left). Sum of burned area by cardinal directions (right) [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

Slope is an important factor for the spread of forest fire, but results indicate also differences ignition (cf. Figure 41). Most of the artificial forest fires occurred on slopes with steepness below 45. Wildfires caused by lightning have not occurred on slopes with steepness below 30%.

Average steepness of artificial forest fires, which occurred in places with high human activity was 27,25% and the median value was 26,95%, in stands with low human activity the average value was 30,47% and the median value 24,58%. Natural forest fires happened in much steeper terrain – average steepness was 53,60% and median value was 51,80%.

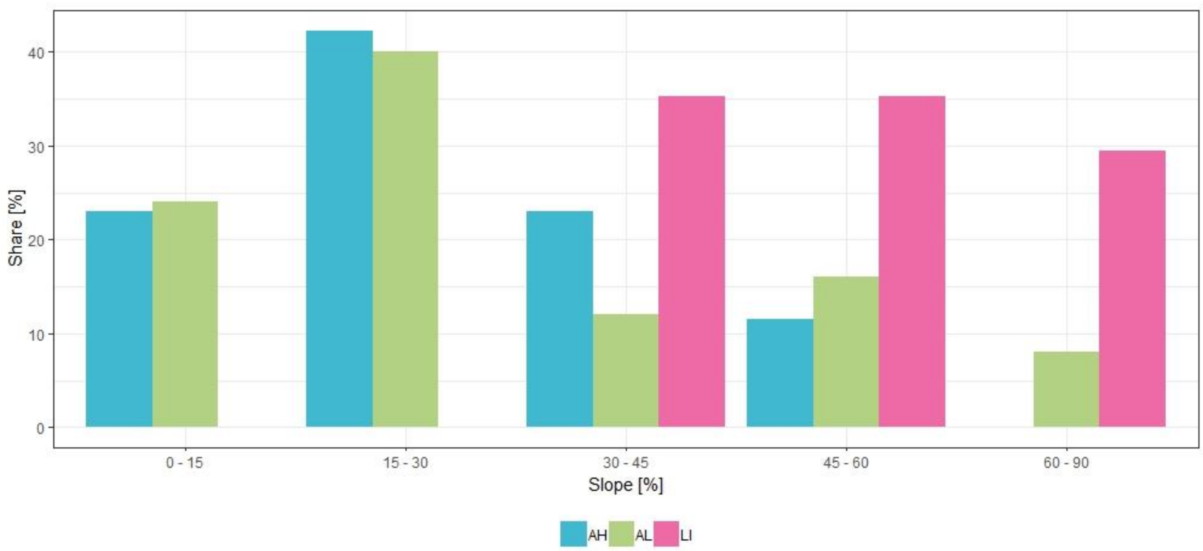

Figure 41: Average steepness of forest fires by ignition cause (AH, AL or LI)[n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

4.8.2. Stand characteristics

The first of the analyzed stand characteristic was the share of conifer species (cf. Figure 42). It was possible to find differences between groups. Lowest share of coniferous tree species was in the AL stands (60,93%), wildfires from AH group occurred on the stands with an average share of coniferous species 67,31%. The highest share of coniferous trees indicates forest stands affected by natural forest fires (LI = 79,99%).

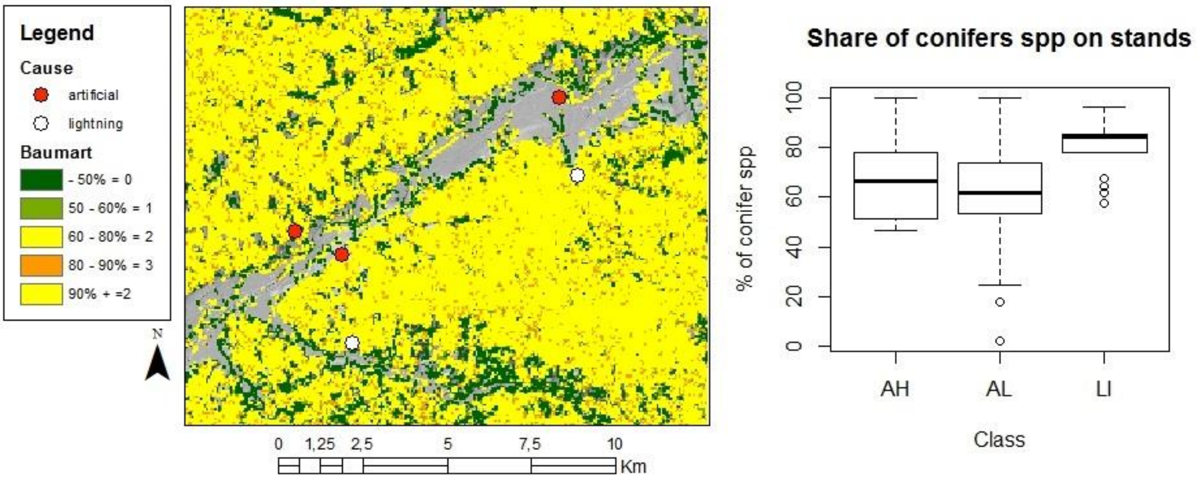

Figure 42: Share of coniferous trees (left), average share of conifers on stands by ignition cause (AH, AL or LI)(right) [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

Canopy cover plays an important role in fire occurrence and the Fire database indicates significant differences in canopy cover between forest fires caused by lightning and caused by human activities (cf. Figure 43). Forest stands affected by natural wildfires show the lowest canopy cover. Canopy cover on such stands reaches in average 66,63% closure. Forested stands, where wildfires caused by humans occurred have in average a higher canopy cover (AL = 72.66% and AH = 73,21%).

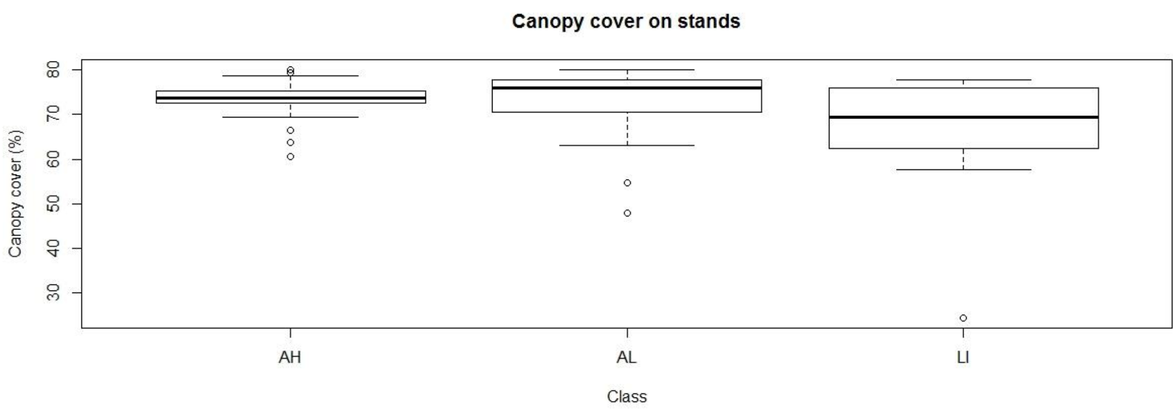

Figure 43: Average canopy cover on stands by ignition cause (AH, AL or LI) [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

Diameter at breast height seems to be similar for both classes of artificially caused forest fires (AH - 44.66 cm, AL - 44.50 cm) (cf. Figure 44). Average DBH of trees on the stands which were affected by forest fires caused by lightning was a little bit smaller with a size of 42,37 cm.

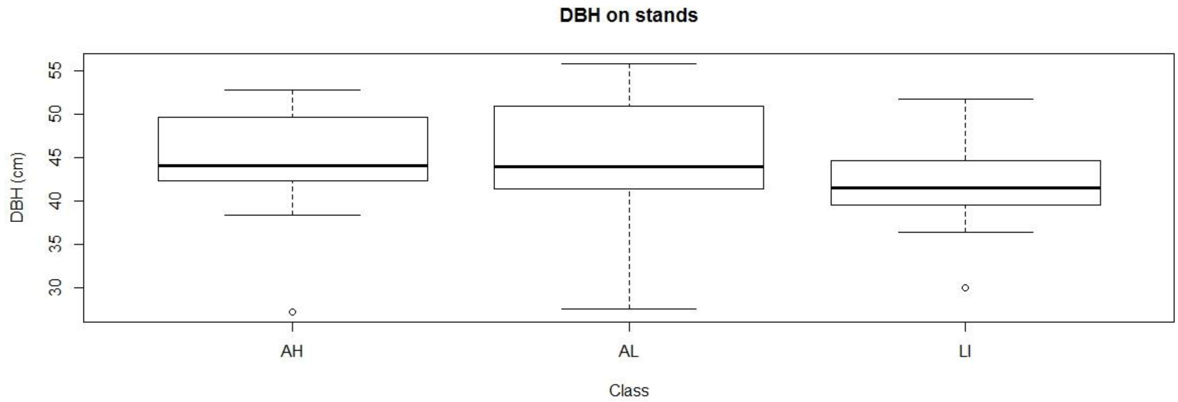

Figure 44: Average DBH on stands by ignition cause (AH, AL or LI) [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

Forest fires caused by lightning happened on average in stands which had around 10% less timber (305,02 m^3) than stands where forest fires were caused by human activity (AH – 333,01m^3 AL – 322,27 m^3) (cf. Figure 45).

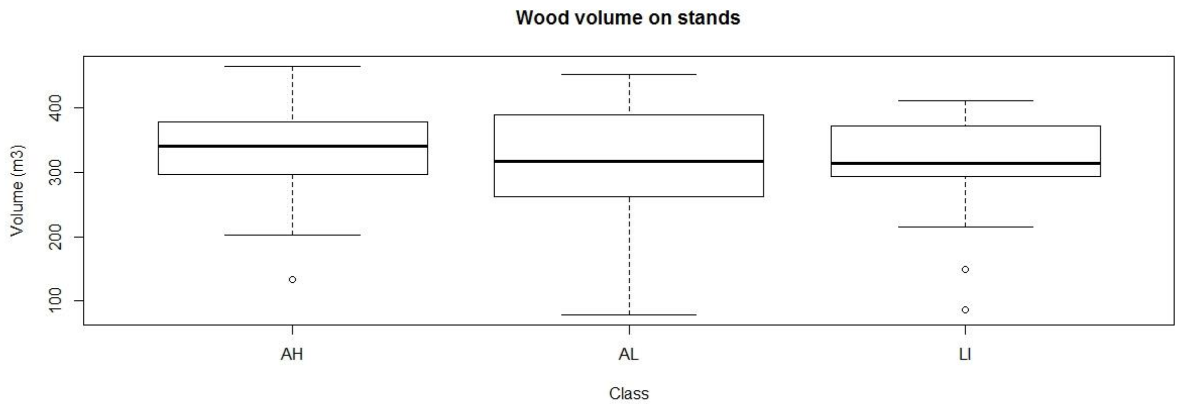

Figure 45: Average stock on stands by ignition cause (AH, AL or LI) [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

The average height of the tree doesn't show any trends regard to the cause of ignition (cf. Figure 46). Average values for artificial forest fires are 25,10 m (AH) and 23,65 m (AL). The average height of trees in lightning caused fires is 23,31 m.

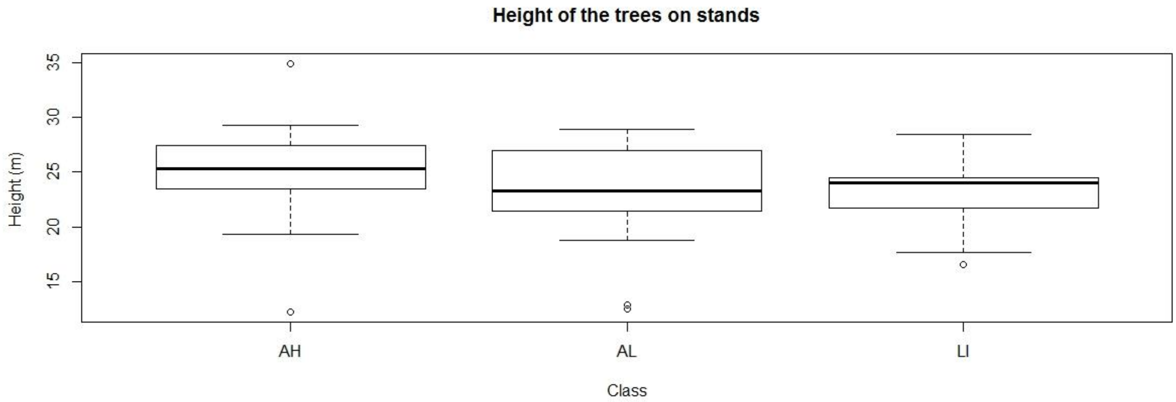

Figure 46: Average height of the trees on stands by ignition cause (AH, AL or LI) [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

The most heterogenic horizontal structure was found in forest stands with lightning-caused fires (2,28 layers). Stands with high human activity had 2,07 and with low human activity had 2,16 layers on average (cf. Figure 47).

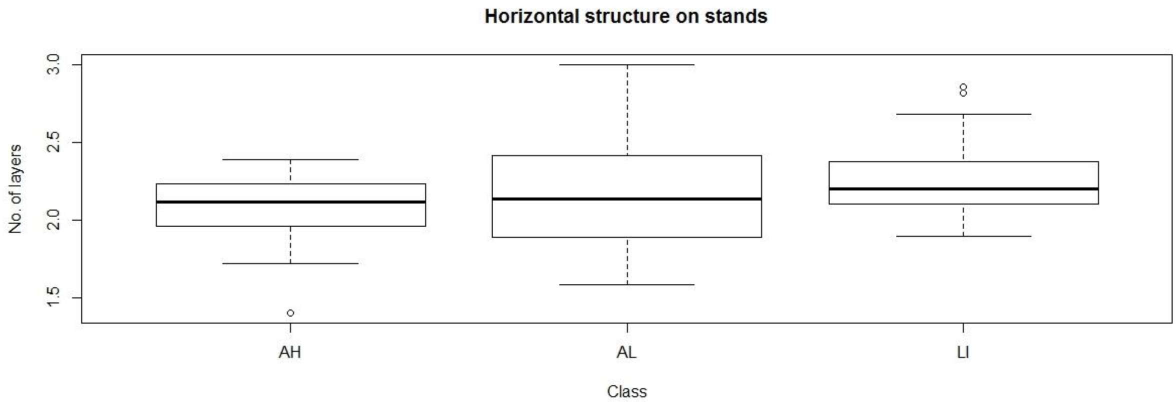

Figure 47: Horizontal structure on stand by ignition cause (AH, AL or LI) [n=68] (Waldbrand-Datenbank Österreich 2016; Stmk 2018)

Figure 48 shows a trend between the size of forest fire (Y-axis – $\log_{10}(m^2)$) and the steepness of the area (X-axis (%)). It is possible to observe a slight increase of the size of the burned area with higher steepness. Influence of slope on the size of forest fires in Styria can be expressed by the equation:

$$y = 1{,}3158x + 32{,}394$$

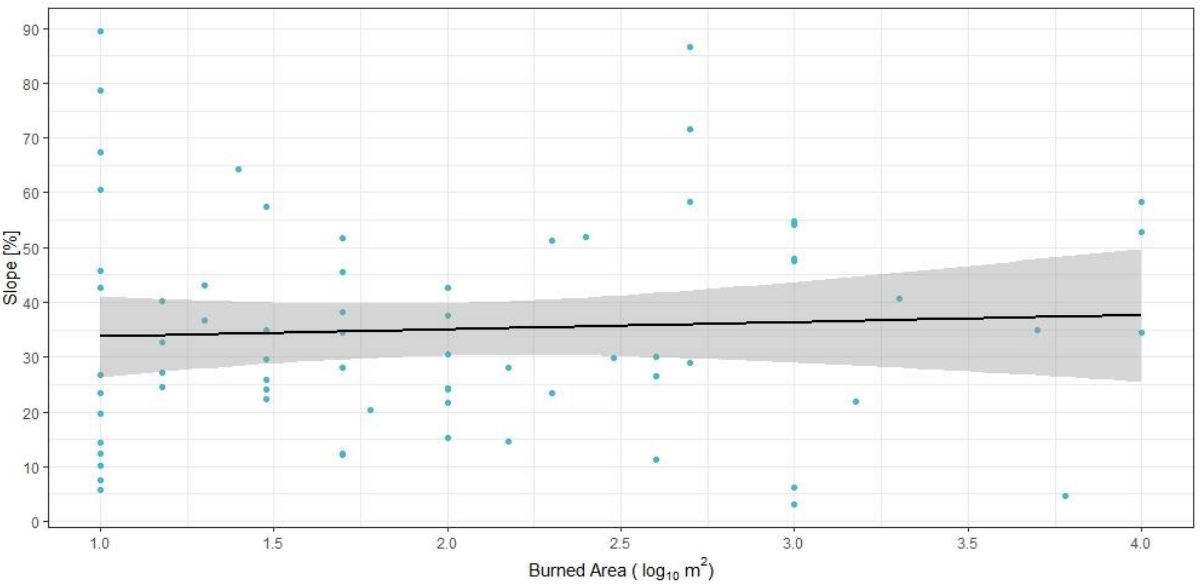

Figure 48: Size of the forest fire by different steepness [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

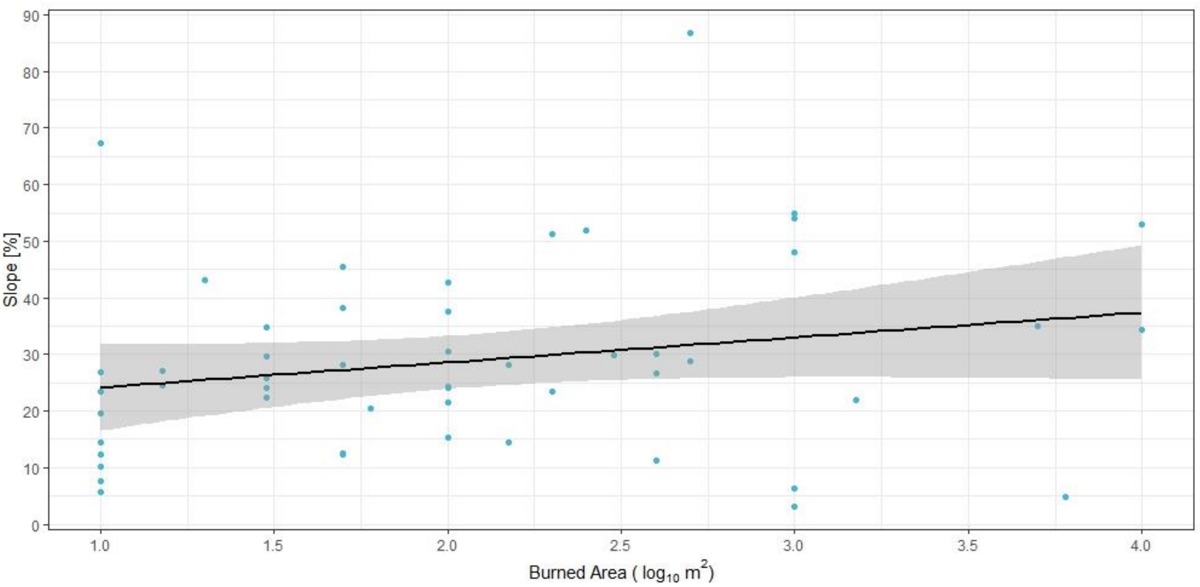

Figure 49: Size of the artificial forest fire by different steepness [n=51](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

Coherence between size of the forest fires and slope is much for visible by records which were caused by humans (cf. Figure 49). Effect of slope on artificial forest fires in Styria can be expressed by the equation:

$$y = 1,3158x + 32,394$$

On the other side, inclination of the slope plays a very small in wildfires which are caused by natural agents (cf. Figure 50). The curve indicates very small decrease of size of burned area by increasing slope. This relation can be expressed by the equation:

$$y = -0,5949x + 54,669$$

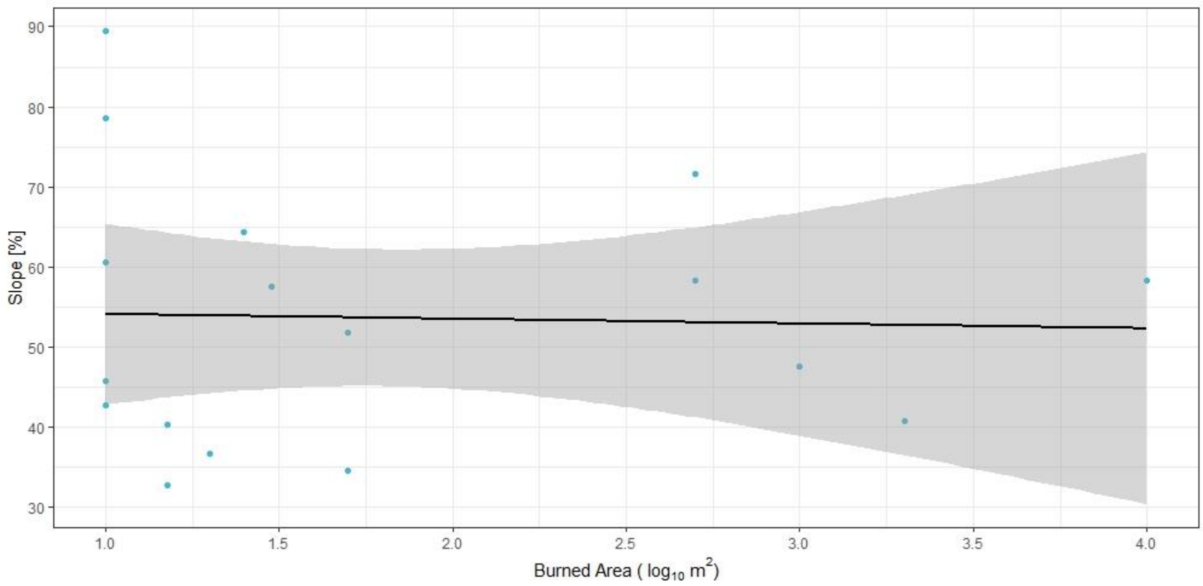

Figure 50: Size of the lightning forest fire by different steepness [n=17](Waldbrand-Datenbank Österreich 2016; Stocks et al. 1989)

4.9. Fire hazard map for lightning caused fire

The final task was to create a map (Lightning map), which can show the probability for a natural forest fire, which can be caused by lightning. The lightning map is based on the index (LMI) - a sum of values from four parameters (altitude - Va, steepness - Vs, canopy cover - Vcc and share of coniferous tree species - Vcs).

$$LMI = Va + Vs + Vcc + Vcs$$

These parameters were chosen, because differences between AL, AH and LI groups were found. Each of these parameters can represent values between 0 and 3 (case apart is canopy cover, which represents just values between 1 – 3), thus the sum of these values, which also represents the probability of a forest fire caused by lightning, is 1 – 12, where 1 represents the lowest probability and 12 the highest one (cf. Table 12 and 13).

Table 12: Column "Value" indicates figure on which was reclassified layers used in Lightning Map

	Range			
Value	Va - Elevation (m)	Vcc - Canopy C. (%)	Vcs - Coniferous spp. (%)	Vs - Slope (%)
0	0 - 400	-	0 - 50	0 - 30
1	400 - 700	0 – 60	50 - 60	30 - 50
2	700 – 1 000	60 - 75	60 - 80	50 - 70
3	1 000 – 2 000	75+	80 - 90	70 - 80
2	-	-	80 – 100	80 +
0	2 000 – 2 931	-	-	-

Lightning map(s) were produced for 3 regions of Styria (West, Northeast and Southeast). The map represents the probability of ignition of natural fire by lightning on a scale 1 – 12 (cf. Figure 53). The lightning map was produced for all three regions and the size of raster cells is

200 x 200 m (theoretically it would be possible to downscale the map to a raster cell size of 30 x 30 meters, but in this case, it would be problematic to consider fire events which vary in the location between 30 and 1 000 meters.)

Table 13: Proportional representation of each danger class (%)

LMI	1	2	3	4	5	6	7	8	9	10	11	12
Share (%)	5,92	7,12	8,11	8,21	9,32	10,72	12,18	13,77	11,68	8,55	4,03	0,41

Forest fires, which were in the fire database labeled as an event caused by lightning and had buffer area smaller or equal 1 000 meters (n = 17), were matched with the lightning map and the LMI values were extracted. These selected records have the average value of LMI = 7,76. The lowest value of LMI, which was recorded is 5 and the highest one is 11. Forest fires caused by artificial (AL + AH, n = 51), have average value of LMI = 4,91. The lowest value of LMI is 1 and the maximum is 11 (cf. Figure 51).

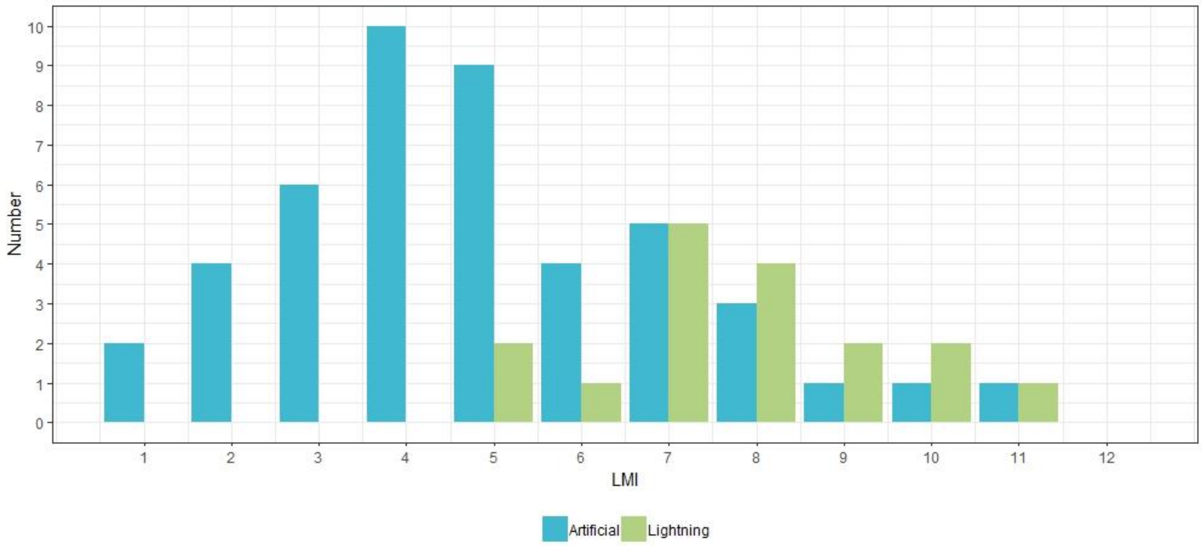

Figure 51: Number of forest fires in each danger class by different cause of ignition [n=68](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

The rest of the records of lightning caused fires from fire database (n = 48), which occurred in one of the three regions, were used for validation of the Lightning map model. These records weren´t use in the analysis, because they have a larger buffer area than 1000 meters. Average value of LMI is 7,25. Average value of LMI for selected record is 7,76. Lowest value LMI is 1 and the highest is 11 (cf. Figure 52).

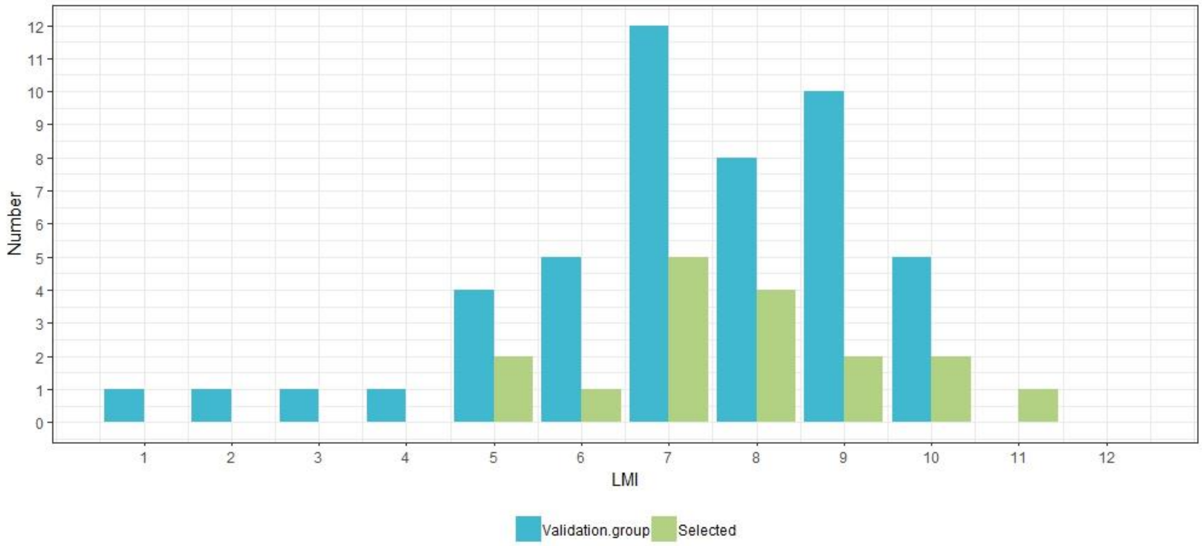

Figure 52: Number of forest fires in each danger class for selected fires and validation group [n=65](Waldbrand-Datenbank Österreich 2016; Stmk 2018)

Same validation was carried out also for rest of the artificial forest fires (n = 239). Average value of LMI is for these records 5,21. Average value of LMI for selected record is 4,91. The lowest value represents 1 and the highest LMI value is 11.

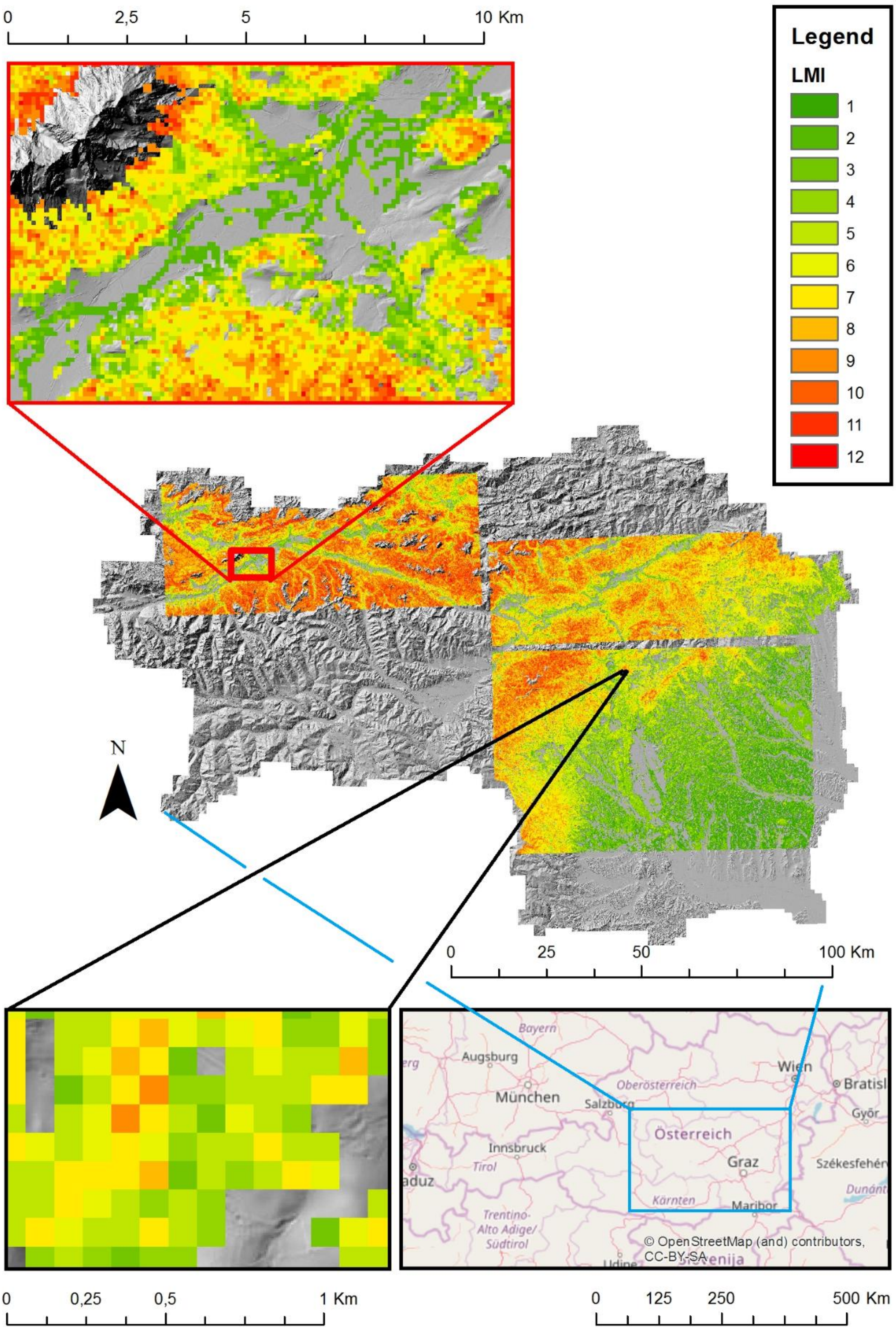

Figure 53: Lightning Map (Waldbrand-Datenbank Österreich 2016; Stmk 2018)

5. Discussion

The province of Styria is a good example of how it is possible to find large topographic and climatic variability in a relatively small area (Strunz 2017; Kilian et al. 1994). Styria has a high share of lightning caused fires, although natural forest fires occur almost exclusively in the northern mountainous part of the province. Lightning caused almost one third of the forest fires in those districts, which is a similar share as in other parts of the Alpine region (Conedera et al. 2006; Wastl et al. 2013). This fact is closely coherent with high thunderstorm activity in Styria and the highest number of flashes from all provinces of Austria (Diendorfer and Schulz 2008).

5.1.Situation and fire regime in Styria

The first records in the forest fire database from the end of the 1950s indicate more annual forest fires and a larger area of burned forest land than in the present time. Roughly one third of forest fires at that time was caused by braking trains on nearby railways (Vacik and Gossow 2011; Gossow et al. 2007). Another factor contributing to the high amount of forest fires are prescribed burning. Prescribed fires were an important part of the management of rural and forest lands in some parts of Upper Styria until the 1960s (Gossow et al. 2007). A decrease in the number of forest fires and the burned area continued until the beginning of the new millennium, this can be connected to multiple factors: depopulation, higher efficiency of agriculture, abonnement of extensive agriculture or higher awareness of forest protection (Bebi et al. 2017; Wastl et al. 2012). From the beginning of the third millennium, it is possible to observe a continuous increase in the number of forest fires. It is especially important to mention the years 2003, 2007, 2011, 2012, 2015 and 2017, as there were more than 250 forest fires in whole Austria in those years (Müller 2018). There can be many reasons for such a change of the current trend: one can be related to a climatic change which increases the average temperature in Styria and leads to (i) prolonged waves of drought, (ii) dry Foehn winds, which can drop in the relative air humidity to values as low as 20% and fast drying off of the fine fuel (Pezzatti et al. 2009), and (iii) higher thunderstorm activity (Conedera et al. 2006). Another aspect is a change in the land use for touristic activities, which have increased due to a healthy lifestyle being more and more popular; there is also a shift towards more extensive forest management, increasing the available ground fuel amounts. Last but not least, it is important to notice, that the data from the 90s and beginning of 00s are most probably not all-embracing and most probably some of the records are missing (Eastaugh and Vacik 2012; Müller et al. 2015; Gossow et al. 2007). A similar tendency is possible to observe also in the Swiss Alps (Seitz and Foppra 2007), but for example the number of forest fires and burned forest area in Germany (Lachmann 2018), and especially in the mountainous part of Bavaria (Wastl et al. 2012), are constantly decreasing.

Land damaged by forest fires show a similar decreasing trend between the 1950s to the end of the 1990s as the number of areas burnt by forest fires from the beginnings of 2000s is quite stable (with some exceptions such as the year 2003), but the number of forest fires dramatically increased. This probably indicates an improvement in fire danger forecasts, monitoring, the work of fire brigades and other aspects, which decrease the time taken to reach and suppress wildfires. Such a situation is not just unique for Styria, a similar trend is observed in the whole of Austria or other Alpine regions (Wastl et al. 2012; Conedera et al. 2006).

5.2.Temporal distribution of forest fires

Climatic change with prolonged heat waves and increasing thunderstorm activity in Central Europe (Müller et al. 2015) seems to be an important agent in the shift of fire regime seasonality in Styria. Until the middle of the 1990s, most of the year’s highest number of forest fires occurred in the spring months – mainly at the end of March and the beginning of April. Recently, in the last 20 years, the share of summer forest fires had risen as well as the number of naturally caused forest fires, and currently the summer seems to be main fire season in Styria. Also, different studies from Alpine regions indicate an increasing role of thunderstorm activity on the fire regime (Reineking et al. 2010).

Not only a bigger number of thunderstorms can be expected in next years, but also a shift in the occurrence of lightning fires to this extended time period could probably be a future trend in Styria. A similar trend was observed also in the mountainous regions of Switzerland (e.g. Canton of Valais and Grisons) or a Mediterranean area, where natural forest fires weren´t for a long time considerated as a threat (Conedera et al. 2006; Reineking et al. 2010).

A different climate, especially a different amount of precipitation and diverse average daily temperatures seems to be a leading reason for the variability in the occurrence of forest fires in Styria. The subillyrian highlands and terraced land has a relatively low amount of precipitation (especially in the winter months) and mild to warm days in the spring (Kilian et al. 1994). This is probably the reason why - together with a high accumulation of dry biomass on the ground - the most southern region of the province already recorded the annual maximum of forest fires in March and April. The northern part of Styria receives annually 25% to 90% more precipitation, and the average yearly temperature is about 2 – 3 °C lower than the area around the city of Graz (Kilian et al. 1994) , likewise the thunderstorm activity in this part of the province is considerable (Prinz et al. 2011; Schulz and Diendorfer 1999) . These climatic and meteorological conditions apparently lead to low forest fire activity in the spring months, and a higher share of summer wildfires with a large contribution of events caused by lightning. A similar regime is typical and it is possible to be observed in the most of the Northern Alpine mountainous regions (Reinhard et al. 2005a; Wastl et al. 2012).

5.3.Cause of ignition

The cause of ignition is an important agent for fire behavior. Forest fires caused by natural agents seem to affect a much smaller area than artificial ones (the average burned area is 1007,52 m^2, artificial fires damaged on average 8661,25 m^2). The reason for such a contrast can be probably found in the climatic differences between the north and south of Syria and the current meteorological situation. Lightning is mostly accompanied by thunderstorms with heavy rainfall (Reineking et al. 2010) and furthermore, the northern part of Styria receives a larger amount of precipitation in the summer months than the southern part of the province (cf. chapter 3.1.3. Climate and forest vegetation types) (Kilian et al. 1994). This leads to a smaller burnt area compared to artificial caused fires.

5.4.Size of the burned area

The winter and autumn months, especially January and February, are not considered to be forest fire-prone months, those findings correlate other regions of the Northern Alps (Wastl et al. 2012; Conedera et al. 2006; Bebi et al. 2017). Between the beginning of October and the end of February, only 16,70% of all forest fires occurred, but more than one quarter (26,19%) of forest fires bigger than one hectare happened in this period of the year (Waldbrand-Datenbank Österreich 2016). Those results lead to the presumption that dry winter weather, often without permanent snow cover at the beginning of the winter season, create suitable conditions for the formation of large forest fires. Such a forest fire regime is possible to observe in French or Italian Alps, where especially south-facing slopes are often also without permanent snow cover (Wastl et al. 2013). These findings have one noticeable exception (sub eco region 8.2): the biggest occurrence of large forest fires in the Subillyrian highlands and terraced land happen in April. This could be the result of a drier climate in the Southern part of the province compare to of the rest of the province, a fast drying out of the appropriate fuel and high human activity.

5.5.Topography – Aspect, Altitude and Slope

The occurrence of forest fires in the northern hemisphere is often associated with south facing slopes. South facing slopes receive more solar radiation, which translates into higher temperatures and lower moisture content (Calviño-Cancela et al. 2017). An analysis of forest fires in Styria shows that aspect can play a significant role in the size of the area burned by forest fires, but probably not as a driver for ignition. The occurrence of forest fires was approximately the same in all cardinal directions. The highest presence of wildfires was recorded on north-facing slopes with 29% share, and the lowest proportional representation show south-facing slopes with 21% share. The proportions of burned area by cardinal directions shows much higher variability. The area burned is approximately six times larger on south-facing slopes than a north-facing slopes. East- and west-facing slopes represent roughly one quarter of the burned area. Those findings can indicate that aspect, or more precisely microclimate (e.g. temperature, humidity and solar radiation) only play a limited role in fire ignition, but they are still an important agent for the spreading of a fire.

Altitude plays an important role in forest fire ignition (Arpaci et al. 2014; Conedera et al. 2006). It is possible to locate 75% of all forest fire records and 83% of fires which are caused by humans in an altitude range of between 300 meters and 1000 meters, although less than half of the Styrian province is in this altitude range – cf. Figure 54. Wildfires caused by lightning are recorded at a higher altitude, and roughly 80% of them in an altitudinal range from 700 to 1700 meters. These results are obviously coherent with a presence of above-average density of strokes. Flash density becomes high for altitudes from 500 to 2000 meters and it reaches its peak at around 1200 – 1500 meters (Prinz et al. 2011; Schulz and

Diendorfer 1999). These results likewise indicate the importance of altitude as a trigger for the ignition of forest fires.

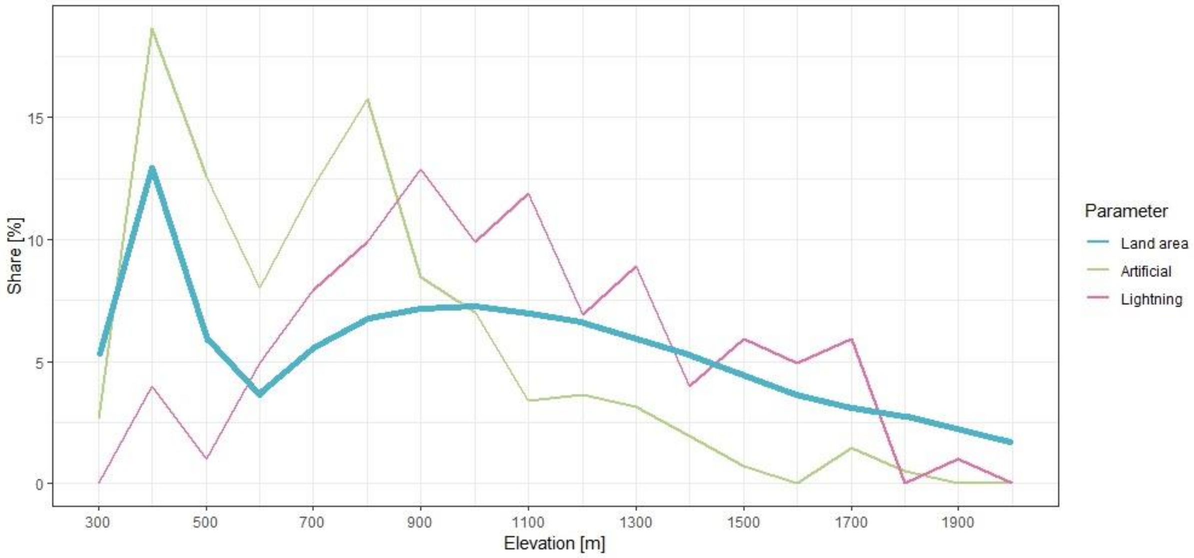

Figure 54: Share of the altitudinal range of natural and artificial caused fires compared to the distribution of the forest area (Waldbrand-Datenbank Österreich 2016; Stmk 2018). The explanation: an altitudinal range from 800 to 900 meters shows that appx. 7% of total area of Styria is in this range, appx. 10% of all fires caused by lightning and appx. 15% of all artificial forest fires occurred there.

These findings are probably related to the occurrence of triggering agents. Human activity is mostly connected to valley bottoms and population density is one of the most important agents for fire occurrence (Arpaci et al. 2014), but also infrastructure (e.g. roads, railways, hiking trails, forest roads and etc.) play a significant role in forest fire ignition (Arndt et al. 2013). On the other side, most of the thunderstorms are in the mountainous parts of Styria, as lightning strikes seek the simplest way from cloud to ground. The strip, which represents the area of medium and high density of flashes (3 – 5; 5+ flashes km^{-2} $year^{-1}$), begins in the southwest on mountain range of West and Central Styrian Highlands (*Lavanttaler Alpen*) and continues in direction northeast over Semmering pass, where it turns to the north and later back to the west, following the province borders with Lower Austria. Also, Rottenmanner and Seckauer Tauern are an area of significant occurrence of thunderstorms (Schulz 2005). All those areas match well with the records of lightning caused forest fires. An interesting phenomenon is visible in the west part of Styria in the Schladminger Tauern, which are hit by a high number of negative flashes (Schulz 2005). The fire database also has a noticeable amount of records from this area.

Based on the above analyses, slope steepness is a significant factor of forest fire ignition. Forest fires which were caused artificially indicate an average steepness of 27,25% in areas with high human activity, and in areas with low human activity 30,47%. Naturally caused forest fires happened in the terrain with an average steepness of 53,60%. Because there is only limited knowledge about the influence of slope steepness on flash occurrences (Bourscheidt et al. 2009), the assumption is that there are two main reasons. It is possible to observe that human activities take place predominantly in areas which are easier to access (Conedera et al. 2006; Reineking et al. 2010). Forest management activities, which are responsible for considerable number of forest fires, are concentrated in areas which are easier to reach by forest machinery and management/harvesting costs are lower (Krumm et al. 2012; Gellrich et al. 2007). These statements can also be supported by the fact that artificial forest fires from the group with high human activity occurred in less steep terrain than the forest fires, which occurred in the areas with lower human activity. The second factor, which answers the question of why forest fires caused by lightning occur generally in terrain with a higher steepness than artificial forest fires, is altitude. It´s possible to observe a positive correlation between altitude and steepness variables in Styria, thus wildfires which take place in higher elevations than artificial forest fires show a higher average value of steepness.

5.6. Vegetation

Vegetation cover plays only a limited role in the cause of forest fires in Styria. These results are similar to findings from studies by Arpaci et al. (2014) or Renard et al. (2012), which declare the relative relevance of vegetation in the successful prediction of forest fires. On the other hand there are signs that lightning-induced fires tend to coniferous and mixed forests than to deciduous-dominated forest (Reineking et al. 2010). In this work, 6 parameters were analyzed, which covered information regarding the current situation of the forest stand and just two of them (Canopy cover and share of coniferous species) show significant differences in the cause of ignition, whilst the rest of them (horizontal structure, height of trees, volume and diameter in breast height) don't indicate any significant influence on cause of forest fires. This might be due to the connection between vegetation cover and topography (Renard et al. 2012). The connection between higher share of forest fires by lightning in forests dominated by coniferous trees can be a consequence of trees with high resin content and low hanging branches. Thus, more suitable fuel for fire ignition (Feurdean et al. 2017; Kelly et al. 2013). Another factor which can have an influence is occurrence of forest fire – dominant tree species in the forest. Deciduous-dominated forests are usually in lower elevations, where also most of the human activity takes place. Coniferous and mixed coniferous forests are usually in higher elevation (Reineking et al. 2010).

The vegetation cover in this work does not appear to have any role in fire behavior, however this does not necessarily mean that it does not have any role. Influence of vegetation on the fire dynamics, is still unclear and complicated due to difficulties to disentangle influence and interactions between fire, vegetation, season of year, infrastructure and climate (Feurdean et al. 2017; Higuera et al. 2014; Reineking et al. 2010). First, the parameters used to analyze the vegetation were just based on a limited number of records and secondly, those 68 forest fires have still quite restricted spatial accuracy. Another important factor can be the high density of fire brigades and observing population, also steep slopes provide favorable conditions to detect a starting fire (Conedera et al. 2006). Authorities are usually very soon informed even about small fires (Müller et al. 2013), thus before vegetation structure can have any significant influence on fire behavior, fire brigades localize the fire and start to extinguish it. This statement can also be endorsed by a comparison between the Initial Spread Index (ISI) and Buildup Index (BUI). ISI indicate a bigger influence on the size of burned area than BUI. The Initial Spread Index is mainly lead by the speed of the wind, which seems to have a larger impact on how fast a wildfire spreads than the availability of suitable fuel.

6. Conclusion

The results of the thesis indicate that it is possible to find significant differences in forest fires caused by different agents. It is possible to observe different moments of ignition, behavior which, for example, leads to a diverse size of burned area, species composition, canopy cover or topography. It was not, however, possible to prove the initial hypothesis that human activity presents differences in forest fire characteristics.

The Austrian Forest Fire database recorded 517 forest fire events which occurred between the years 1992 and 2016 in Styria, but as it has already been mentioned above, a considerable amount of forest fires lack information (data about burned area, exact cause of ignition, time of ignition or affected species are frequently missing). The spatial accuracy in most of the records is also insufficient to analyze coherence with forest stand data.

Nevertheless, it was possible to choose a satisfactory number of records to develop a model which demonstrates the risk of thunderstorms igniting forest fires. These factors are represented by two groups of parameters – variables related to topography, which contain information about elevation and slope steepness and by forest stand data, representing the share of coniferous tree species and canopy closure. Such knowledge together with prediction of actual forest fire danger from ZAMG and ALDIS could lead to better estimation for occurrence of forest fires caused by lightning. Lightning-induced forest fires will probably generate more and more damages in future, are often “discovered” after several hours/days and early localization could decrease burned area and losses on the forest.

The Canadian Forest Fire Weather Index (FWI) shows overall a limited applicability in forecasting forest fire risk in the context of Styria. The Fine Fuel Moisture Code appears to be valuable, as it indicates a significant correlation with the ignition of forest fires. Likewise, the Initial Spread Index can, in an acceptable way predict the size of the area burned by artificial forest fires, but for naturally occurring forest fires, it is not possible to use it, probably because precipitation plays a bigger role in fire behavior, especially in fire spreading, than does slope steepness in Styria. Other indexes of FWI show very limited applicability in the context of this study.

In general, it is possible to observe increasing quality of data in the Austrian Forest Fire Database, especially regarding spatial data accuracy. At the beginning of the 90s, the spatial accuracy of forest fire localizations was on average almost 2 500 meters, whilst records from the year 2016 show an accuracy of ± 1 500 meters. To analyze the impact of the forest stand on fire ignition and behavior, it would be essential to work with data which can have a spatial accuracy bellow 100 meters.

It´s almost impossible to influence the number of lightning-induced forest fires, but it´s for sure possible to increase public awareness about human caused forest fires. Twelve percent of all anthropogenic forest fires are caused during forest management. This could be reduced by on improved training of employees, positive and negative motivations, better control of working place by supervisors or automatic fire detections systems.

A huge part of artificial forest fires is caused by carelessness and ignorance of forest visitors. There are many ways how to improve public awareness – from (pre)school education over information in mass media, social media networks or local guides and municipalities for locals or tourists as well (e.g. fire.blog.ac.at).

Smoking of cigarettes in forest caused around 6% of all artificial forest fires in Styria. This problem can be decreased or even eliminated with increasing public awareness of the consequences of dropping a single cigarette on the forest floor. Also, it´s possible to find inspiration in other countries where complete prohibition of smoking in forests is valid (e.g. Czech Republic) or partial (e.g. National parks in Australia or in United States of America).

Overall, different forest fire ignition sources require different strategies to decrease the financial and material losses.

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8. Appendix

Number of forest fires during a year caused by different agents in each sub eco region (Waldbrand-Datenbank Österreich 2016)

	Sub eco region								
Artificial	22	30	31	32	41	42	53	82	Sum
January	1	1	3	6	0	0	4	11	26
February	1	0	2	3	0	0	7	8	21
March	2	2	4	19	0	0	6	45	78
April	9	2	17	20	1	1	18	49	117
May	3	3	6	4	1	0	4	10	31
June	2	1	5	4	0	0	1	6	19
July	3	1	1	9	1	0	4	8	27
August	4	1	5	10	3	3	4	14	44
September	2	0	5	0	0	0	1	2	10
October	1	1	1	2	0	0	0	2	7
November	0	0	0	2	1	0	1	6	10
December	0	1	3	2	1	0	6	10	23
Sum	28	13	52	81	8	4	56	171	413

	Sub eco region								
Lightning	22	30	31	32	41	42	53	82	Sum
January	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	2	0	2
May	1	0	2	3	0	0	0	2	8
June	2	3	5	2	1	1	2	1	17
July	8	0	8	6	0	4	5	3	34
August	6	1	9	9	0	1	8	5	39
September	1	0	0	0	0	0	0	0	1
October	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0
Sum	18	4	24	20	1	6	17	11	101

	Sub eco region								
All	22	30	31	32	41	42	53	82	Sum
January	1	1	3	6	0	0	4	11	26
February	1	0	2	3	0	0	7	8	21
March	2	2	4	19	0	0	6	45	78
April	9	2	17	20	1	1	20	49	119
May	4	3	8	7	1	0	4	12	39
June	4	4	10	6	1	1	3	7	36
July	11	1	9	15	1	4	9	11	61
August	10	2	14	19	3	4	12	19	83
September	3	0	5	0	0	0	1	2	11
October	1	1	1	2	0	0	0	2	7
November	0	0	0	2	1	0	1	6	10
December	0	1	3	2	1	0	6	10	23
Sum	46	17	76	101	9	10	73	182	514

Percentage of forest fires during a year caused by different agents in each sub eco region (Waldbrand-Datenbank Österreich 2016)

	Sub eco region							
Artificial (%)	22	30	31	32	41	42	53	82
January	3,57	7,69	5,77	7,41	0,00	0,00	7,14	6,43
February	3,57	0,00	3,85	3,70	0,00	0,00	12,50	4,68
March	7,14	15,38	7,69	23,46	0,00	0,00	10,71	26,32
April	32,14	15,38	32,69	24,69	12,50	25,00	32,14	28,65
May	10,71	23,08	11,54	4,94	12,50	0,00	7,14	5,85
June	7,14	7,69	9,62	4,94	0,00	0,00	1,79	3,51
July	10,71	7,69	1,92	11,11	12,50	0,00	7,14	4,68
August	14,29	7,69	9,62	12,35	37,50	75,00	7,14	8,19
September	7,14	0,00	9,62	0,00	0,00	0,00	1,79	1,17
October	3,57	7,69	1,92	2,47	0,00	0,00	0,00	1,17
November	0,00	0,00	0,00	2,47	12,50	0,00	1,79	3,51
December	0,00	7,69	5,77	2,47	12,50	0,00	10,71	5,85

Lightning (%)	Sub eco region 22	30	31	32	41	42	53	82
January	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
February	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
March	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
April	0,00	0,00	0,00	0,00	0,00	0,00	11,76	0,00
May	5,56	0,00	8,33	15,00	0,00	0,00	0,00	18,18
June	11,11	75,00	20,83	10,00	100,00	16,67	11,76	9,09
July	44,44	0,00	33,33	30,00	0,00	66,67	29,41	27,27
August	33,33	25,00	37,50	45,00	0,00	16,67	47,06	45,45
September	5,56	0,00	0,00	0,00	0,00	0,00	0,00	0,00
October	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
November	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
December	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

All (%)	Sub eco region 22	30	31	32	41	42	53	82
January	2,17	5,88	3,95	5,94	0,00	0,00	5,48	6,04
February	2,17	0,00	2,63	2,97	0,00	0,00	9,59	4,40
March	4,35	11,76	5,26	18,81	0,00	0,00	8,22	24,73
April	19,57	11,76	22,37	19,80	11,11	10,00	27,40	26,92
May	8,70	17,65	10,53	6,93	11,11	0,00	5,48	6,59
June	8,70	23,53	13,16	5,94	11,11	10,00	4,11	3,85
July	23,91	5,88	11,84	14,85	11,11	40,00	12,33	6,04
August	21,74	11,76	18,42	18,81	33,33	40,00	16,44	10,44
September	6,52	0,00	6,58	0,00	0,00	0,00	1,37	1,10
October	2,17	5,88	1,32	1,98	0,00	0,00	0,00	1,10
November	0,00	0,00	0,00	1,98	11,11	0,00	1,37	3,30
December	0,00	5,88	3,95	1,98	11,11	0,00	8,22	5,49