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Master Thesis

The influence of landscape fragmentation on fire spread behaviour along slopes

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This thesis has been written in cooperation with the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) in the division of Community Ecology and Insubric Ecosystems in Cadenazzo, Switzerland.

Support and guidance has been given by:

Patrik Krebs, MSc and
Dr. Gianni Boris Pezzatti

Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Sempach, 8. August 2023 Sara Maria HILDEBRAND *(manu propria)*

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Table of content

Abstract

For the spread of forest fires the connectivity of fuels is an important factor, but the understanding of fragmentation on fire spread behaviour is still incomplete. In this research, effects of landscape fragmentation on surface fire spread in an alpine environment are analysed by using a modelling approach and different landscape patterns. Four hypotheses are tested: (1) metrics of landscape fragmentation like *edge* and *patch density* together with the *degree of forest cover* allow describing fire spread behaviour along slopes, (2) no difference between the methods for setting the ignitions within the modelling approach can be observed, (3) the degree of landscape fragmentation has an influence on the number of blocked fire paths and (4) the length of the blocked fire paths along slope. The hypotheses are tested within 90 research areas of 2x2 km extent with a similar topography. The fire spread is simulated with an algorithm, taking topography into account and modelling fire spread uphill in direction of the steepest slope. The algorithm is applied to all research areas and fragmentation traits are analysed with a set of metrics with the R package *landscapemetrics*. Results show that through landscape fragmentation about 63 % of the paths can be stopped by barriers with no forest cover and shorted about 73.5 % in length. The highest number of paths stopped can be observed at a degree of forest cover of 10-40 % and a steep average slope of the research area between 30.14 and 41.5°. The variation in the relative path lengths and the percentage of blocked fire paths can be partially explained by metrics of *edge density*, the *percentage of landscape class* and additionally by the relative path lengths, the metric of *patch density*. These results contribute to a better understanding of the effects of landscape fragmentation on fire spread behaviour. This thesis provides a solid basis for continued research on integrated landscape planning to reduce the fire spread potential.

Keywords: landscape ecology, forest fire spread, fragmentation, landscape metrics

Kurzfassung

Für die Ausbreitung von Waldbränden ist die Konnektivität von Brennstoffen ein wichtiger Faktor, jedoch ist das Verständnis über die Bedeutung einzelner Indizes, welche die Fragmentierung beschreiben und das Feuerverhalten beeinflussen unvollständig. In dieser Arbeit werden Einflüsse der Landschaftsfragmentierung auf das Ausbreitungsverhalten von Bodenfeuern entlang von Hängen in einem Modellierungsansatz untersucht. Vier Hypothesen werden dabei getestet: (1) Indizes wie *edge density* oder *patch density* erlauben zusammen mit dem *Waldbedeckungsgrad*, die Ausbreitung von Bränden entlang von Hängen zu beschreiben, (2) es kann kein Unterschied zwischen den verschiedenen Methoden zur Setzung der Entzündungspunkte beobachtet werden, (3) der Grad der Fragmentierung hat einen Einfluss auf die Anzahl und (4) auf die Länge der geblockten Pfade. Die Hypothesen werden innerhalb von 90 Untersuchungsflächen à 2x2 km Ausdehnung mit ähnlicher Topografie anhand eines Algorithmus untersucht, der die Feuerentwicklung entlang der steilsten Hangneigung simuliert. Die Fragmentierung wird anhand ausgewählter Indizes mit dem R package *landscapemtrics* berechnet. Die Resultate zeigen, dass durch eine Fragmentierung 63 % der Feuerpfade durch waldfreie Barrieren gestoppt und in ihrer Länge um 73.5 % verkürzt werden können. Der höchste Anteil an geblockten Pfaden kann bei einem Deckungsgrad von 10-40 % und einer mittleren Hangneigung zwischen 30.14-41.5° beobachtet werden. Die Variation in den relativen Pfadlängen und des Anteils an geblockten Pfaden kann insbesondere durch die Indizes *edge density* und den *Waldbedeckungsgrad* erklärt werden. Zusätzlich spielt die *patch density* für die Pfadverkürzungen eine Rolle. Die Resultate tragen zu einem besseren Verständnis von Fragmentierungseffekten auf das Ausbreitungsverhalten von Feuer bei und bilden die Basis für weitere Forschungsarbeiten zu einer integralen Landschaftsplanung, welche das Potential für die Ausbreitung von Feuern reduzieren.

Schlüsselwörter: Landschaftsökologie, Feuerausbreitung, Fragmentation, Landschaftsmetriken

1. Introduction

Forest fires have historically been experienced in many regions of the world (Power et al., 2008) and have been present in the European Alps for a long time (Tinner et al., 1999). Since around 7500 YBP had fires an impact on forest and landscape dynamics by the use of fires to expand pastures for grazing in mountain forests (Bebi et al., 2016; Conedera et al., 2017). For the evolution and regulation of terrestrial ecosystems and biodiversity wildfires are of high importance and contribute to the sustainable provision of valuable ecosystem services (Pausas & Keeley, 2019). In Switzerland forest fires are for example the most important natural hazards after wind-throws, in terms of the area of forest disturbed (Bebi et al., 2016) and are a key process to shape the spatial pattern of vegetation cover. Besides the costs for fire suppression and financial losses (Sadowska et al., 2021), the loss of protection function can also follow a fire event. Subsequent to a fire event vegetation destruction and the change of site specific characteristics can lead to new natural hazards like erosion or mudslides (Bebi et al., 2016; Conedera et al., 2003; Wohlgemuth et al., 2008).

Forests are sensitive to their environment and a wide range of changes in this environment can be observed. Trough human induced climate change, higher surface temperatures, an increase in drought periods, heatwaves and floods can already be observed and are expected for the future decades (Intergovernmental Panel on Climate Change, 2022). Especially in regions on higher latitudes and in mountain regions as the European Alps, a much stronger warming is presumed (Dupire et al., 2019; Wastl et al., 2012), leading to a shift in site conditions and tree species composition (Schumacher & Bugmann, 2006). This along with an increase in population, the abandonment of land-management in rural areas on border yield sites and a decrease in the exploitation of timber and wood resources, builds an increased danger for expected forest fires (Loran et al., 2017; Moreira et al., 2011; Müller et al., 2020). Those changes have already been observed in the European Alps and Switzerland (Dupire et al., 2019; Loran et al., 2017; Wastl et al., 2012).

1.1. Forest fire propagation danger

The danger of forest fires can be separated in a danger of ignition and a danger of spread. The danger of ignition is determined by factors like weather, topography, type of vegetation and the proximity to human settlements. The danger for spread of a fire, after ignition has taken place, is modulated by factors like wind, slope, fuel moisture content and fuel availability (Calviño-Cancela et al., 2017; Driscoll et al., 2021; Duane et al., 2021). The spread of a fire will therefore occur in direction of the most favourable spread conditions (e.g. (Rego et al., 2021; Rothermel, 1972)). With the so-called “fire triangle”, consisting of the three equally important factors of topography, fuel and weather, the fire behaviour can be described and analysed (Agee, 1996). As the fuel component is the only controllable factor of the fire triangle, fuel availability, structure and spatial arrangement are of high interest, when analysing fire spread behaviour and derivate forest fire prevention measures. Therefore, the connectivity, size and shape of forest patches, which might be burnable landscape elements, is of importance (Ryu et al., 2007). With the definition of wildfires as uncontrolled vegetation-fires, which occur outside of built-up areas (Müller et al., 2020), the functional connectivity in the context of wildfires according to Turner et al. (1989) is defined as “(...) the potential to spread between different land cover types”. In contrast, forest fires are defined as fires, which at least partially capture forested areas independent of meteorological drivers (Müller et al., 2020). To spread over a landscape, a fire needs to have enough initial spread energy (Duane et al., 2021). Effects of forest structure on stand level and forest species are having minor effects on the fire spread after a steady spread capacity is reached, compared to landscape structure and weather conditions (Duane et al., 2021). Landscape structure and spatial proximity of flammable landscape elements allow for the continuation of the endothermic-exothermic chain reaction, which can only persist through heat transfer mechanisms to nearby fuels (Beverly et al., 2021). For the Alpine regions surface fires, which are characterized by burning and propagation only in surface fuels, are observed to be most abundant (Conedera et al., 2018).

Slope and terrain, which are elements of topography, play an important role in fire propagation, besides the fuel availability and weather conditions (Müller et al., 2020), as they determine the rate of spread (Sánchez-Monroy et al., 2019). Hereby slope, characterizing elevation, aspect and latitude can influence the microclimatic parameters like temperature, precipitation and solar radiation. These parameters determine the fuel moisture content (Dillon et al., 2011), a key fuel characteristic. For the considerable increase in the rate of spread along slope, compared to a horizontal fire spreading, are also flame characteristics of importance (Rothermel, 1972). Through slope, flame geometry is strongly influenced as the flame tilt angle is increased, leading to an increase in radiation of the flame facing the slope (Weise & Biging, 1997). Thereby, pre-heating and drying out of upslope fuels facilitates the ignition and fire spread (Dupuy, 1995). With the increased flame tilt angle, flames can also tilt over the potential fuel upslope and ignite the vegetation through direct heat transfer (Rothermel, 1972). Other effects of slope on the fire characteristics are an increased flame residence time and mass loss rate (Dupuy et al., 2011) as well as up-slope winds through thermal conditions, favouring fire spread.

1.2. Landscape fragmentation and forest fires

As an increase in forest fires under the projected climate change and the resulting vegetation changes is expected, the understanding of fire patterns and the spread behaviour is important. Several factors have to be taken into account to estimate the forest fire hazard (Calviño-Cancela et al., 2017). One important factor, to accurately determine forest fire propagation is the degree of connectivity of flammable patches (Duane et al., 2021; Miller & Urban, 2000; Ryu et al., 2007), respectively the linking by patterns and processes of a landscape. For the process of forest fires, connectivity would be given, if fire can spread from one site to another (Miller & Urban, 2000). Bebi et al. (2016) observed an increase in forest cover in all regions of the Alps, which may lead to higher forest connectivity’s . For Switzerland, a change in forest cover is observed to be bound to natural gradients. Thereby, the greatest increases in forest cover were observed on slopes > 30°, especially in the Central Alps (Bebi et al., 2009). Likewise, on the treeline ecotone between 0-200 meters and > 800 meters below the potential treeline considerable changes were monitored since 1880. An increase of forest connectivity and forest cover in secondary forests since 1880, might be potential factors for an increase of forest fires in the Alps (Bebi et al., 2016; Zumbrunnen et al., 2009).

The opposite to the concept of connectivity is the concept of fragmentation. Under the Convention on Biological Diversity (2006) forest fragmentation is defined as "(…) any process that results in the conversion of formerly continuous forest into patches of forest separated by non-forested lands." Thereby a patch is one of many possible definitions for a basic element or unit, forming a landscape with relatively homogenous environmental conditions (McGarigal, 2013, 2013; McGarigal & Marks, 1995). As the definition of a patch is perceived relative to the perspective of interest, from a fire propagation perspective a patch could be seen as a connected burnable element. Additionally patches have to be perceived as dynamic elements which occur on different spatial scales (McGarigal & Marks, 1995). Forest fragmentation can result from natural (wind storms, insects) as well as anthropogenic (harvest, land use change) factors (e.g. (Hermosilla et al., 2019)). Three main ways of fire and fragmentation interaction can be observed according to Driscoll et al. (2021), whereby the focus of this meta-analysis was laid on aspects of biodiversity. First, fire influences fragmentation, second fragmentation influences fire and third where fire and fragmentation do not influence each other, but fire interacts with fragmentation to affect responses like species richness or abundance. If a direct interaction of fragmentation and fire occurs, feedback loops can lead to an ecosystem conversion (e.g. forest to grassland). Regarding fire propagation behaviour in fragmented landscapes the influence of fragmentation on fire behaviour is of special interest. Fragmentation characteristics as changes in edge conditions and an increase in edge length were most often associated to lead to more fires in the meta-analysis of Driscoll et al. (2021). It has to be taken in account, that most of the studies leading to this results were conducted in the Central and South America, where sociocultural factors highly influenced the fire occurrence (Armenteras et al., 2013; Silva Junior et al., 2018). A reduction of fire occurrence in North America and Europe associated with an obstruction through fragmentation is in several studies observed (e.g. (Hermosilla et al., 2019; Lloret et al., 2002)). Thereby, an increase of fragmentation has shown a raise in the number of forested patches and a decrease in forest cover and mean forest patch size in a study of Hermosilla et al. (2019). Landscape patterns and fragmentation can be quantified and compared through applying spatial pattern metrics (McGarigal, 2013; Turner et al., 1989; Turner et al., 2001).

Effects of fragmentation on fire occurrence can be negative or positive, which might differentiate from point of view. Negative effects of forest fragmentation through forest fires can occur from habitat destruction but can, through habitat loss, also increase the access opportunities for humans with an often-increased occurrence of ignitions and edge flammability. On the other hand, species who prefer early successional stages can profit from fires and fragmentation effects. The described effects differ by ecosystem type and geographic region and cannot be generalized (Driscoll et al., 2021). Besides the spatial arrangement of fuels, the functional connectivity is also influenced by meteorological conditions and may for example have a strong effect under very windy and dry conditions (Miller & Urban, 2000).

1.3. Modelling of forest fire spread

Forest fire modelling is a helpful method and can be used for different aspects of knowledge building, prevention, and planning. Existing forest fire propagation models like FARSITE (Fire area simulator) (Finney, 1998) need various other inputs besides topography like weather conditions and climatic patterns, also known as top down or exogenous controls on the process. In addition so-called bottom-up or endogenous controls on fire propagation for example the spatial forest cover distribution are (Beverly et al., 2021) needed. The number of factors controlling forest fire behaviour and the interaction of biotic and abiotic processes led to complex forest fire spread models. In the basis, statistical and deterministic (semi-empirical or mathematical) models can be distinguished. Deterministic models are thereby based on physical conservation laws, formed through the environment and flame characteristics (Hernández Encinas et al., 2007). Results from laboratory experiments and real experimental forest fires form the base for empirical models (e.g. (Hernández Encinas et al., 2007; McArthur, 1966, 1967)). Multiple empirical and deterministic models can be brought together in so-called fire modelling systems, like in FARSITE (Finney, 1998) and BehavePlus (Stratton, 2006).

For deterministic models, fire growth and spread rates can be modelled by one of the principal methods of cellular automata or wave propagation approach or even in combination, as applied in FARSITE. The Huygen’s principle, which is based on wave-propagation on the travel of light waves is combined in FARSITE with the Rothermel model, one of the most common methods, based on the rate of spread to simulate the spread of forest fires (Driscoll et al., 2021; Li et al., 2022; Tymstra et al., 2010). As in Rothermels approach the direction as well as the shape and location of fire spread are missing, the change in fire contours can be mapped through the so-called Huygens principle for vector based methods (Li et al., 2022). For grid-based fire spread models the cellular automata can be applied to obtain information about fire spread direction and shape. In grid-based fire growth models it is assumed, that within one square cell the conditions are homogenous. Fire spread from one cell to another is based on a search mechanism for cell adjacency or a spread template, where each cell is independent of another and behaves as an ignition source (Tymstra et al., 2010).

The integration of non-combustible areas or areas which can burn but are resistant to fire spread play an important factor for the modelling of fire propagation danger and behaviour. In the, on the Huygens principle-based, model FlamMap (Finney, 2006) so-called barriers are incorporated, which can be filled or unfilled. Thereby filled barriers are resistant to burning, which makes the fire in the model to flank around the barrier or even spot across it. On the other hand, unfilled barriers lead to blockage of an existing fire path and are represented in FlamMap as areas which can burn, but are resistant to surface fire spread (Forest Service, U.S. Department of Agriculture, 2023).

1.4. Research aims and hypotheses

Accurate knowledge about forest fire behaviour is the fundament for authorities and firefighters in supressing fires and reducing the forest fire danger trough adequate planning. Appropriate suppression techniques but also landscape planning aspects and further risk reduction measures can be improved based on scientific findings.

It is still not well understood, how landscape fragmentation within temperate climate zones of the mountainous global north influences the forest fire spread behaviour, where slope can be assumed to be a driving factor of fire spread. For example in Switzerland, different patterns of landscape fragmentation north and south of the Alps can be observed. Analysis of landscape fragmentation and modelling of the fire spread behaviour along slope could be an important information for fire danger risk assessment and measures. Furthermore, it is important for forest- and landscape management to know, under which levels of forest-landscape connectivity the fire is capable to spread. This can be an important factor in managing forests and landscapes, to reduce the risk of forest fires as efficiently as possible and in applying appropriate suppression methods.

The aims of this Master thesis are i) to follow an exploratory simulation approach, to develop and analyse a fire spread algorithm on landscape level, to estimate the spatial variation of upward surface fire spread potential under homogenous forest conditions. This based on forest cover distribution and terrain slope as entry data. Terrain slope and forest connectivity, representing fuel connectivity, are two main characteristics of mountain landscapes and among the most decisive in determining the spread of fire. Within the simulation approach, fire paths are represented through vectors. If such a fire path is blocked through effects of landscape fragmentation, they are classified as blocked fire paths. Additionally, ii) appropriate metrics to describe landscape fragmentation will, based on literature review be brought in context to the results of the developed algorithm.

As the methods and approaches changed during the thesis, the hypotheses did not exist from the beginning, but evolved during time to the following four, which will be tested:

1. The metrics of edge and patch density along with the percentage of landscape classes can describe the influence of fragmentation on the number of blocked fire paths and their lengths
2. Calculated fire paths from three different methods of setting the ignition points within the forested landscape, do not show a significant difference in their main characteristics of the blocked fire paths, when applying the fire spread algorithm
3. The degree of landscape fragmentation influences the actual length of the blocked fire paths along slopes
4. The degree of landscape fragmentation has an influence on the number of blocked fire paths along slopes

1.5. Thesis structure

In this thesis, first the different tools and methods for the selection of study areas (section 2.3.1), the analysis of forest fragmentation respectively connectivity (section 2.3.2) as well as the fire behaviour modelling along slopes are explained (section 2.3.3). In section 2.3.4 the method for analysing the influence of landscape fragmentation on fire behaviour is introduced.

As a start to the presentation of the results, in section 3.1 the results from a literature review about appropriate metrics describing forest fragmentation in the context of fire spread behaviour are presented. With a selection of metrics thereon the results of the fragmentation analysis are given (section 3.2). After presenting the results for methodological variants of setting the ignitions for the fire spread modelling (section 3.3), the results from the application of the algorithm are presented and brought into context to the selection of the fragmentation metrics (section 3.4). The results are discussed and set in context to the current literature related to the topic (section 4). In section 5 the most important findings are summarized once again, and further recommendations are given based on knowledge obtained throughout this thesis.

2. Materials and methods

For the exploratory method development and analysis, it was decided to focus on the territory of Switzerland, due to open access data availability. This despite that this approach could be performed on other landscape extents with appropriate geodata.

2.1. Tools

In the framework of this thesis the statistical computing software R (version 4.2.2; (R Core Team, 2022)) with the graphical user interface RStudio (version 2022.12.0; (Posit team, 2022)) are used. Analysis of topographical landscape features, for the study areas selection, has been conducted with the open-source R tool wbt_geomporphons within the whitebox package (section 2.3.1.1). Forest fragmentation characteristics were analysed with the open-source R tool landscapemetrics (Hesselbarth et al., 2019), which allowed to calculate a set of fragmentation metrics (section 2.3.1.2 and 2.3.2). For analyses and input data preparation to the algorithm calculating the fire paths along the steepest slope, the geographic information system ArcGis Pro (version 3.0.0; (ESRI, 2022) was used.

2.2. Data

The geodata to perform the analysis within this thesis was obtained from the federal office of topography (swisstopo), in Switzerland. The topographic landscape model swissTLM3D (swisstopo 2022), from which land cover types were extracted, is freely available (Bundesamt für Landestopografie swisstopo, 2023). The digital elevation model (swissALTI3D LV95 LN02 2019) of Switzerland, with a resolution of 2 m, as well as 5 m, 20 m and 50 m, has been provided by the WSL.

2.3. Methods

The approach presented in this thesis to analyse the influence of landscape fragmentation on fire spread behaviour along steepest slopes, consists of three main modules. Additional data processing in between the modules was performed. An overview of the procedure is given in the flowchart (Figure 1). The development and testing of the algorithm to describe forest fire spread behaviour along the steepest slope is applied to a set of research areas, which are characterized by topographical features and the degree of the forest cover. The detailed procedures for module 1 focusing on the study areas selection based on topographical similarity, are described in the section 2.3.1. Before deepening into module 2 some prior procedures to the study area selection based on landcover features, here consisting of the share of forest cover, are described. The analysis of landscape fragmentation with specific metrics is further described in module 2 in section 0. In the final module 3 (section 2.3.3) the methods for the calculation of the steepest path along slopes, under consideration of landscape fragmentation and the final products of the algorithm are explained. The model building process is thereafter followed by the description of the statistical analysis (section 2.3.4). For the framework of this research it is assumed, that ignition can only take place within the areas classified as forest (section 2.3.1.2).

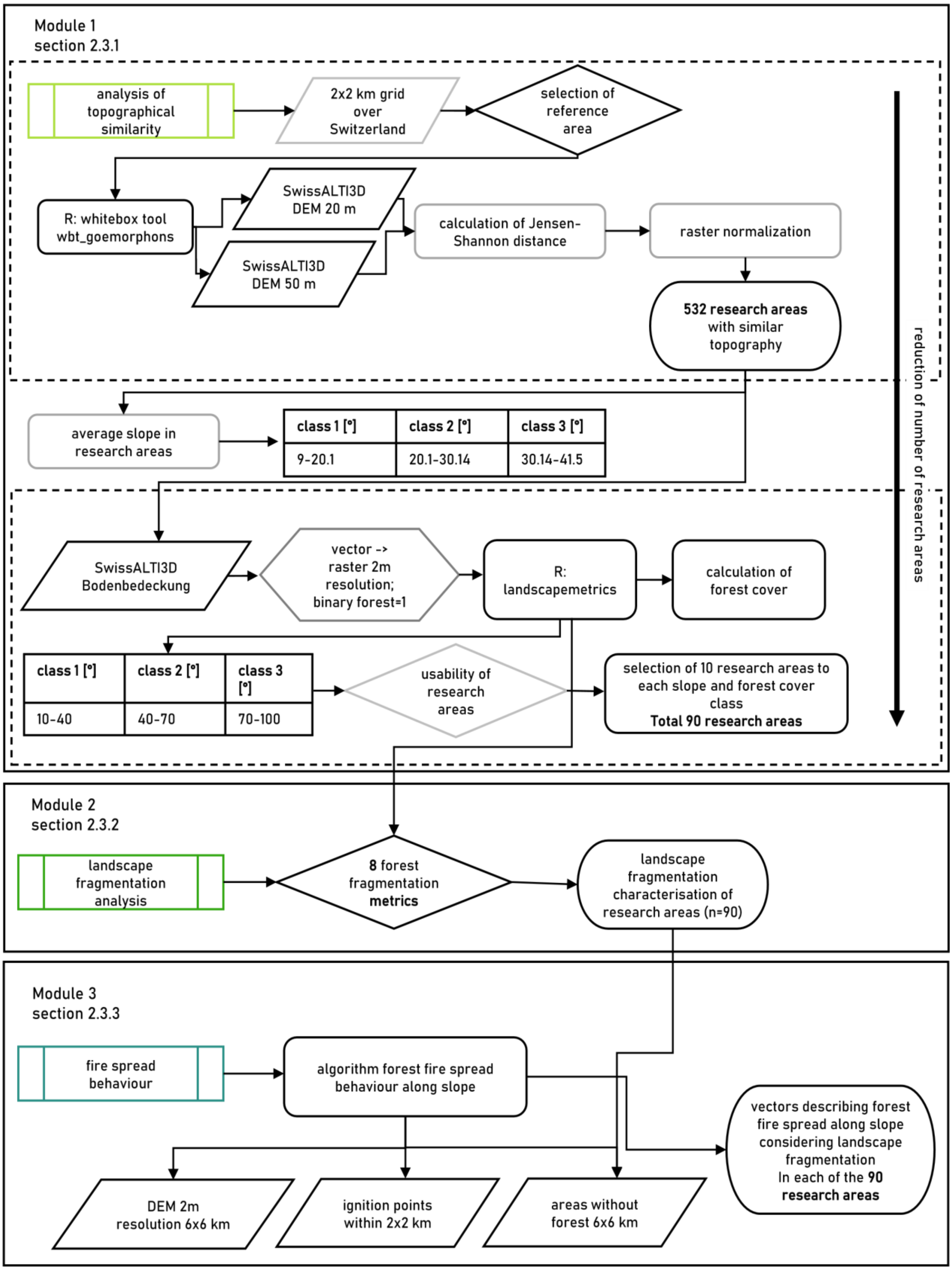


Figure 1: Flowchart of the methodological approach to analyse the influence of forest fragmentation on the behaviour of forest fire spread along steepest slopes.

2.3.1. Selection of research areas

A total of 90 research areas were selected throughout Switzerland. To ensure comparability between different research areas, these had to be selected based on criteria of topography and forest cover. In the subsections below a detailed description of the performed selection process is given.

2.3.1.1. Analysis of topographical similarity

In a first step research areas were selected, based on their similarity of terrain topography. As this analysis was based on DEM data of the territory of Switzerland, a grid spanning the extent of the whole area had to be created. Those same sized areas could be analysed for their topographical similarity. Grid sizes of 2 km, 3 km and 4 km were visually analysed, aiming for a relatively uniform aspect within a grid cell. This to best be able to analyse the effects of forest fragmentation of fire spread behaviour and not topography. It was decided, that due to the small scaled topography of Switzerland, this criterion could best be met with a grid size of 2 km. This grid was considered for the selection of one reference area whose topography forms the template for the other research areas which would in terms of topographical similarity best correspond. Several possible reference areas were selected based on gentle topography, no crossing of valley bottoms, big ridges or the presence of extensive water areas or rock walls. The final selection for the reference area which can be seen in Figure 2, has been done in discussion with the supervisor (P. Krebs, personal communication, November 3, 2022).

For the analysis of the terrain topography the function wbt_geomorphons within the whitebox R package (Wu & Brown, 2022) was used. This function allows, based on a DEM, to determine the corresponding geomorphon for the 10 most common landforms. Thereby a geomorphon is defined, according to (Jasiewicz & Stepinski, 2013) as "(…) a simple ternary pattern that serves as an archetype of a particular terrain morphology." Geomorphons have been calculated for the two rasters in resolutions of 20 m and 50 m of the swissALTI3D LV95 LN02 2019. To capture smaller scaled topographical features (20 m resolution) as well as wider ones (50 m resolution), within the 2x2 km study areas. For the two raster layers, the Jensen Shannon distance, describing the similarity of one study area to the reference area has been calculated with the lsp_search function of the motif R package. After raster normalization and summation of the two rasters the areas representing the 5^{th} percentile were selected. In total 531 study areas belonged to the 5^{th} percentile of being similar to the chosen reference area.

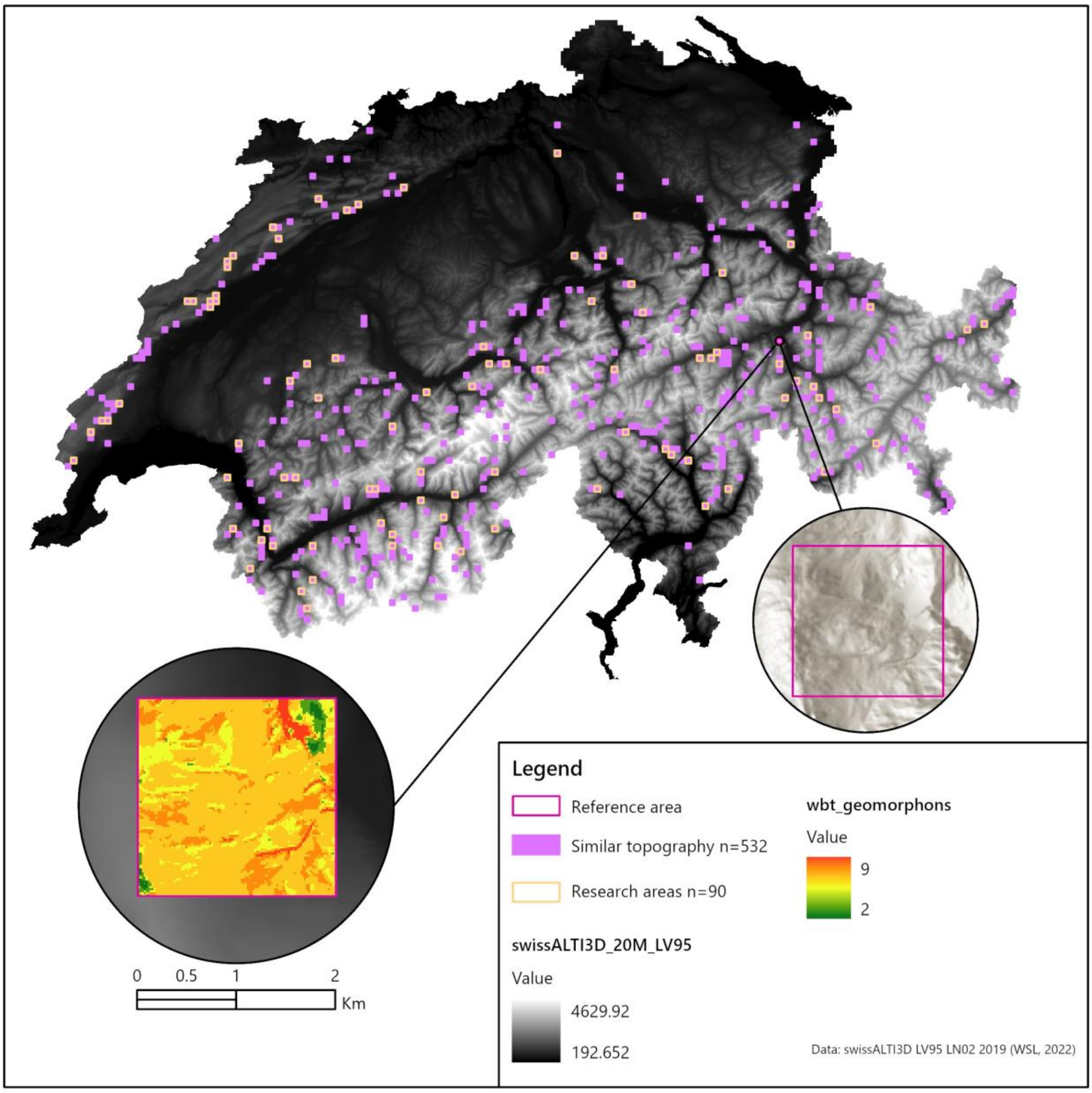


Figure 2: Research areas in Switzerland. Based on analysis of geomorphological similarity for the territory of Switzerland, 239 research areas (2x2 km) were determined to be similar (in violet) to the reference area (round excerpt and pink square). Further research area selection with inclusion of forest cover degree resulted in the final 90 research areas (in apricot).

2.3.1.2. Forest cover analysis

The selection of the research areas continued from the preselection which had been done as described in section 2.3.1.1. From the swissTLM3D Bodenbedeckung (Bundesamt für Landestopografie swisstopo, 2023) shapefile forest, open forest, bushes as well as grove areas were classified to value 1 (further named as forest area) whereas all other landscape classes were set to 0. After a transformation of the shapefile to a binary raster (1 = forest; 0 = non-forest) in a 2 m resolution, the forest cover was calculated for the 532 research areas with the function lsm_c_pland from the R package landscapemetrics (Hesselbarth et al., 2019). To minimize the calculation time, it was decided to classify these test areas in 4 groups of usefulness, so that test areas classified as not useful (classes 2-4) could be eliminated (Table 1). This check for the classification was carried out visually and based on the results of the calculation of the degree of forest cover onto the 532 research areas. The evaluation considered those fire paths, which as described in in section 2.3.3, were able to develop unhindered from topographical features and had a minimal degree of forest cover above 10 percent. This should allow to minimize the effects of other features than the forest fragmentation on the development of the fire paths. The classes of usability and associated criteria can be seen in Table 1.In class one a total of 239 research areas were present.

Table 1: Classes of usability of research areas according to the potential for fire path development.

Class	*Criteria*
4	Degree of forest cover below 10 percent Crossing of the Swiss territory border
3	On upper timberline with forest cover of around 10 percent Extended and very steep rock walls and rock bands Crossing of high mountain ridges in or close to research area centre Crossing of deep valley bottoms
2	Crossing of small ridges
1	All other test area which do not belong to class 2, 3 or 4

2.3.1.3. Final selection of research areas

In order to achieve an approximately even distribution of the research areas according to forest cover and slope angle across the entire range, three classes were formed for each characteristic. First the 239 research areas were classified according to the degree of forest cover in class 1 (10 - 40 %), 2 (40 - 70 %) and 3 (70 - 100 %) (Table 3). Through calculation of the average slope angle for each research area and setting the class boundaries the way, that an even distribution of the research areas within each class could be achieved, the slope classes were defined as 1 (0° - 20°), 2 (20° - 30.1 °) and 3 (30.1° - 42 °). To determine the amount of needed research areas per forest cover or slope class, a Levene test has been calculated with the G-power application (Faul et al., 2007), with a power of 0.8 and an alpha level of 0.5. The resulting 22 research areas per group have been scaled up to 30 research areas. Based on the average slope and the degree of forest cover the class boundaries were set so, that in each class 10 research areas were present, as it can be seen in Table 3. The minimum, maximum, mean and median values of slope and forest cover for the 90 research areas can be seen in Table 2. In Appendix A; Table A1, the characteristics of slope and forest cover are shown for each of the total 90 research areas, that has been used in the following analysis of section 2.3.2, 2.3.3 and 2.3.4.

Table 2: Characteristics of slope and forest cover for the final 90 research areas.

	min	max	mean	median
Slope [°]	9.8	41.5	25.2	26.5
Forest cover [%]	11.7	96.3	53.9	53.0

Table 3: The classes according to the slope and the degree of forest cover. 10 study areas were assigned to each class.

Slope class	***Forest cover class***		
	10 - 40 %	*40 - 70 %*	*70 - 100 %*
9 - 20.1 °	1	2	3
20.1 - 30.14°	4	5	6
30.14 - 41.5°	7	8	9

2.3.2. Analysis of landscape fragmentation

Analysis of forest fragmentation with the R package landscapemetrics is based on the binary 2 m resolution raster as described in section 2.3.1.2. Examples of 4 research areas showing degrees of forest cover of about 17 % and 59 %, but each with different patterns of fragmentation can be seen in Figure 3. Fragmentation metrics which were selected on a literature review (see section 3.1) have been calculated for each of the 90 research areas. The metrics calculated are named as in the R package landscapemetrics (Hesselbarth et al., 2021), lsm_c_area_mn, lsm_l_contag, lsm_l_ed, lsm_c_pd, lsm_l_lpi, lsm_l_np, lsm_c_pland and lsm_l_shdi. Descriptive statistics of the fragmentation metrics for the 90 research areas have been calculated and analysed. To better understand the behaviour of metrics especially to the percentage of landscape cover (forest, lsm_c_pland), scatterplots were made and linear regressions calculated (section 3.2). Based on the developed methodology within this thesis further metrics connecting effects of fragmentation and fire spread behaviour, were developed and are described in section 2.3.4.

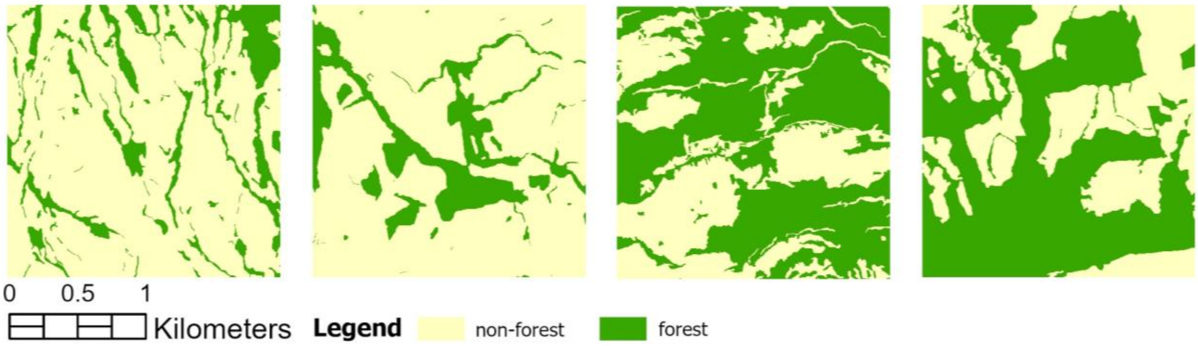


Figure 3: Binary landscape raster in 2x2 m resolution. In yellow the so-called fire barriers (non-forest land) and in green are forested landscape elements represented. The 1. and 2. image from the left show landscapes with a degree of forest cover of 17 percent whereas the 3. and 4. image show landscapes with a degree of forest cover of 59 percent.

2.3.3. Modelling of fire spread behaviour along steepest slopes

To be able to simulate fire spread behaviour along slope while considering the landscape fragmentation, an algorithm was developed in collaboration with WSL. The vector-based algorithm has a high degree of model simplification, which focuses on capturing the key aspects of fire spread along slope and the influence of landscape fragmentation on the process. As known from literature (section 1), fire is prone to spread upwards along slope also under homogenous and non-wind conditions (e.g. (Sánchez-Monroy et al., 2019; Weise & Biging, 1997)). The algorithm, taking topography into account, models fire spread behaviour uphill in direction of the steepest slope, based on differential equation solving with the function deSolve::ode. To prevent unrealistic fire spread behaviour and to map local maxima, the ode solver is interrupted, if the speed of the fire spread falls below a predefined velocity. As ascent stops in this case, the surroundings are searched for higher points, to which the fire might jump. The look-up distance, defined as the radius from the local maxima, can be specified. If within the radius no increase in elevation is present, the calculation of a fire trajectory is stopped. This prevents the calculation of erratic paths in flat terrain, which are not of interest for this research. Within this thesis the look-up distance was set to 200 m.

Derived from the concept of fuel breaks, often applied in the framework of forest fire prevention and reduction of fire propagation danger, fire barriers are introduced in this research. Fire barriers hereby represent non-burnable landscape patches of non-forest land and lead together with areas classified as forest to landscape fragmentation. If fire barriers correspond to a certain expansion, they might stop fire spread. Instead of stopping fire spread, fire barriers are more often used, with smaller expansions, to reduce the fire intensity which allows intervention or to reduce natural spread behaviour. Different distances are proposed in literature, depending on vegetation types, type of fire and the action target. Different values ranging between 30 m- up to 100 m or under certain circumstances even more are proposed for fuelbreak construction within literature (e.g.

(Ascoli et al., 2020; Frank, 1983; Frost et al., 2022; Rossi et al., 2019). The maximum distance a fire can travel outside of the forested area, before being stopped, can be specified in the model. As the influence of fragmentation on fire spread behaviour is of interest in this research, a realistic fuel break distance which could stop a forest fire, was considered. Therefore, a slope along distance of 80 m was chosen for modelling, which represents a non-burnable area between forested patches being able to block the propagation of a forest fire, as a fire barrier. Based on this concept fragmentation effects are represented through fire paths which are blocked through fire barriers and therefore won't reach their highest possible point within the specific research area.

Data needed for running the algorithm involve a shapefile in expansion of the 2x2 km research area containing the points, which indicate ignitions of the fires. Additionally, a shapefile containing the polygons which indicated the areas without burnable landscape elements (fire barriers), was needed. Those were derived as a negative of the areas classified as forest as described in section 2.3.1.2. The extension of this shapefile was set to 6x6 km. With this it was possible to avoid fire paths, meandering around the inner research area borders, because of searching for higher altitudes, which did not represent the real fire path behaviour (lengths). After calculation of the fire spread behaviour in the 6x6 km area, the 2x2 km research areas and respective path lengths were clipped out (Figure 4). As a base for the topographical information a DEM must be supplied likewise in 6x6 km expansion. Data preparation included the extraction of the non-forest area and DEM in a 2 m resolution for the selected 90 research areas as described in section 2.3.1.3. For the shapefile with the points representing the ignitions, a grid with 65 m spacing was created and laid over the research areas. The grid intersections were thereafter extracted as points and those points intersected with the forested areas, representing all ignitions within areas classified as forest. Different methods for defining the ignition points (see section 3.3) were chosen to test the effect of the ignition pattern on the length of the fire paths.

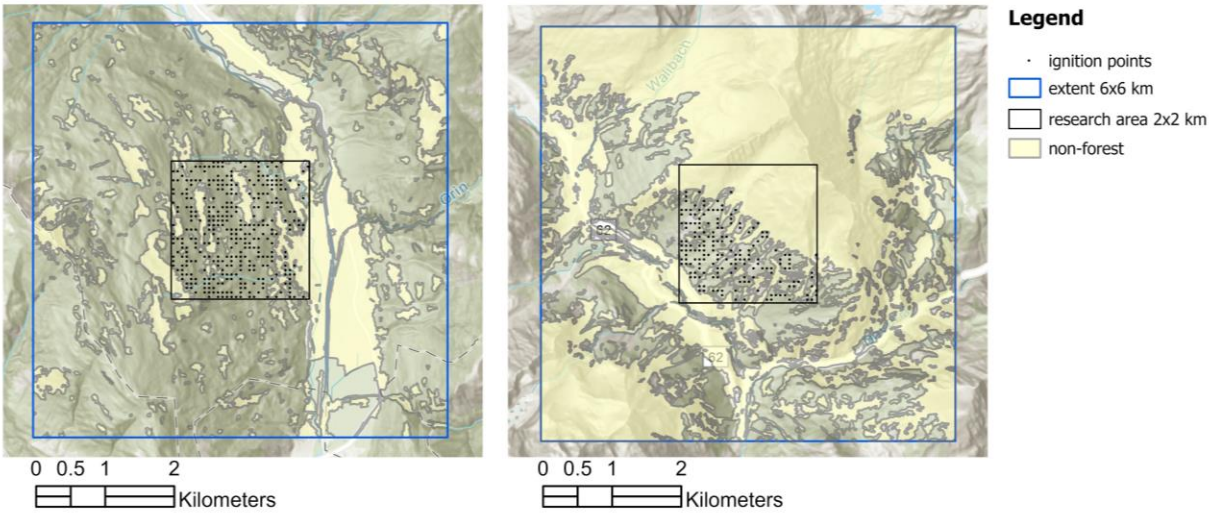


Figure 4: Two examples for the research areas nr. 421 (left) and nr. 85 (right) with the black centre frame as research area [2x2 km] and the ignition points (black dots) in the forested area. For the extent of 6x6 km (blue) the non-forest area is represented in light yellow (Background data: ESRI, swisstopo).

Performing the algorithm leads, among other parameters to 2D and 3D lengths of each individual path with three different lengths. The total possible length of fire paths from the point of ignition to the highest point within the research area [2x2 km], irrespective of forest cover, just based on topography is called “Len3Dtot”. On the other hand, paths travelling through forested areas to the highest point of the respective upper timberline are called “Len3Dlast_forest”. Paths being blocked on their way to the highest point, through fire barriers with a width along slope of more than 80 m, are called “Len3Dblocked”. These 3 types of fire paths can be seen in Figure 5.

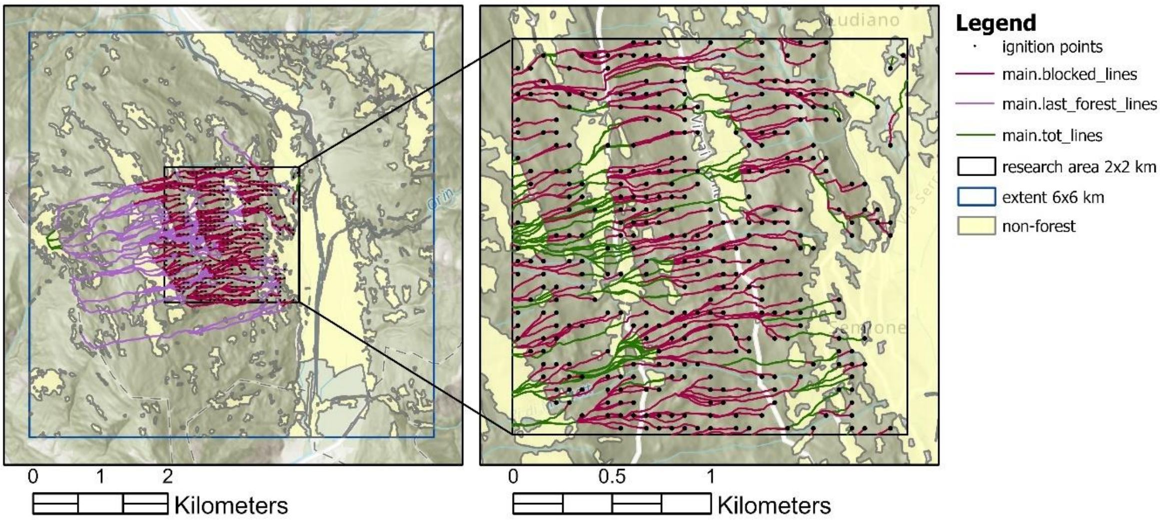


Figure 5: The procedure of the calculation of the different paths. On the left the extent of 6x6 km with the paths blocked through fire barriers (where non-forest distance along slope > 80 m; light yellow) in red. The violet paths stopped at the upper timberline and the green paths representing the maximum possible length for the corresponding paths. On the right the paths used for the further analysis are shown; paths were cut at the boundary of the 2x2 km research area. Green paths are representing the longest possible path length. Red paths were stopped, but caution must be paid, as just red paths, which afterwards lead to green ones are stopped in the inner of the research area through landscape fragmentation. (Background data: ESRI, swisstopo).

Descriptive statistics for the different paths were calculated. For further analyses of path characteristics, the paths stopped in the inner of the research area were separated into the ones stopped at the artificial research area boundary and the ones stopped within the research area through effects of fragmentation. Paths stopped at research area boundary were determined by the fact, that the total path length corresponded with the blocked path length. With this approach paths reaching local maxima are also classified as stopped at the research area boundary. As this does not represent effects of fragmentation on the fire spread behaviour but the effect of topography, it was considered to be appropriate to exclude those paths from analysis. Only paths stopped within the research area were considered for further analyses in regard of the effects of landscape fragmentation on fire spread behaviour.

2.3.4. Analysis of fire spread behaviour under landscape fragmentation

For the 90 research areas the relative number of paths blocked within the research areas and their relative mean path length, as well as their relative mean path length shortening were calculated. These metrics are required as response variables, which were introduced in section 0, specifically describing fire spread behaviour under landscape fragmentation.

Relative median length of 3D blocked fire paths within the research area boundary is calculated through:

$$\boldsymbol{Rel. median\ length\ 3D\ blocked} = (median\ \boldsymbol{Len3Dtot} - median\ \boldsymbol{Len3Dblocked_{inner}}) * 100$$

Following the relative median length 3D blocked will be named as **relative blocked path length**.

The relative median 3D path length shortening of paths blocked in the inner of the research area can be calculated through:

$$\boldsymbol{Rel. median\ 3D\ path\ length\ shortening} = \frac{median\ \boldsymbol{Len3Dblocked_{inner}} - median\ \boldsymbol{Len3Dtot}}{median\ \boldsymbol{Len3Dtot}} * 100$$

The relative median 3D path length shortening is called **percentage of path shortening** in the following.

These additional metrics were analysed descriptively and in accordance to slope and forest cover classes. To test the influence of specific fragmentation traits, represented within the 8 fragmentation metrics, on the response variables mean blocked path lengths and the relative number of blocked paths per research area, Pearson correlations and linear regressions were calculated. This was done for the response variables relative blocked path length of paths and the number of blocked fire paths within the research areas. Predictor variables were all 8 fragmentation metrics. Due to high multicollinearity of the metrics the first intended calculation of multiple linear regressions was not possible. This did not change after the reduction of highly correlated predictor variables.

3. Results

In the following section results of the conducted research will be presented. According to the sequence of the hypotheses, first relevant landscape fragmentation metrics to better understand forest fire spread behaviour will be presented, based on the conducted literature review (section 3.1). Thereafter, the analysis of fragmentation for the research areas with a set of landscape metrics is given (section 3.2). This is followed by the results of three different methodological variants for setting the ignitions, as being the starting points for the calculation of the fire paths (section 3.3). Finally, the results of the application of the developed algorithm within this thesis, to analyse forest fire spread behaviour under landscape fragmentation, are presented (section 3.4).

3.1. Fragmentation metrics and tools to understand forest fire spread

Landscape metrics are according to McGarigal (2013): "(…) algorithms that quantify specific spatial characteristics of patches, classes of patches or entire landscape mosaics" and allow comparison among different landscapes. Fragmentation metrics can be either calculated at patch, class or landscape level, where not all metrics can be calculated at each level. For the analysis of landscape fragmentation on fire spread behaviour several studies propose the use of landscape level metrics, although depending on the perspective on categorical map patterns also class level metrics find application (e.g. (Lloret et al., 2002; McGarigal & Marks, 1995)). With appropriate landscape metrics size, shape and connectivity of forest patches can be measured and described (McGarigal & Marks, 1995). The basic components which can be characterized by the metrics are besides fragmentation, composition and configuration. The very basic metric of percentage of landscape of a class (e.g. forest) is a fundamental measure in analysis of landscape characteristics. As with many metrics, correlation among themselves can often be observed (McGarigal, 2013). Riitters et al. (1995) found in a study analysing 55 different landscape metrics by factor analysis, that only 5 metrics were independent and measuring different qualities of spatial pattern. The choice of metrics must be well-considered to be able to answer specific research questions. Using just one metric which should be able to characterize a landscape might often not be enough for the complexity of landscape patterns, but on the other hand using several highly correlated metrics might make the analysis and interpretation of results more difficult (Turner et al., 2001).

For the calculation of landscape metrics different products, which are based on raster input data, are available. On the one hand the stand-alone software FRAGSTATS (McGarigal et al., 2023), which has a main drawback in the application, as data import and export is needed. This does not allow integration into bigger workflows. For FRAGSTATS the calculation of metrics based on vector data is possible as well. Another application is the GuidosToolbox (Graphical user interface for the description of image objects and their shapes), which has been developed at a joint research center of the European Commission (Vogt, 2023). Although this toolbox is user friendly and allows the calculation of a variety of landscape characteristics, data in-and export similar as in FRAGSTATS must be done. A simple and in the variability and number of disposable metrics extended application is the freely available R package landscapemetrics (Hesselbarth et al., 2019), which can be integrated into complex automated calculation procedures through programming. Besides being an open-source package, landscapemetrics has several utility functions to facilitate visualization, extraction as well as sampling and development of metrics (Hesselbarth et al., 2019). A drawback of the applications using raster data as input is, that based on raster data for some metrics like edge length it is not a real length of edge calculated, as with raster's are lines represented in stairsteps. The effect is dependent on raster resolution. By choosing a smaller raster resolution the effect can be minimized (McGarigal & Marks, 1995).

Applications of fragmentation metrics to analyse the influence on fire spread or the connectivity of fuels, can be found for example in Duguy et al. (2007), Ryu et al. (2007) or Viedma et al. (2006) and (Lloret et al., 2002). Those studies show that the spatial distribution of forest, respectively fuel is greatly influential on forest fire propagation. In the context of a literature review, 18 studies were considered to select appropriate fragmentation metrics for the purpose of this thesis. This included studies from the more general area of landscape ecology and more specifically from the influence on fire characteristic through fragmentation effects. The metrics used to describe fragmentation were recorded subsequently and each assigned to the classification according to Hesselbarth et al. (2019). Figure 6 shows the number of studies, which have been selected in a literature review and applied the corresponding fragmentation metrics within their research. In Appendix B,Figure B1, a detailed overview can be found.

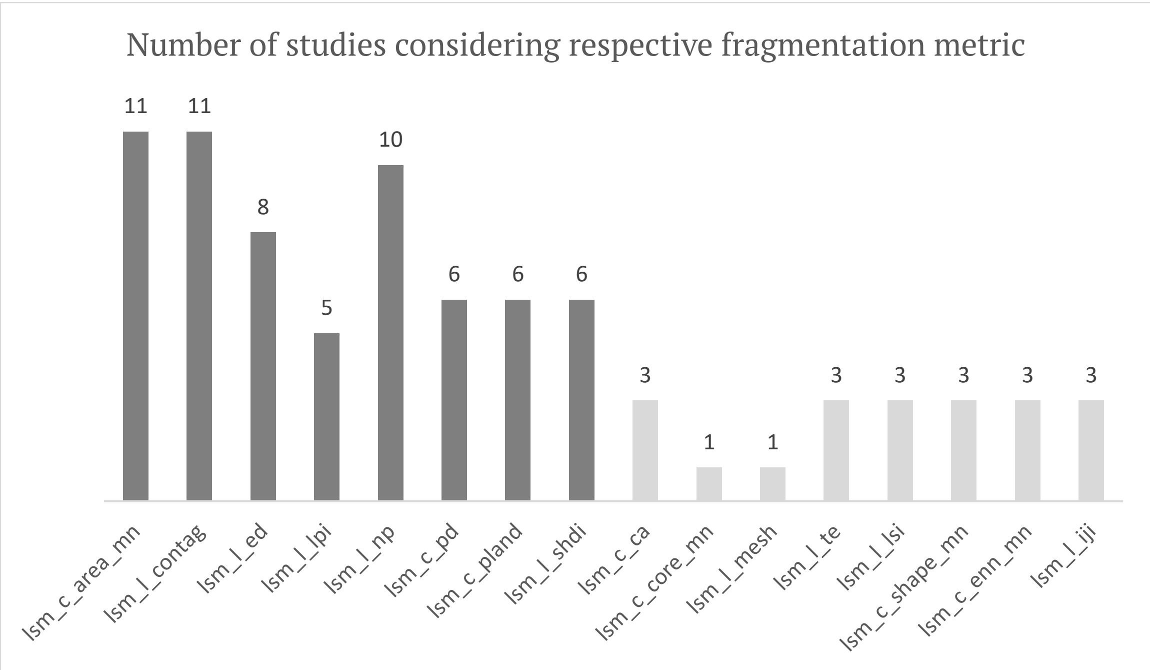


Figure 6: The number of studies (from a total of 18) considering the respective fragmentation metrics according to the naming in the R package landscapemetrics (Hesselbarth et al. 2019). In dark grey the 8 metrics which were further considered.

Eight metrics, of which each is describing different aspects of fragmentation and were the most abundant ones within the considered studies, were finally calculated within this thesis. Detailed description of the fragmentation metrics can be found in Table 4.

Table 4: Overview about the metrics being selected to calculate landscape fragmentation. Naming according to the R package landscapemetrics (Hesselbarth et al., 2019).

Metric	Description	Calculation	Range
lsm_c_area_mn	Mean of patch area (area and edge metric) for landscape **composition** Summarizes the landscape as the mean of all patches in the landscape.	$AREA_{MN} = mean(AREA[patch_{ij}])$ where $AREA[patchi_{ij}])$ is area of each patch in hectars	AREA_MN > 0 [in hectares]
lsm_l_contag	Contagion (aggregation metric) Probability of two random cells belonging to same class.	$Contag = 1 + \frac{\sum_{q=1}^{n_a} p_q \ln(p_q)}{2\ln(t)}$ Where *pq* is the adjacency table for all classes divided by the sum of that table and *t* = number of classes in landscape	0 < Contag <= 100 [in percent]
lsm_l_ed	Edge density (area and edge metric) for landscape **configuration** Equals all edges in the landscape in relation to landscape area	$ED = \frac{E}{A} * 10000$ Where E = total landscape edge in meters and A = total landscape area in square meters	ED >= 0 [in m per hectares]
lsm_l_lpi	Largest patch index (area and edge metric) Percentage of landscape covered by the largest patch in the landscape	$LPI = \frac{\max(a_{ij})}{A} * 100$ Where $\max(a_{ij})$ is the area of the patch in square meters	0< LPI <= 100 [in percentage]
lsm_l_np	Number of patches (aggregation metric) for landscape **fragmentation**	$NP = N$	NP >=1
lsm_c_pd	Patch density (aggregation metric) for landscape **fragmentation**	$PD = \frac{n_i}{A} * 10000 * 100$	0< PD <=1e+06 [number per 100 hectares]
lsm_c_pland	Percentage of landscape of class (area and edge metric) Measure for landscape **composition**	$PLAND = \frac{\sum_{j=1}^{n} a_{ij}}{A} * 100$	0 < PLAND <= 100 [in percentage]

	Percentage of landscape belonging to class i		
lsm_l_shdi	Shannon's diversity index (diversity index)	$SHDI = -\sum_{i=1}^{m}(P_i * lnP_i)$	SHDI >=0

The three main characteristics of landscape, which can be described by the metrics Table 4 are landscape fragmentation, configuration and compositions (McGarigal & Marks, 1995). Landscape composition can be represented through the basic metric of percentage of landscape of a class (lsm_c_pland). This metric also builds the fundament for the calculation of many other metrics. Specifically describing landscape fragmentation is the metric patch density (lsm_c_pd). This metric incorporates the same information as the number of patches does, but under constant total landscape area. A higher density of forest patches could under constant forest cover degree considered to be more fragmented and to be more spatially heterogenous. On landscape level, patch size is redundant with the metric of mean patch area (lsm_c_area_mn), as they are a function of number of patches and total landscape area (McGarigal & Marks, 1995). Metrics of edge like edge density, are measures to characterize landscape configurations and is represented with the standardized per unit area metric of edge density (lsm_l_ed). A higher degree of edge density is an expression for a more fragmented landscape with less connectivity (Leitão & Ahern, 2002).

3.2. Fragmentation analysis with selected metrics

Fragmentation metrics which have been calculated with the R package landscapemetrics (Hesselbarth et al., 2019) for the 90 research areas showed when tested for normality, that metrics of lsm_l_ed, lsm_l_lpi, lsm_c_area_mn and lsm_c_pland are approximately normally distributed. This can be seen in histograms and Q-Q plots in Appendix C, Figure C1-Figure C8. Metrics of lsm_c_pd and lsm_l_np were left skewed, whereas all other metrics showed to be clearly not normally distributed.

Calculated descriptive statistics for the metrics describing landscape fragmentation within the 90 research areas can be seen in Table 5.

Table 5: Table with the descriptive statistics for the 8 selected metrics describing landscape fragmentation, within the 90 research areas.

	lsm_l_contag	lsm_l_ed	lsm_l_lpi	lsm_c_area_mn	lsm_l_np	lsm_c_pd	lsm_c_pland	lsm_l_shdi
min	42.12	11.59	29.09	0.3022	9	0.5	11.71	0.1569
1.quant	47.2	72.88	54.28	2.5171	44.25	4.375	36.37	0.5316
median	52.03	92.28	64.78	6.0207	60	8.875	53.03	0.6117
mean	54.38	96.5	64.29	15.0533	64.96	10.542	53.9	0.5799
3.quant	58.54	123.14	74.63	13.855	82	14.5	74.03	0.6735
max	88.15	233.25	96.3	188.0172	194	38.75	96.34	0.6929

Degree of forest cover (lsm_c_pland), which is a basic information for many other metrics, was analysed for the 90 research areas. It shows a median forest cover of 53.03 percent. Minimum of lsm_c_pland laid, as defined in section 2.3.1.2 for the research area with the lowest degree of forest cover (research area nr. 390) at 11.71 percent. Maximum degree of forest cover was found in research area 366 with 96.34 percent.

Within the 90 research areas high variations in the degree of fragmentation were observed and an example can be seen in Figure 7 for two very contrasting research areas.

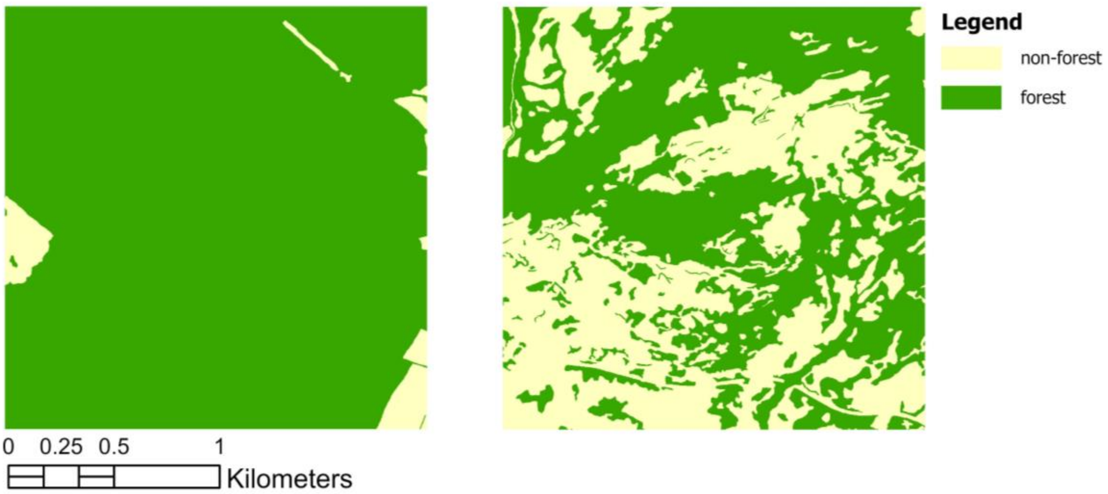
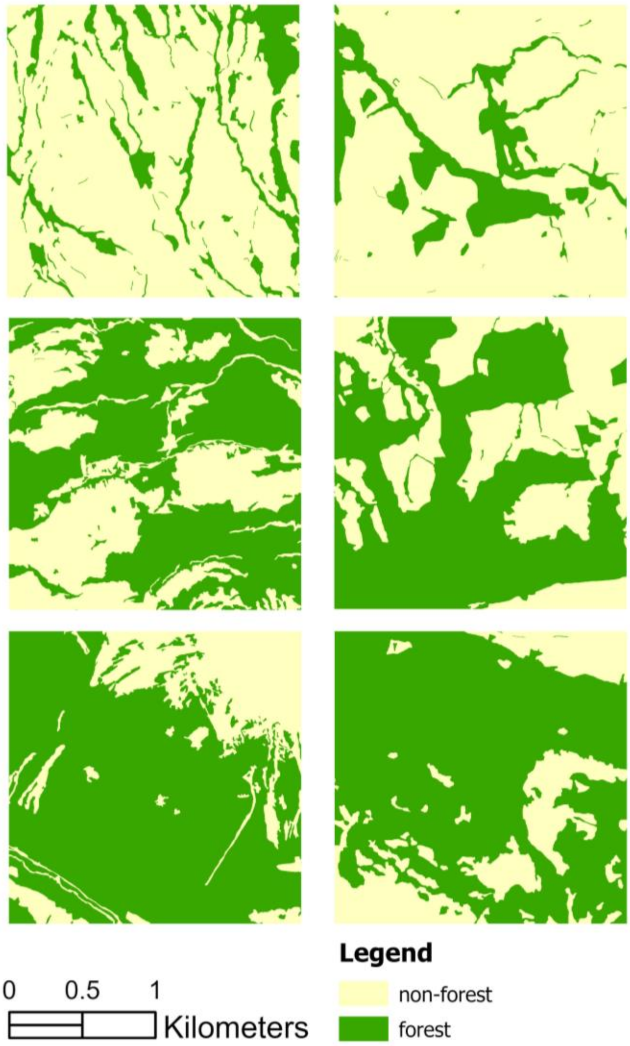


Figure 7: Two of the 90 research areas with extremely contrasting degrees of fragmentation, with research area nr. 366 (left) and nr. 254 (right).

For the understanding of the behaviour of the fragmentation metrics and their close relation in behaviour to each other, examples are given in Figure 8. At three contrasting degrees of forest cover (lsm_c_pland) are research areas shown with high and low degrees of fragmentation (left/right).



Forest cover 17 %

	research area nr. 238	research area nr. 466
mertic	value	value
lsm_l_contag	62.03	63.8
lsm_l_ed	145.26	78.0
lsm_l_lpi	71.78	82.57
lsm_l_area_mn	0.68	1.63
lsm_l_np	111	46
lsm_c_pd	24.75	10.5
lsm_c_pland	16.92	17.15
lsm_l_shdi	0.45	0.45

Forest cover 59 %

	research area nr. 195	research area nr. 137
mertic	value	value
lsm_l_contag	45.68	47.62
lsm_l_ed	146.38	88.4
lsm_l_lpi	38.69	58.37
lsm_l_area_mn	4.91	13.96
lsm_l_np	82	38
lsm_c_pd	12	4.25
lsm_c_pland	59.0	59.3
lsm_l_shdi	0.67	0.67

Forest cover 74 %

	research area nr. 13	research area nr. 164
mertic	value	value
lsm_l_contag	54.91	56.34
lsm_l_ed	105.4	74.33
lsm_l_lpi	69.6	74.55
lsm_l_area_mn	6.61	29.99
lsm_l_np	69	44
lsm_c_pd	11.25	2.5
lsm_c_pland	74.4	74.98
lsm_l_shdi	0.56	0.56

Figure 8: 6 different research areas with contrasting degree of forest cover from top to bottom. Research areas on the left thereby generally show contrasting metrics values to the research areas on the right. Row one with research areas nr. 238 and nr. 466 has a forest cover degree of around 17 %, row two with research areas nr.195 and nr. 137 of about 59 % and row 3 with research areas nr. 13 and nr. 164 of about 74 %.

For the metric lsm_c_area_mn (mean of patch area) all research areas with exception of three outliners showed, a mean patch area size below 75 hectares. The median patch size of all research areas laid at 6.27 hectares which represents about 1.57 percent of research area size. The biggest mean of the patch area of 188 hectares was found in research area 24, having a degree of forest cover of 94 percent. In general, a positive trend was for the linear regression of mean patch area size and the percentage of forest cover observed. The model is significant with $R^2 = 0.37$, $p < .000$. With a decrease in mean patch size, an increase in number of patches (lsm_l_np) per research area was observed ($R^2 = 0.22$, $p < .000$) (Figure 9; left). Additionally, areas with a smaller mean patch area showed a lower contagion index, representing higher class dispersion and interspersion with a R^2 of 0.5 and $p < .000$ (Figure 9; right). Smaller mean patch areas furthermore showed a higher edge density for the 90 research areas ($R^2 = 0.3$, $p < .000$).

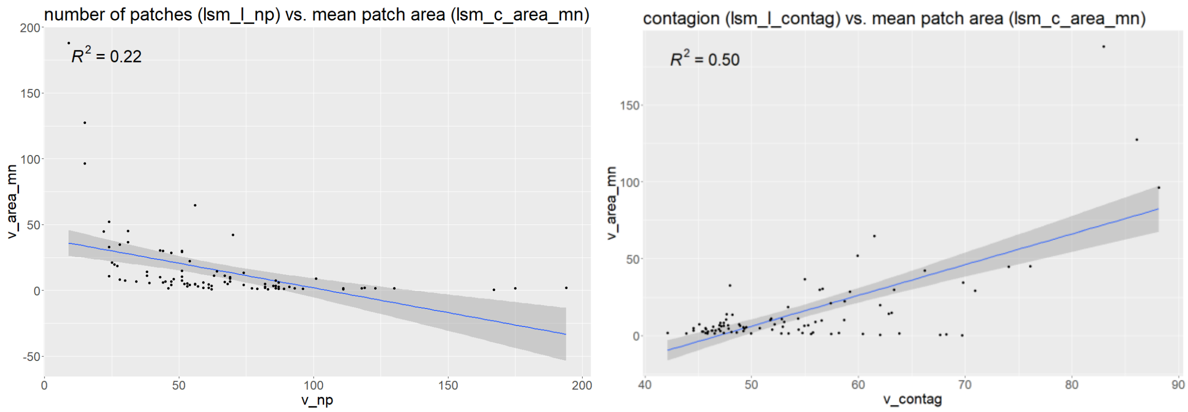


Figure 9: Scatterplot and fitted linear regression line of the mean patch size (lsm_c_area_mn) to the number of patches (lsm_l_np) (left) and the mean of patch area (lsm_c_area_mn) to contagion (lsm_l_contag) (right).

Mean number of patches (lsm_l_np) per research area were 64, whereas the minimum at research area 24, with a forest cover degree of 94 percent, laid at 9 patches. The maximum 194 patches per research area were found in research area 254, with a forest cover degree of 52.8 percent. The percentage of forest cover, represented in lsm_c_pland can only explain 18 percent of the variation in the number of patches per research area ($p < .000$) (Figure 10; left). Whereas the number of patches is representative on landscape level, lsm_c_pd describes the number of patches per 100 hectares. Patch density showed a mean of 8.87 patches per 100 hectares with a minimum of 0.5 patches per 100 hectares and a maximum of 38.75 patches per 100 hectares. A negative relationship between patch density (lsm_c_pd) and the percentage of landscape (lsm_c_pland) was observed with a R^2 of 0.4 ($p < .001$). Patch density (lsm_c_pd) shows a strong relationship with the edge density (lsm_l_ed, $r = 0.635$, $p < 0.001$) (Figure 10; right).

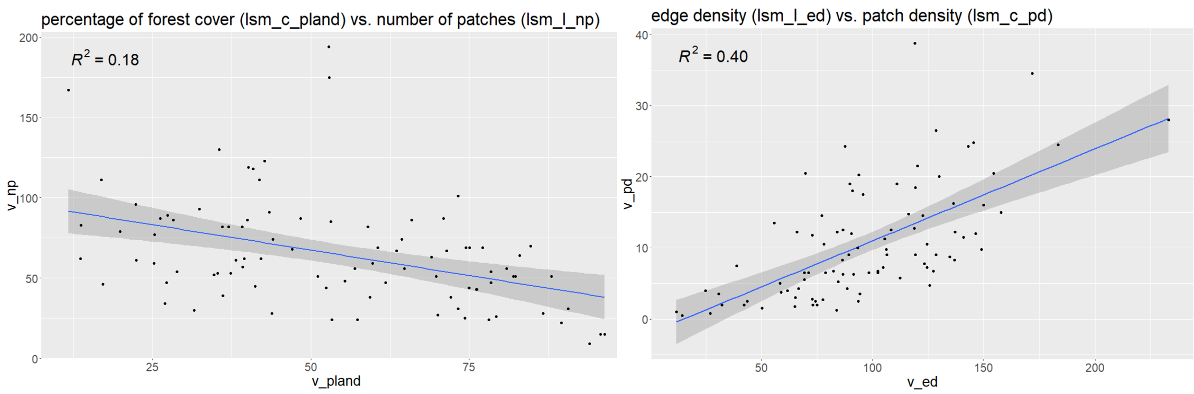


Figure 10: Scatterplot and fitted linear regression line of number of patches (lsm_l_np) to the percentage of landscape (lsm_c_pland) (left) and the patch density (lsm_c_pd) to the edge density (lsm_l_ed) on the right.

Edges of landscape in relation to the research area, represented by lsm_c_ed, showed a median of 92.28 meters per hectares. The minimum edge density of 11.59 meters per hectares was mapped in research area nr. 366, with a degree of forest cover of about 96 percent. Largest edge density was observed in research area 254, with a degree of forest cover of 52.8 percent is 233.25 meters per hectare. This area 254, corresponds to the area with the highest number of patches. A moderate negative trend of the edge density is present with increasing degree of forest cover ($r = -0.423$, $p < .001$).

Metric of contagion was ranging between 42.1percent (research area nr. 254) to 88.15 percent (research area nr. 366) and had a median of 52.03 percent. A Scatterplot with the percentage of landscape showed a u-shaped behaviour with the lowest point at around 45 percent for the contagion index, at a degree of forest cover from around 50 percent (Figure 11; left). The contagion index showed a strong negative correlation to the edge density ($r = -0.646$, $p < .001$).

The metric of largest patch index per research area had a median of 64.78 percent of forest cover. Smallest largest patch was found, in research area nr. 49 with a degree of forest cover of 29.09 percent. Biggest largest patch was present in research area nr. 366, with a degree of forest cover of 96.3 percent. A scatterplot with the values of lsm_l_lpi and lsm_c_pland showed non- linear v-shaped behaviour, with a decrease of largest patch index to around 50 percent of forest cover, followed by an increase (Figure 11; right). A strong positive correlation was observed for the metric of contagion (lsm_l_contag) with the metric of largest patch index (lsm_l_lpi) ($r = 0.794$, $p < .001$) (Figure 12; left).

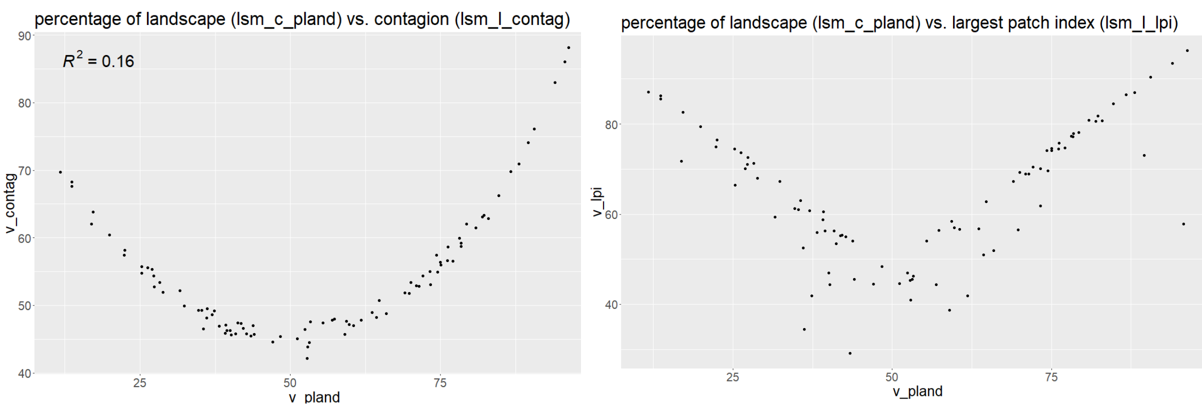


Figure 11: Metric of contagion (lsm_l_contag) (left) and largest patch index (lsm_l_lpi) (right) plotted against the percentage of landscape (lsm_c_pland), representing the degree of forest cover.

Shannons diversity index, represented in the metric of lsm_l_shdi showed a median value of 0.6117 with a minimum of 0.1569 in research area nr. 366 and a maximum value of 0.6929 in research area nr. 294. An inverted u-shaped distribution was observed, when plotting lsm_l_shdi against the percentage of landscape (Figure 12; right). The maximum value was observed at around 50 percent degree of forest cover.

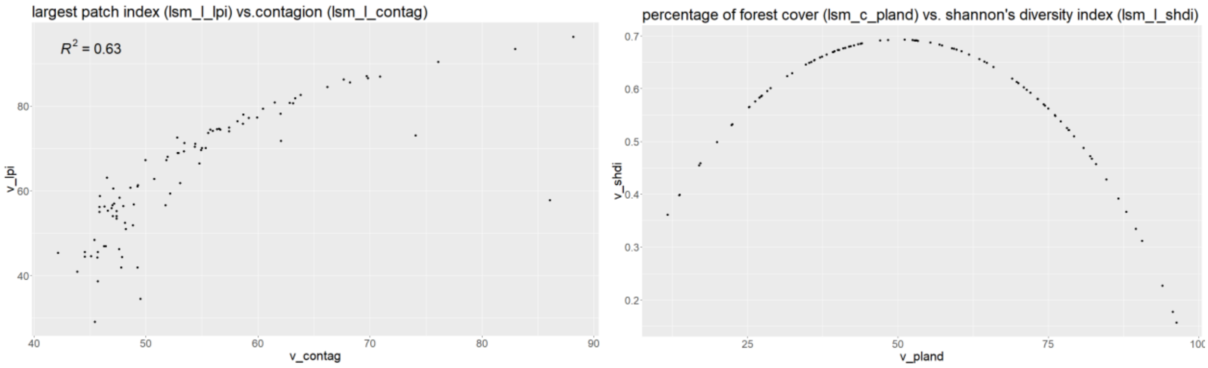


Figure 12: Scatterplot of the metric contagion (lsm_l_contag) to the largest patch index (lsm_l_lpi) on the left and the metric of Shannon's diversity index (lsm_l_shdi) plotted against the percentage of forest cover (right).

3.3. Influence of ignition points method selection

Setting of ignition points to calculate the fire paths within the differently fragmented 90 research areas was tested with 3 different methods. This to evaluate, if a reduction of ignition points could be made, without reducing the significance of the computed results. With a reduction of ignition points, calculation time can be reduced. Three different methods were thereby tested on a set of 6 research areas, characterised by differing degrees of forest cover. As describe in the methods section 2.3.3, ignition points were set based on a grid, spanning the single research areas with a spacing of 65 meters. Method one as seen in Figure 13 (left), used all ignition points, which fall within the forest of a research area. For a reduction of ignition points, method two uses randomly selected 50 percent of the original ignition points (Figure 13; middle), whereas in method 3, 50 percent of the original ignition points were selected belonging to 50 percent of ignition points laying at the lower range of altitude (Figure 13; right). The third method takes into account, that ignitions often take place in the interface of settlements, which are expected to be more often represented in lower than in higher altitude (Calviño-Cancela et al., 2017; Moreira et al., 2011). For these three methods, fire path characteristics as described in 2.3.3 were calculated, whereby the mean path lengths were calculated. For this analysis outliers were ignored.

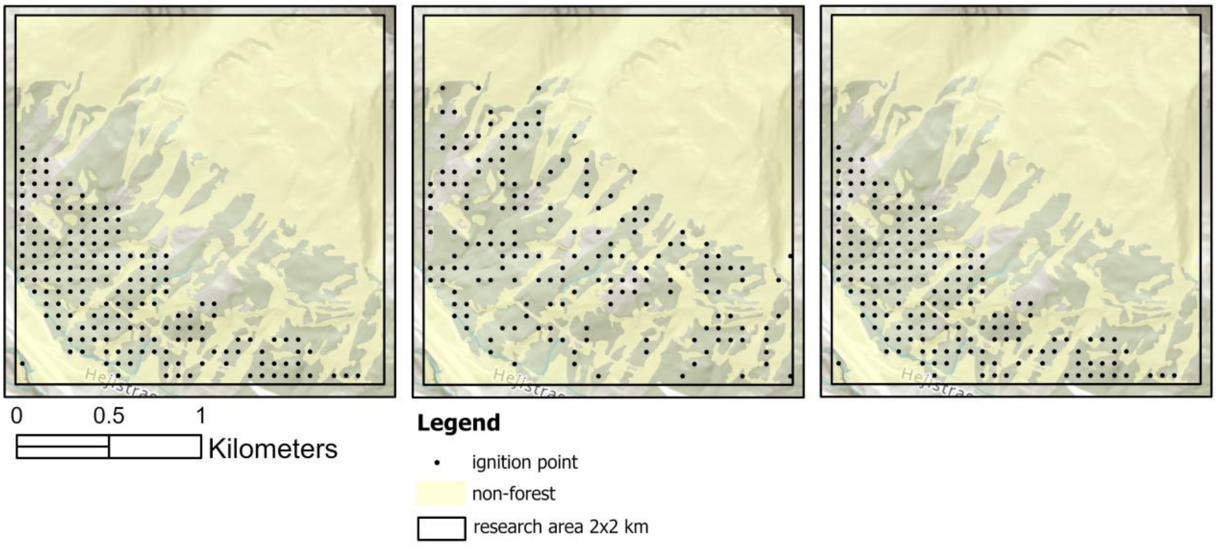


Figure 13: The three different methods for setting the ignition points which were tested. Left all ignition points within the forested area, extracted from grid intersections with distances of 65 m (= original). Middle randomly selected 50 percent of all ignition points from the original version. And on the right, 50 percent of the points (from the original version) at the lower altitude.

For the visualisation of the data distribution boxplots were made for the three target variables relative mean blocked path length, percentage of mean path shortening through fire barriers (all blocked within the research area and at boundary) and the percentage of fire paths blocked within the research area through fragmentation (see Figure 14). The medians of the target variables for the three different methods of setting the ignitions do not show high variation. Only for the percentage of paths blocked within the research areas a slight variation of the median value of the variant “lower” can be observed, compared to the other two variants.

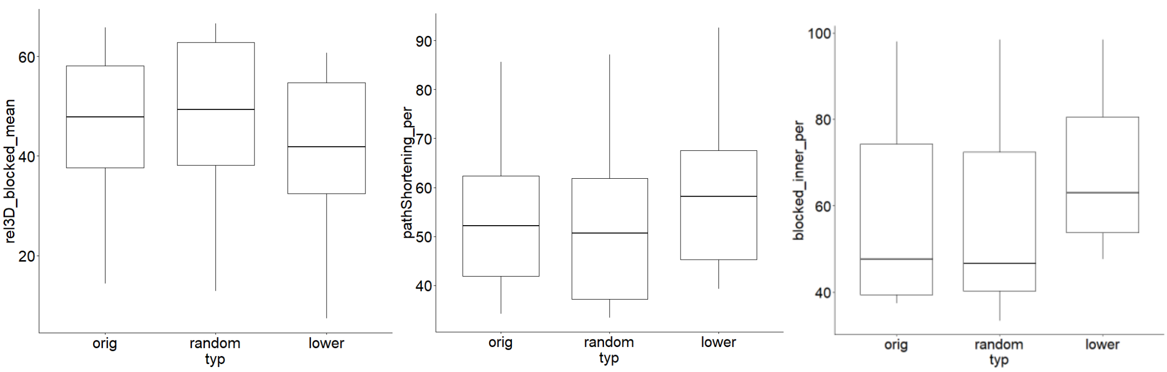


Figure 14: Boxplots of the three target variables grouped by the method of setting the ignition points. Left boxplot the mean of the relative blocked path lengths, middle the percentage of path shortening through fire barriers and on the right the percentage of paths blocked within the research area through fragmentation. X-axis labels correspond to the 3 different methods (orig = all ignition points within forest according to grid), (random = 50 percent randomly selected from the orig) and (lower = 50 percent of the orig ignition points with the lowest altitude).

Distribution of the variables did show to not be normally distributed. Paired two-samples Wilcoxon test was used, to test for significant differences between the variants. The paired Wilcoxon test was applied for every target variable in paring of orig – random and orig – lower. None of the tests showed a significant difference, indicating that the different methods would lead to other results.

3.4. Spread behaviour under landscape fragmentation

Results from the application of the algorithm to calculate the fire paths within the 90 differently fragmented research areas are presented below.

3.4.1. Characteristics of blocked fire paths

Fire spread behaviour calculations with the vectors starting from the ignition points and travelling through forested areas along steepest slope, were analysed descriptively (Table 6) and some key characteristics are given below.

For the 90 research areas, a total of 22'980 fire paths were calculated. Paths with values of 0 for the length at last forest exit and paths blocked with a length below 2 meters were excluded from further analysis, leading to a total of 22'624 fire paths, being used.

Table 6: Paths characteristics for all paths, the ones blocked at the research area boundaries and in the inner of the research areas.

Paths	number	mean length	median length	minimum length	maximum length
3D blocked (all) absolute	22624	459.3	313.5	2.002	2850
3D blocked (all) relative	22624	57.03	55.1	0.087	100
3D blocked at boundaries absolute	8183	606.5	454.9	2.005	2850
3D blocked inner absolute	14441	375.8	251.1	2.002	2494.9
3D blocked inner relative	14441	32.7	26.5	0.087	99.9

The median length of blocked fire paths for the 90 research areas was 313.5 meters, with a minimum length of two meters and a maximum blocked path length of 2850 m. Relative blocked path length was about 55.1 percent of the possible path length within the research area, assuming no fragmentation. A density plot of absolute blocked path lengths (Figure 15; left) showed a high density of short, blocked paths and a decrease to longer paths. The highest density of blocked fire paths can be found at a path length of 69.9 meters. Relative length of the blocked paths showed a weak binominal pattern, with a little peak at around 7 percent and a high peak at 100 percent (Figure 15; right). The high number of paths being observed with a relative length of 100 percent stands for those paths where total path length was equivalent to the blocked length. Those paths were the ones, which were stopped at research area boundaries and not through forest fragmentation within the research area. A small number of paths may also fulfill the condition of a total path length being equal to the blocked path length, if local maxima were reached within the research area. As those paths do not represent fire spread behaviour based on landscape fragmentation but effects of topography, it seemed appropriate to exclude them in further analysis.

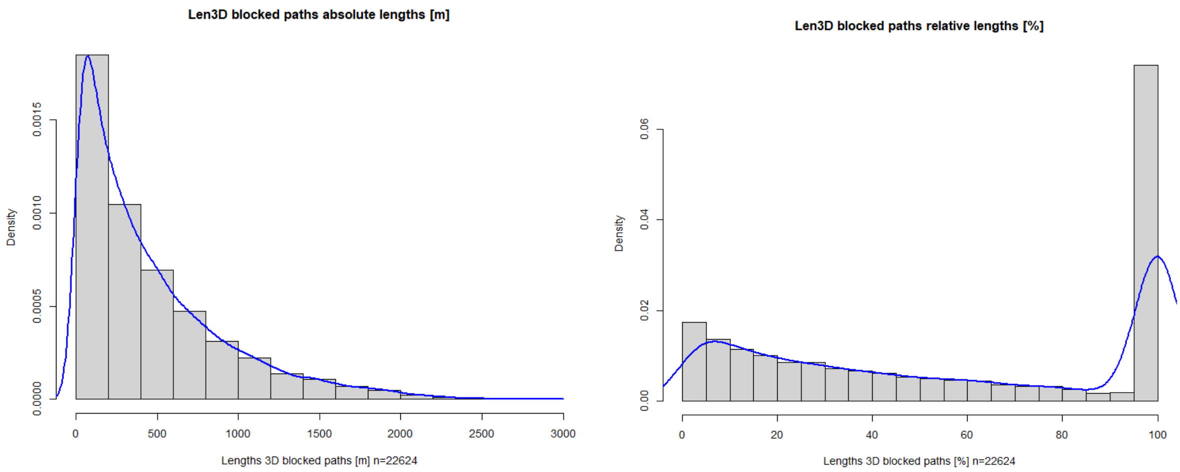


Figure 15: Histogram for the absolute lengths of blocked fire paths (left) and relative blocked fire path lengths with an integrated density plot in blue.

Separation of blocked fire paths being either stopped at research area boundaries or through local maxima and the ones being stopped within the research area through forest fragmentation, was done.

From the total of 22’624 paths, 8183 of the blocked fire paths were stopped at research area boundaries. This are 36.2 % percent of all blocked fire paths. About 63.8 % of the fire paths were blocked through landscape fragmentation within the research areas (14441 paths). Fire paths blocked at research area boundaries showed a median length which was 1.8 times longer (~ 203 m) than the median lengths of paths blocked within the research areas through landscape fragmentation. The number of paths stopped at the research area boundaries showed a positive relationship with the degree of forest cover (lsm_c_pland). Simple linear regression was used, to test, if the percentage of forest cover significantly predicted the relative number of paths blocked at research area boundaries. The fitted regression showed a positive trend and is statistically significant ($R^2 = 0.49$, $F(1,87) = 84.79$, $p < 1.683e-14$) (Figure 16).

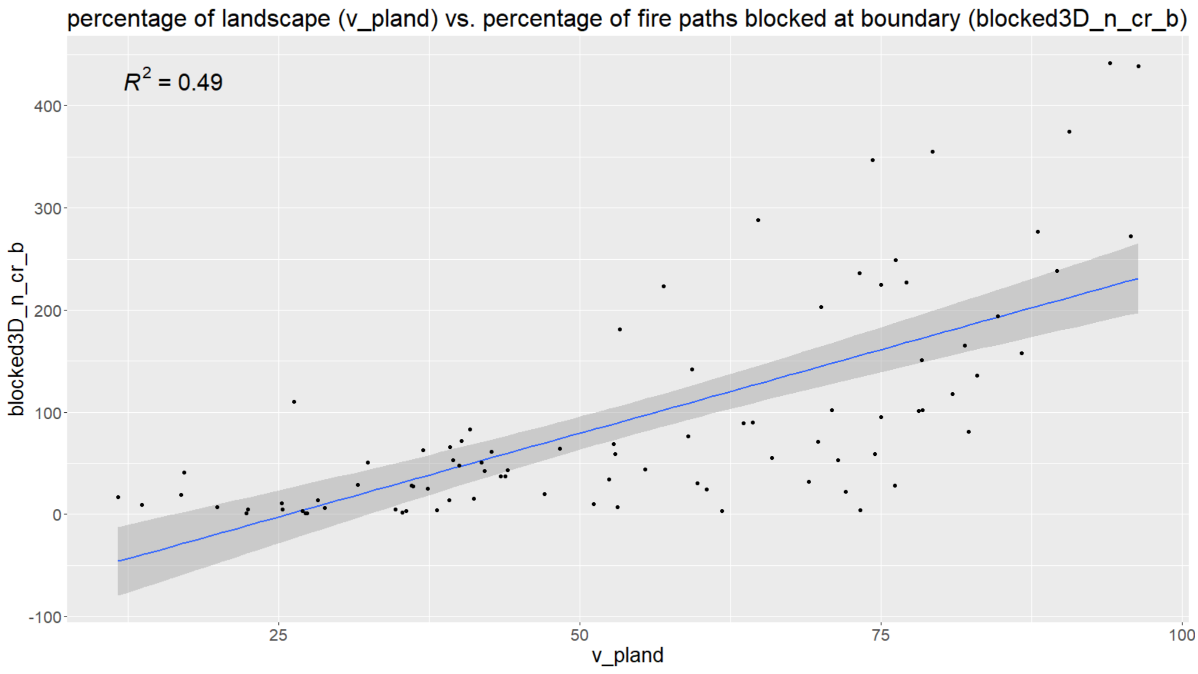


Figure 16: Fitted regression line for the percentage of fire path crossing the research area boundary to the percentage of landscape class (lsm_c_pland).

Application of the metric described under section 2.3.4 to calculate the path shortening of paths blocked within the research areas showed, that blocked paths are reduced in length in median by about 73.5 percent. This is in contrast to the blocked path lengths, which would only have been stopped at research area boundaries, through a higher degree of connectivity of forested areas.

3.4.2. Path shortening with forest cover and slope angle

The relative blocked path length within the research areas is directly related to the percentage of fire paths shortening (as described in section 2.3.4). In the following the percentage of path shortening by forest cover and slope will be discussed, whereas in section 3.4.4 the results of the relative blocked path lengths will be presented, in context of the fragmentation metrics.

Analysis of paths stopped within the research areas showed (Table 7), that the biggest reduction of path lengths can be observed in research areas with a forest cover of (10-40 %). The mean percentage of path shortening for the 30 research areas having a degree of forest cover of about 10-40% laid at 76 percent and was according to a Welch two-sample t-test significantly different to the class of forest cover of 40-70 % (10-40 % (M = -76.73, sd = 21.98) and 40-70% (M = -70.21, sd = 24.1); t = -12.92, p< .000). Research areas with a degree of forest cover of about 70-100 % showed a mean reduction of path lengths of about 59 %, which was compared to the forest cover class of 10-40% about 17 % less and about 11 % less compared to the forest cover class of 40-70 %.

Table 7: Percentage of path shortening of blocked fire paths within the research areas, separated for the forest cover classes but united for all slope classes.

Slope	***Forest cover class***		
	10-40 %	*40-70 %*	*70-100 %*
9-41.5°	median: -83.69 mean: -76.73 sd: 21.98 n:3287	median: -76.08 mean: -70.21 sd: 24.1 n: 5408	median: -62.29 mean: -59.21 sd: 27.55 n: 5746

Slope influences the percentage of path shortening not as strongly as the forest cover does (Table 8). Highest mean in the percentage of path shortening was observed in the 30 research areas having a slope between 20.1° and 30.14 °with a mean of 68 percent. This was significantly different to the mean percentage of path shortening of research areas with a slope between 9-20.1° (9-20.1° (M = -63.55, sd =29.12) and 20.1-30.14° (M = -68.46, sd = 25.18); t = 8.04, p <.000). In contrast, no significant difference between the mean percentage of path shortening was observed for research areas with slope angles between 20.1-30.14° and 30.14-41.5° (20.1-30.14° (M = 68.46, sd =25.18) and 30.14-41.5° (M = -59.21, sd = 24.73); t = -0.054, p = 0.95). Here the highest percentage of path shortening under all degrees of forest cover was observed on slopes with an angle between 20.1 - 30.14°.

Table 8: Percentage of path shortening of blocked fire paths within the research areas separated for the slope classes, but united for all forest cover classes.

Forest cover	***Slope class***		
	9-20.1°	*20.1-30.14°*	*30.14-41.5°*
10-100 %	median: -70.01 mean: -63.55 sd: 29.12 n:3323	median: -74.24 mean: -68.46 sd: 25.18 n: 5433	median: -62.29 mean: -59.21 sd: 24.73 n: 5685

Overall, the highest percentage of path shortening was observed in research areas of the class which had a degree of forest cover between 10-40 % and a slope of 30.14-41.5° (mean =-79.24, sd = 17.69) (Table 9; Figure 17). The smallest percentage of path shortening was in contrast found in research areas with a degree of forest cover between 70-100 % and a slope of 9-20.1 ° (mean = -51.38, sd = 28.59). Higher variation was apparent within the forest cover classes, where the influence of the slope classes did not cause high variation in the percentage of path shortening.

Table 9: Percentage of path shortening of blocked fire paths within the research areas. Split into the 9 classes according to forest cover and slope class as introduce in section 2.3.1.3 (class numbers in blue).

Slope class	***Forest cover class*** *10-40 %*	***Forest cover class*** *40-70 %*	***Forest cover class*** *70-100 %*
9-20.1	1 Median: -83.98 Mean: -73.82 Sd: 25.83 N:772	2 Median:-74.44 Mean: -68.76 Sd: 27.52 N:1330	3 Median: -53.02 Mean: -51.38 Sd:28.59 N: 1221
20.1-30.14	3 Median: -83.64 Mean: -75.85 Sd: 23.23 N: 1199	4 Median: -73.33 Mean: -68.77 Sd: 23.87 N: 1949	5 Median: -69.34 Mean: -64.30 Sd: 26.32 N: 2285
30.14-41.5	6 Median: -83.65 Mean: -79.24 Sd: 17.69 N: 1316	7 Median: -76.90 Mean: -72.43 Sd: 21.68 N: 2129	8 Median: -61.20 Mean: -58.27 Sd: 27.11 N: 2240

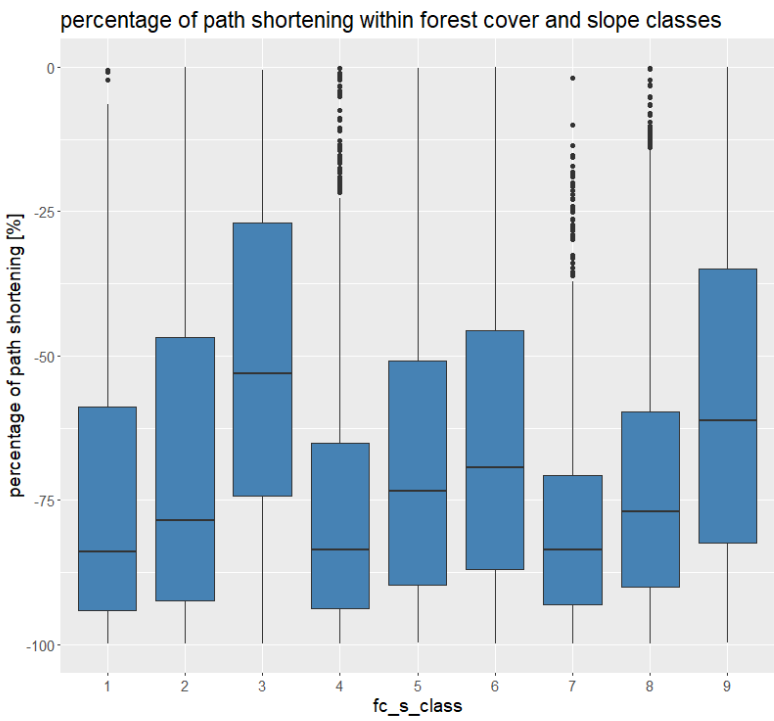


Figure 17: Boxplot for the percentage of path shortening within the 9 forest cover and slope classes.

3.4.3. Path blockage with forest cover and slope angle

Analysis of the percentage of fire paths blocked within the research areas showed, that generally a higher number of paths was stopped within research areas of lower degree of forest cover compared to research areas with a higher degree of forest cover. Research areas with a degree of forest cover of about 10-40 % had a mean of percentage of fire paths blocked within the research areas of 82 %. This compared to research areas with a degree of forest cover of about 70-100 percent, where the mean of the percentage of fire paths blocked was 52 percent (Table 10). Research areas with a degree of forest cover of about 40–70 % having a mean of 72 % of the fire paths blocked, were not significantly different to research areas with a degree of forest cover of 10-40 % (Welchs test: 10-40 % (mean = 82.51, sd = 23.24) and 40-70 % (mean = 72.56, sd = 23.24); $t = 1.8$, $p = 0.076$). On the other hand, research areas with a degree of forest cover of 40-70 % were significantly different to research areas with a forest cover degree of 70 - 100 % (40-70 % (mean= 72.56, sd = 23.24) and 70 - 100 % (mean = 52.52, sd = 28.9); $t = 2.94$, $p = 0.0047$). Through an increase in the degree of forest cover from 10-40 % to 70-100 %, a decrease in fire paths stopped of 30 percent was observed.

Table 10: Descriptive statistics for the percentage of fire paths blocked within the 90 research areas according to the three forest cover classes and for the slope classes.

Slope	***Forest cover class***		
	10-40 %	*40-70 %*	*70-100 %*
9-41.5°	median: 88.14 mean: 82.51 sd: 23.24	median: 78.92 mean: 72.56 sd: 23.24	median: 57.03 mean: 52.52 sd: 28.9

An increase in slope angle of the research areas leads on average, to an observed increase in the percentage of fire paths blocked. For research areas where the mean slope ranged between 9-20.1° the mean percentage of fire paths blocked laid at 51 %, whereas in research areas with a mean slope angle of 30.14-41.5° the mean laid at 80 % (Table 11). An increase in slope from 9-20.1° to 30.14-41.5° therefore shows an average increase in the mean percentage of fire paths blocked within the research areas of about 29 percent. The percentages of fire paths blocked from slope classes 9-20.1 and 20.1-30.14 are significantly different from each other (Welchs test: 9-20.1° (mean = 51.56, sd = 31.4) and 20.1-30.14° (mean = 76.04, sd = 15.93); $t = -3.83$ and $p = 0.0004$). This in contrast to slope classes of 20.1 - 30.14° and 30.14–41.5 ° which showed not to be significantly different (Welch's test: 20.1-30.14° (mean 76.04, sd = 15.93) and 30.14-41.5 (mean = 80.25, sd = 22.18); $t = -0.83$, $p = 0.406$).

Table 11: Descriptive statistics for the percentage of fire paths blocked within the 90 research areas according to the three slope classes and for all forest cover classes.

Forest cover	***Slope class*** *9-20.1°*	*20.1-30.14°*	*30.14-41.5°*
10-100 %	median: 61.06 mean: 51.56 sd: 31.14	median: 78.97 mean: 76.04 sd: 15.93	median: 89.58 mean: 80.25 sd: 22.18

Overall, the highest percentage of fire paths blocked within the research areas was observed in research areas with a degree of forest cover between 10-40 % and a steep average slope of 30.14-41.5 ° (mean = 96.62, sd = 2.86) (Table 12; Figure 18). On the contrary, research areas with a degree of forest cover of about 70-100 % and a mean research area slope of about 9-20.1 ° showed the lowest percentage of paths blocked within the research areas (mean = 31.58, sd=30.34). This means, that generally with an increasing slope and a decreasing degree of forest cover, the percentage of fire paths blocked increases.

Table 12: Descriptive statistics for the percentage of blocked fire paths within the research areas, according to the 9 classes based on forest cover and slope angle (class numbers in blue).

Slope class	***Forest cover class*** *10-40 %*	*40-70 %*	*70-100 %*
9-20.1°	1 Median: 64.01 Mean: 65.95 Sd: 22.78 N: 659.5	2 Median: 70.44 Mean: 57.14 Sd: 31.25 N: 571.4	3 Median: 32.74 Mean: 31.58 Sd: 30.34 N: 315.8
20.1-30.14°	4 Median: 85.1 Mean: 84.96 Sd: 8.68 N: 849.6	5 Median: 77.65 Mean: 77.9 Sd: 13.41 N: 778.9	6 Median: 69.18 Mean: 65.25 Sd: 18.46 N: 652.5
30.14-41.5°	7 Median: 97.6 Mean: 96.62 Sd: 2.86 N: 966.2	8 Median: 81.86 Mean: 83.77 Sd: 10.68 N: 753.9	9 Median: 69.06 Mean: 60.72 Sd: 26.22 N: 607.2

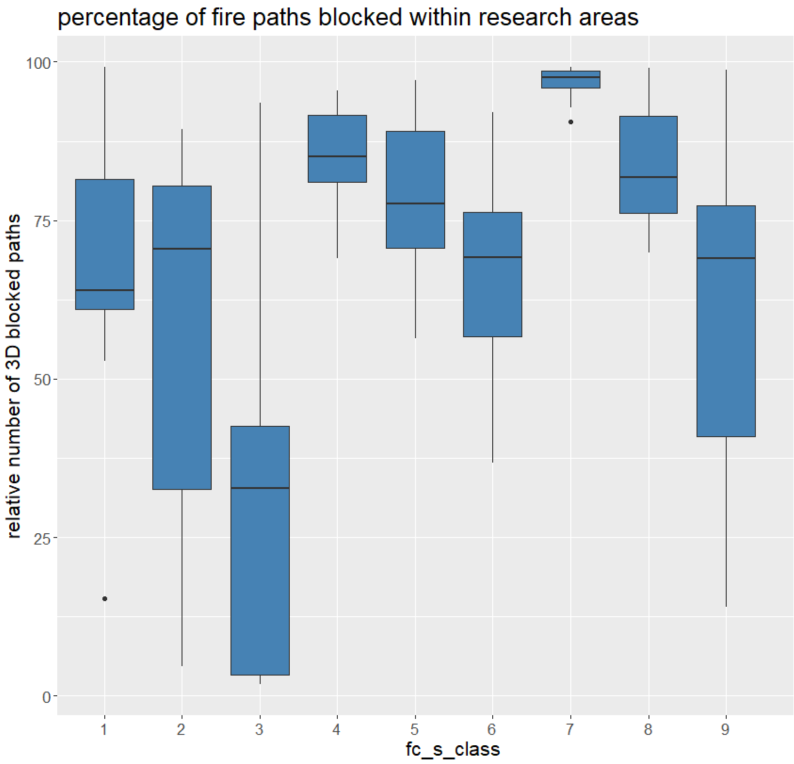


Figure 18: Boxplot for the percentage of blocked fire paths within the 9 forest cover and slope classes.

3.4.4. Influence of fragmentation on fire path length

To analyse the effect of fragmentation on the fire path length, both calculated and analysed metrics of the research areas are here brought together. Correlations of each of the metrics to the relative blocked path lengths were calculated, to measure the relationship (see Appendix D, Figure D1-Figure D8). The results indicate that the degree of forest cover (lsm_c_pland) has a moderate positive relationship with the relative path length ($r= 0.550$, $p < .001$). Metrics of edge density (lsm_l_ed), patch density (lsm_c_pd), and number of patches (lsm_l_np) showed a highly significant moderate relationship to the percentage of path shortening ($p < .001$) Furthermore the correlations of lsm_l_ed, lsm_c_pd and lsm_l_np show a negative relationship to the relative path length. The metric of contagion (lsm_l_contag) showed a moderate significant correlation to the relative path length ($r = 0.301$, $p < .01$), as well as the mean of patch area (lsm_c_area_mn, $r = 0.257$, $p < .01$). For the metric of Shannon's diversity index (lsm_l_shdi) a negative significant relationship was observed with $r = -0.268$, $p < .01$. No significant relationship was apparent for the metric of largest patch index (lsm_l_lpi) at a significance level of 0.05 ($r= 0.178$), with the relative blocked path lengths.

Table 13: Pearson's correlation coefficients (r) and the amount of explained variation (R^2) of the 8 fragmentation metrics, to the relative blocked fire path lengths within the research areas. Levels of significance are represented with the significance codes (*** = p-value [0, 0.001]; ** = p-value [0.001, 0.01]; * = p-value [0.01, 0.05] = p-value [0.05, 0.1]).

	lsm_l_ed	lsm_c_pd	lsm_c_pland	lsm_l_np	lsm_c_area_mn	lsm_l_shdi	lsm_l_lpi	lsm_l_contag
r	-0.416 ***	-0.433 ***	0.550 ***	-0.387 ***	0.257 *	-0.268 *	0.178 _	0.301 **
R^2	0.152 ***	0.212 ***	0.305 ***	0.156 ***	0.086 **	0.08 **	0.025 _	0.395 **

The amount of variation which can be explained when fitting a linear regression model for each of the fragmentation metrics to the relative blocked path lengths, was highest at a level of significance of $p < .001$ for the metric of percentage of landscape (lsm_c_pland, $R^2 = 0.31$, $p < .001$,) (Figure 19). It was found that lsm_l_contag predicted at a significance level of $p < .01$ about 39.5 % percent of the variation in the relative lengths of the blocked fire paths. About 24 percent of the variation of the relative blocked path lengths can be explained through the linear regression model for the patch density (lsm_c_pd, $p < .001$, $R^2 = 0.21$), 15% through the edge density (lsm_l_ed, $R^2 = 0.15$, $p < .001$,) and 16 % with the number of patches (lsm_l_np, $R^2 = 0.16$, $p < .001$,). Additional fragmentation metrics, which can be seen in Table 13, could only explain small parts of the variation in relative blocked path lengths. The metric of largest patch index showed to have no significant influence on the relative lengths of blocked fire paths.

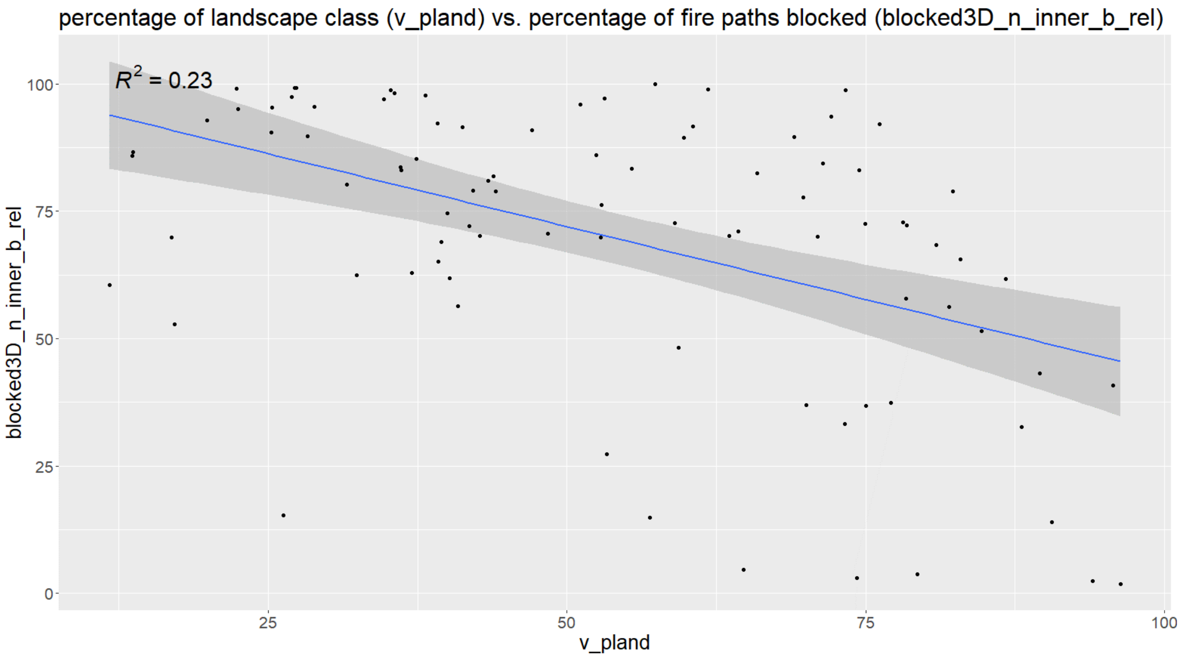


Figure 19: Linear regression for the metric of percentage of landscape to the percentage of fire paths blocked.

3.4.5. Influence of fragmentation on blocked number of fire paths

Effects of fragmentation on fire spread behaviour were also analysed in terms of the percentage of fire paths blocked within the research areas. Calculated correlations for each of the fragmentation metrics to the percentage of fire paths blocked within the research areas showed that the strongest relationship could be observed for the metric of edge density (r= 0.535, p < .0001). Moderate correlations were observed for the metrics of percentage of landscape class(forest, lsm_c_pland, r = -0.489, p < .001), contagion (lsm_l_contag, r = -0.473, p < .0001), Shannons diversity index (lsm_l_shdi, r = 0.434, p < .001) and mean of patch area (lsm_c_area_mn, r = -0.460, p< .001). Less significant correlations were for the number of patches (lsm_l_np r=0.262, p< .05) and largest patch index (lsm_l_lpi r=-0.336, p < .05) observed. No significant correlation was for the patch density (lsm_l_pd, r = 0.199, p > .05) with the number of blocked fire paths discovered (Table 14 and Appendix D,Figure D9-Figure D16).

Table 14: Pearson's correlation coefficients (r) and the amount of explained variation (R^2) of the 8 fragmentation metrics, to the percentage of fire paths blocked within the research areas. Levels of significance are represented with the significance codes (*** = p-value [0, 0.001]; ** = p-value [0.001, 0.01]; * = p-value [0.01, 0.05] = p-value [0.05, 0.1]).

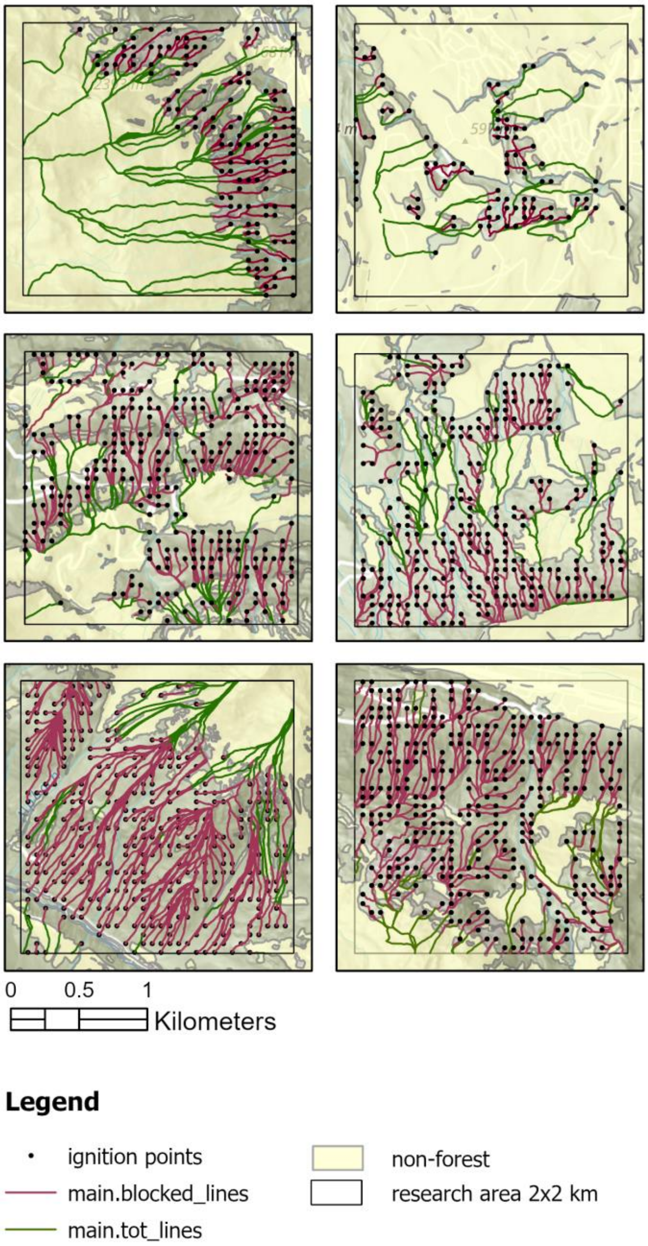
	lsm_l_ed	lsm_c_pd	lsm_c_pland	lsm_l_np	lsm_c_area_mn	lsm_l_shdi	lsm_l_lpi	lsm_l_contag
r	0.535	0.199	-0.489	0.262	-0.460	0.434	-0.366	-0.473
	***	.	***	“	***	***	**	***
R^2	0.27	0.038	0.23	0.065	0.218	0.18	0.11	0.22
	***	-	***	*	***	***	**	***

With the fitting of a linear regression model for each of the fragmentation metrics it could be seen that with the metric of edge density, the highest variation in the number of fire paths blocked within the research areas could be explained (lsm_l_ed, p < .001, R^2 = 0.27) (. Of similar range for the explanation of the variation in the number of blocked path lengths were also the metrics of percentage of landscape class (forest, lsm_c_pland, p < .001, R^2 = 0.23), contagion (lsm_l_contag, p < .001, R^2 = 0.22), Shannons diversity index (lsm_l_shdi ,p < .001, R^2 = 0.189) and mean of patch area (lsm_c_area_mn, p < .001, R^2 = 0.218). Patch density did show to not be able to explain the variability in the number of blocked fire paths (Table 14).

3.4.6. Examples of fragmentation and fire behaviour

For 6 research areas as already presented in Figure 8, characteristics of the fire spread behaviour are calculated with three different levels of forest cover degree and the key landscape fragmentation metrics (Figure 20). In the tables, the calculated fire spread behaviour characteristics are the percentage of fire paths blocked within the respective research area, the relative length of the blocked paths and the percentage of path shortening.

For this example of comparison, it was observed that in general the research areas having a higher degree of fragmentation (left column), showed a higher percentage of fire paths blocked within the research areas. Generally, over the three levels of degree of forest cover an increase in the percentage of fire paths blocked was observed, which contrasts with the results in section 3.4.3, but might be an effect of the sample selection. Effects of slope were not controlled in this example comparsion. For the percentage of shortening of 3D blocked fire paths, a general decrease in the percentage of path shortening was observed from areas with a lower degree of forest cover, to research areas with a higher degree of forest cover. This is connected to the behaviour of the relative median path lengths of 3D blocked fire paths, which show an increase with the degree of forest cover and correspond with the observations made in sections 3.4.2 and 3.4.4.



	research area nr. 238	research area nr. 466
mertic	value	value
lsm_l_ed	145.26	78.0
lsm_c_pd	24.75	10.5
lsm_c_pland	16.92	17.15
percentage of fire paths blocked	69.8 %	52.87 %
relative blocked path length	3.98 %	11.17 %
percentage of path shortening	-96.01 %	- 88.83 %

	research area nr. 195	research area nr. 137
mertic	value	value
lsm_l_ed	146.38	88.4
lsm_c_pd	12	4.25
lsm_c_pland	59.0	59.3
percentage of fire paths blocked	72.7 %	48.2 %
relative blocked path length	38.1 %	11.6 %
percentage of path shortening	-61.9 %	-88.4 %

	research area nr. 13	research area nr. 164
mertic	value	value
lsm_l_ed	105.4	74.33
lsm_c_pd	11.25	2.5
lsm_c_pland	74.4	74.98
percentage of fire paths blocked	82.9 %	72.5 %
relative blocked path length	49.9 %	37.8 %
percentage of path shortening	-50.1 %	-62.1 %

Figure 20: Fire path characteristics for 6 research areas, with contrasting degrees of forest cover (lsm_c_pland) from top to bottom. The 3D blocked paths within the research areas (red) and total possible path lengths (green) within the 2x2 research areas are visible. In the table the characteristics of the relative number of blocked paths within each research area, the relative medium length of 3D blocked fire paths and their inverse, the percentage of median 3D path shortening are visible as used in the linear regression models, in addition to the essential landscape metrics. Generally, research areas on the left column are more fragmented.

4. Discussion

Within the modeling approach of this thesis, it is assessed whether fire spread behaviour is highly influenced by the horizontal connectivity of burnable landscape elements and slope. Interruptions of continuous forest through fragmentation may alter fire behaviour, which has for example been observed in studies of Duguy et al. (2007), Lloret et al. (2002) and Ryu et al. (2007). The identification of the key metrics, describing landscape fragmentation allowed to test, whether effects of landscape fragmentation are relevant for fire spread behaviour, represented by a vector approach with resulting fire path lengths and the relative number of fire paths blocked. For the presented research here, the degree of abstraction is high and differentiation between different types of forest (i.e. dense vs. open) was not made. The comparison to more detailed research which for example took into consideration land cover types and weather information, had to be made carefully. Within the following sections the results are discussed and put into context to each of the hypotheses, together with a critical evaluation of the methodology.

4.1. Fragmentation metrics to describe fire behaviour

For the characterization of landscape fragmentation, one metric is often not enough, but several different ones are used to cover all aspects of landscape composition, configuration and fragmentation (Riitters et al., 1995). Within the literature review, a set of possible metrics in the context of the analysis of fragmentation with fire behaviour, were selected. From these, the 8 most abundant metrics (section 3.1) showed to be often brought into context when analysing effects of landscape fragmentation on fire spread and fire behaviour. For the calculated metrics a mutual influence is apparent, which had been observed by Hargis et al. (1998). Under the condition of a constant research area extent, it can for example be observed that through a higher degree of forest cover (lsm_c_pland), the cell adjacencies expressed through the metric of contagion (lsm _l_contag), show a u-shaped behaviour with lowest contagion values at a degree of forest cover at around 50 percent. This is based on the underlying theory for the contagion metric, showing lowest adjacency values in a landscape being organized like a chessboard. Shannon's diversity index, evaluating patch richness within the landscape, showed an inverted u-shaped curve with its highest values at around 50 percent and is therefore contrary in its behaviour to the contagion metric. The curve from the Shannon's diversity index follows the observed exact line, as the metric is influenced by the research area selection. With the division of the research areas and assignment of 30 research areas to each forest cover class the observed graph originates. This based on the fact, that the metric of Shannon's diversity index (lsm_l_shdi) does not take into account any spatial distribution of individual patches (Dušek & Popelková, 2017). Research areas with the same degree of forest cover can under spatial different dispersion have the same Shannon's diversity index. The behaviour of the Shannon's diversity index (lsm_l_shdi) and contagion (lsm_l_contag) implies small mean patch areas (lsm_l_area_mn), for low contagion indices and high Shannon's diversity indices. This as within the analysis of metrics correlations, the positive relationship between the mean patch area (lsm_l_area_mn) and the contagion index (lsm_l_contag) showed to be strong, with a R^2 of 0.5. The observed behaviour of a decreasing number of patches (lsm_l_np) and patch density (lsm_c_pd) leads to an increase in forest cover (lsm_c_pland) area strongly linked to the cell adjacency theory (lsm_l_contag).When low values of contagion are present, edge densities are generally high, which showed the strong correlation coefficient of r = -0.646. The same observation was made by Hargis et al. (1998), where the understanding of the behaviour of several fragmentation metrics to describe landscape fragmentation, based on artificial and controlled landscapes was the key interest. Furthermore within my research, with an increase in the density of patches (lsm_c_pd), the edge density increases and can explain about 40 % of the variation (section 3.2., Figure 10).

For the observed behaviour of edge and patch density as well as the mean patch size, Lloret et al. (2002) found corresponding results. The study conducted on the Iberian Peninsula in Spain showed that with lower values of patch and edge density and a mean higher patch size, a decrease in fragmentation and an increase in heterogeneity could be observed. Same effects were also observed in studies of Sabr et al. (2016), which are in agreement with the research area examples seen in Figure 8. Through the observed behaviour of the fragmentation metrics it can be concluded, that using only metrics of edge density, patch density and the degree of forest cover (lsm_c_pland), would not be enough to represent the influence of fragmentation on the fire spread behaviour, which is further discussed in section 4.3.

Generally, caution must be paid to the absolute calculated values of landscape metrics, as with the underlaying 2x2 m raster of landscape classification no sharp borders are represented. For example edge lengths are longer than they would be when represented in vector data, as raster's form stairsteps (McGarigal & Marks, 1995). Nevertheless, variations in absolute values of landscape metrics due to the high resolution of the landscape classification data are expected to be minimal.

4.2. Methodological approach for fire ignition

The three different methods for setting of the ignition points showed that no significant difference could be observed between the methods (section 3.3). Nevertheless, for the percentage of fire paths blocked a difference between the variants was observed. Compared to the original variant, where ignition points were set within the forest in spacing of 65 m, the median value of the relative path length for the variant with 50 percent of the ignition points at the low-lying position, was higher. This also compared to the variant where 50 percent of the original ignition points were chosen randomly. The observed difference can be explained through a higher probability of ignitions being blocked within the research area through non-forested landscape fragments before reaching the research boundary, when the ignition took place in a low-lying location of the research area (variant 50 percent lower altitude). Having the least divergence from the original version of ignition point setting, the method of randomly selecting 50 percent of the ignition points performed best. With this variant, it was under almost the same median values possible, to calculate the fire paths under considerable shorter time and produce comparable results.

As the location of an ignition might be of importance for analysing fire spread behaviour the method of setting the ignitions could be significant (Massada et al., 2011). Setting the ignitions based on the 65 x 65 m grid, the applied approach is not totally random, but does not represent a non-random distribution of ignitions either. Both human induced and natural ignitions for example through lightning were observed to follow a non random distribution (Calviño-Cancela et al., 2017). That a random distribution of ignition locations for fire spread modelling could be of concern, showed Massada et al. (2011). In this research random distributions of the ignitions lead under non-wind conditions to significantly larger fires, than a non-random distribution of the ignition locations. Thereby no information was given on the lengths from the point of ignition to the fire front, which could allow a comparison to our vector-based modelling approach. As the approach of setting the ignition locations within this thesis is neither totally random nor no-random, an effect on fire path characteristics is possible, as observed in the research of Massada et al. (2011). Nevertheless, it is expected that the effect of the random ignition location on the fire size is particularly influenced by the surrounding spatial configuration of fuels and therefore not relevant for this conducted research. With the chosen grid-based preselection of ignition points and a chosen distance between ignitions of 65 meters, a certain degree of non-randomness is given.

4.3. Influence of fragmentation on fire spread

The analysis of the calculated fire paths showed that through landscape fragmentation about 63 % of the fire paths could be stopped before reaching the boundary of the research area and that the median length of the fire paths was reduced about 73 percent (section 3.4.1). As expected, the percentage of forest cover, representing the continuity of the fuel did show to have an important influence on fire behaviour. The degree of forest cover is of significant influence in shortening of the fire paths, whereas the biggest reduction on fire paths length was found in research areas with a low degree of forest cover (10-40 %). Effects of slope were observed to be not as strong as the degree of forest cover, but were significantly different between steepest and shallowest slopes, where the highest percentage of path shortening was observed in slopes between 20.1-30.14 °.When analysing the landscape fragmentation effect on the percentage of path shortenings, respective the fire path lengths, it was observed within the linear regressions that the metric of contagion and the percentage of landscape can explain about 39.5 % and 30.5 % of the variation of the fire path lengths. The explanation through a linear regression model was weaker for metrics of edge density, patch density and the number of patches, but still significant at a significance level of 0.05. As observed in section 3.2, higher degrees of forest cover lead to a decrease in edge density, which can among other metrics indicate a lower degree of fragmentation, leading to longer fire path lengths. That higher edge densities are associate with higher degrees of fragmentation and a reduction in fire spread is shown in research of Lloret et al. (2002). This research conducted within the Mediterranean ecozone did also find a relationship between a higher patch density and lower mean patch sizes representing more fragmented landscapes, having a positive effect on the reduction of forest fire spread danger. That the strongly correlated patch density to the edge density was, among other landscape metrics, of significant influence on the burnt area has been observed by Ryu et al. (2007) as well.

For the number of fire paths blocked it was observed that the percentage of forest cover was of significant influence. Like the fire path lengths, forest cover degrees of 10-40 % did show the strongest influence on the percentage of fire paths blocked. Slope generally showed a trend of an increased percentage of fire paths blocked with an increase in mean slope angle of research areas. The highest percentages of paths blocked were observed in very steep terrain with a low degree of forest cover, whereas the lowest percentages of fire paths blocked were observed in shallow research areas with a high degree of forest cover. These results might suggest that fragmentation effects on steeper slopes are more pronounced than on shallower slopes, leading to a higher percentage of fire paths blocked. Under similar degrees of forest cover, the landscape fragmentation might be varying along with the slope classes. Research from Zhang et al. (2018) conducted on a Chinese basin, suggests in this context that gentle landscapes are normally dominated by human factors controlling fragmentation, whereas highly-undulating areas were more often controlled through natural effects of fragmentation. Artificially created fragmentation might then possibly reduce for example edge lengths through creation of straight lines and therefore reduce edge density, being an important indicator of fragmentation along with other metrics as seen from the analysis. An other factor which is likely to reduce edge densities is the detected increase of forest cover, especially in steeper areas above 30° in the Alps (Bebi et al., 2016). With the decrease in edge density a decrease in fragmentation and an increase in fuel connectivity can be expected. This might then favour longer fire path lengths and less blocked fire paths, as observed within this thesis. That an increase in edge density leads to an observed decrease in fire proneness, is in accordance with observations of Lloret et al. (2002) and research in holm oak stands (Azevedo et al., 2013). Both of those studies were conducted within the Mediterranean area, where fire is an integral part of landscape. For temperate forests of Europe, no studies could be found that specifically analyse the effects of forest fragmentation of fire spread behaviour using landscape metrics.

A contrast to our results, is a synthesis of Driscoll et al. (2021), who found, that with an increase in edge density more fires could be observed in most cases (13 out of 17). For the interpretation of those results it has to be taken into account that studies where a higher degree of edge density leads to an increase in forest fires, were most often conducted in Central or Southern America, within the tropical forests (Armenteras et al., 2013; Silva Junior et al., 2018). In these moist environments most often not climatic and vegetational factors, but rather socioeconomic factors are the cause for wildfires (Silva Junior et al., 2018). In a broader context of fragmentation the synthesis of Driscoll et al. (2021) showed, that whether fragmentation traits lead to an increase or decrease of fire was significantly related to the ecosystem type and ecoregion. This would underline the results, whereby the fire spread logarithm is based on assumptions corresponding to central European conditions controlling fire spread behaviour. Landscape patterns are not only observed to influence processes like fire spread but are also key aspects for ecological processes (e.g. (Harper et al., 2005)). It is for example known that edges are key landscape elements for species conservation as well as biodiversity and are in this respect also often created and maintained. Through artificial or natural edge creation the edge conditions can be altered, for example with increased drought, higher fuel loadings and changes to more fire prone vegetation (Harper et al., 2005).

That landscape and fuel characteristics are of influence on the fire behaviour was also shown by a study of Ryu et al. (2007). Metrics of patch density, mean patch size, patch size standard deviation, area weighted mean shape index and Shannon's diversity index were in this study found to be important predictors for fire spread behaviour, controlled by effects of fragmentation. The authors did also observe that not just the spatial landscape pattern influenced the burnt area, but also the fuel pattern, respectively the composition of fuel types. Within spatially more heterogenous fuel conditions and a higher degree of landscape fragmentation, the burnt area was decreased, whereas under more homogenous fuel conditions a decrease in the effect of landscape fragmentation on the burnt area was observed. These results indicate that it might be of importance to create more detailed fuel characteristics maps, compared to the approach taken in this thesis. A higher number of fires was for example observed in denser forests, compared to open forests in the Mediterranean (Lloret et al., 2002). With a more detailed mapping of fuel characteristics, the fire spread behaviour analysis could be extended. This then would not only allow to analyse the effect of fragmentation on the fire behaviour but also the interaction of fragmentation with a variation of fuel type classes.

Finally, it can be observed that metrics of edge density and percentage of landscape class (forest cover) are suitable, to describe the effects of fragmentation on fire spread characteristics, as applied within this thesis. Additionally, the metric of patch density can be a good indicator for the relative blocked path lengths. That patch density did not show a relationship with the percentage of fire paths blocked, was unexpected. This as for example Lloret et al. (2002) observed bigger burnt areas where lower patch densities were present. With a higher degree of patch density, a higher degree of heterogeneity would be expected, which then would increase the percentage of fire paths blocked. From the other five calculated metrics within this thesis, the metric of contagion, largest patch index but also Shannon's diversity index show a high interaction with the degree of forest cover and therefore make an interpretation of the results more difficult. Nevertheless, these additional metrics are helpful for understanding fragmentation and the mutual influence on each other.

4.4. Methodological approach

For the selection of topographically similar research areas with the R:whitebox tool *Geomorphons* (Jasiewicz & Stepinski, 2013), a fundamental comparison of similarity of topography was conducted, based on a reference area. Since through the selection of this reference area the selection of all other areas was highly influenced, in a renewed application of the procedure it would be beneficial to calculate the landscape characteristics with the whitebox tool for a sample of possible reference areas. Based on the results then, a reference area could be chosen on analytical results, based on predefined criteria. Applying this procedure can be a good way, if specific areas are of interest, and additional sample areas should have the same underlaying topographical characteristics. Nevertheless, the procedure for the reduction of research areas was time consuming and high variabilities regarding slope and coupled with the degree of forest cover still occurred. It would have been an option to create artificial landscapes with varying degrees of forest cover, fragmentation and slope to better control the factors which would later be analysed.

With the developed modelling approach, no statements can be made about fire intensities and severities, which are in many fire spread modelling approaches central target variables. Although the aim of this thesis was not to improve or update fire spread models, some aspects within the modelling process could have been specified, to bring the potential fire spread under landscape fragmentation closer to the real conditions. For example the breaching distance, i.e. the distance a fire can cross of non-forested area, considered to be a fire barrier, can be more variable with underlaying varying breaching distances. This as fuel loads and flammability can be very different for landscape classes (Calviño-Cancela et al., 2017; Miller & Urban, 2000; Ryu et al., 2007). In a more dynamic approach of fire spread modelling effects of slope, which were observed to be stronger in steeper areas, could be taken into account (Santoni & Balbi, 1998). Because no climatic parameters were considered in the presented approach of fire spread modelling along slopes in this thesis, a high degree of simplification in the methodology was achieved. As for the fire spread behaviour wind is often described as a driving factor governing direction and distances (Duane et al., 2021; Hély et al., 2010), this could be seen as an additional option for improvement. Nevertheless, the chosen approach allows, to gain a better understanding of the influence of landscape fragmentation on fire spread behaviour.

Furthermore, the statistical analysis for the interaction of the fragmentation metrics with the relative blocked path lengths and the percentage of fire paths blocked, were kept simple. This was due to high multicollinearity between the fragmentation metrics, which did not allow to calculate multiple linear regressions with the scaled fragmentation metrics. As a further development and to better understand which of the metrics could explain a large portion of the variation in the dataset, the application of a principal component analysis could be of interest.

5. Conclusions and future recommendations

The goal of this thesis was to develop and apply a methodology with which the effects of landscape fragmentation on fire spread behaviour can be analysed. With the developed methodology, it was possible to analyse effects of fragmentation and slope on fire spread behaviour. This considering topography and a binary classified landscape as basic information for the analysis. The results indicate that landscape fragmentation has an effect on the fire spread behaviour. Generally, research areas with a higher degree of fragmentation show a higher percentage of fire paths blocked and a higher degree of relative blocked path shortening. Thereby the metric of percentage of landscape class (lsm_c_pland) is of high influence. Also, the metric of edge density is of importance for the relative blocked path lengths as well as the percentage of blocked fire paths. Additionally, the metric of patch density can partially explain the variation in the relative blocked path lengths. Other metrics like contagion, largest patch index and Shannon's diversity index are highly related to the percentage of landscape class (lsm_c_pland). As strong correlations between the metrics were observed, would the use of just one fragmentation metric not be sufficient, to capture all aspects of landscape fragmentation.

The results of this thesis may contribute to fire spread danger analysis. This as forest fire danger should be addressed more closely in forest management but also in aspects of landscape planning, as fuel loads but also the spatial distribution of fuel can be controlled (Ferreira et al., 2015). Under the expected climate changed and the higher expected danger of forest fires, considering spatial arrangement of forest patches and landscape fragmentation could be of great value. Nevertheless, it must be taken into account that the modelling approach has a high degree of abstraction. For example, vegetation characteristics including information about vertical connectivity, inclusion of more than 2 landscape types with varying burn probabilities and all kind of climatic parameters and weather scenarios are missing. Additionally, the fire spread modelling approach is based on a simple vector approach and does not illustrate a spatial fire propagation also incooperating slope parallel fire spread. Therefore, this approach should not be considered as an approach for the prediction of fire spread but may help in the understanding of landscape fragmentation effects, which could be of significant influence for fire spread behaviour.

The results showed that the percentage of fire paths blocked within the research areas were lower in flatter than in steep terrain (Table 12). A potential natural increase of inhomogeneity in the forest structure in steep terrains could be supportive for the reduction of the fire spread potential. For forest fire spread prevention, priority should therefore be given on fragmenting forests in the slope classes between 9-30.14°, especially where high degrees of forest cover are present (70-100%). These recommendations are based on the set class boundaries defined in the methodology of this research. For both the relative path lengths and the percentage of blocked fire paths can be seen that the degree of forest cover is an important factor determining their performance. As just reducing the degree of forest cover to reduce the potential of fire spread could be an undesirable option due to ecological, social and economic considerations, interesting aspects in regard to the analysed fragmentation metrics arise. For example, an increase in edge densities and a reduction of contagion could be targets within a preventive forest fire management planning. As landscape composition and forest structures can be highly variable, should prevention planning focus on an integral landscape approach and be tailored to the desired protection goals.

For the further improvement in the understanding of fire spread danger and adapted landscape and forest management, there is great potential for further research. For increased control of topographical factors like slope but also characteristics of fragmentation within simulation modelling, the use of artificial landscapes could be interesting (e.g. (Hargis et al., 1998), for landcover patterns). This might also help to deepen the understanding of different metrics describing fragmentation and to find thresholds at which effects of fragmentation no longer reduce fire spread.

6. References

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7. List of Figures

8. List of Tables

Appendix A: Characteristics of research areas

Table A1: The characteristics for the 90 research areas with the degree of forest cover [%], slope [°] and the class in which the research area was allocated based on the degree of forest cover and slope.

original .tif number research area	forest cover [%]	slope [°]	class according to forest cover and slope
5	70.9	28.4	6
11	41.8	21.4	5
13	74.5	35.8	9
20	39.2	16.0	1
24	94.0	18.3	3
44	42.1	19.8	2
45	74.3	13.4	3
49	43.4	16.2	2
55	28.3	30.1	4
60	48.4	11.9	2
68	80.9	29.4	6
77	76.2	19.8	3
80	36.1	28.0	4
82	53.1	29.8	5
85	38.2	31.7	7
91	36.2	21.4	4
94	27.4	17.2	1
101	37.0	15.4	1
102	55.4	26.3	5
103	76.1	28.8	6
107	78.1	33.0	9
113	60.5	27.2	5
122	72.1	19.0	3
130	27.0	41.5	7
134	64.4	32.5	8
136	57.3	34.4	8
137	59.3	14.8	2
138	78.4	27.9	6
143	84.7	32.3	9
144	77.1	34.3	9
146	73.2	19.9	3
158	64.8	17.5	2
163	52.4	19.0	2
164	75.0	30.5	9
167	69.8	20.3	6
170	61.8	30.9	8
178	88.0	38.7	9

Original .tif number research araea	forest cover [%]	slope [°]	class according to forest cover and slope
187	41.2	30.6	8
195	59.0	28.7	5
196	44.0	31.5	8
197	19.9	34.4	7
211	35.3	35.5	7
215	53.3	10.0	2
220	75.0	24.2	6
223	82.0	29.1	6
225	32.4	11.3	1
226	39.1	25.0	4
227	73.3	33.2	9
228	52.9	32.3	8
237	89.6	16.1	3
238	16.9	18.9	1
248	35.6	35.8	7
254	52.8	31.2	8
256	13.7	24.3	4
259	34.7	39.0	7
261	59.8	15.6	2
263	43.8	32.4	8
283	27.2	30.1	7
291	26.3	9.8	1
294	51.1	40.1	8
302	40.9	26.7	5
305	95.7	14.1	3
317	40.0	27.4	4
332	63.6	22.5	5
334	28.8	33.7	7
338	69.0	31.9	8
346	82.9	36.4	9
349	42.7	18.3	2
350	31.6	24.5	4
366	96.3	18.7	3
375	40.2	25.3	5
381	22.5	21.1	4
390	11.7	19.8	1
394	65.9	26.2	5
407	37.4	13.9	1
410	79.3	19.0	3
414	90.6	34.7	9
421	71.4	27.7	6
426	82.3	32.1	9
427	86.7	13.1	3

Original .tif number research araea	forest cover [%]	slope [°]	class according to forest cover and slope
434	25.3	27.2	4
445	25.3	30.5	7
465	70.0	22.3	6
466	17.2	10.2	1
468	47.1	24.6	5
486	22.3	34.1	7
499	39.5	26.2	4
507	56.9	12.1	2
511	78.4	29.0	6
521	13.6	14.4	1

Appendix B: References fragmentation metrics

		Study																		Count
Metric	**Metric abbreviation** According to Hasselbarth et al. 2021	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Total area	lsm_c_ca		x							x			x							3
Percentage of landscape class	lsm_c_pland	x	x			x					x					x		x		6
Number of patches	lsm_np	x	x	x		x	x			x	x		x			x		x		10
Mean of patch area	lsm_c_area_mn		x	x	x	x			x	x			x	x	x	x		x		11
Mean core area of patches	lsm_c_core_mn																		x	1
Largest patch index	lsm_l_lpi		x							x	x		x	x						5
Patch density	lsm_c_pd		x						x				x	x	x				x	6
Effective mesh size	lsm_l_mesh										x									1
Total edge	lsm_l_te	x									x		x							3
Edge density	lsm_l_ed			x	x				x	x	x		x		x				x	8
Landscape shape index	lsm_l_lsi									x	x		x							3
Mean shape index	lsm_c_shape_mn												x	x	x					3
Euclidean nearest-neighbour distance	get_nearestneighbour		x										x							2
Mean Euclidean nearest-neighbour distance	lsm_c_enn_mn						x		x				x							3
Interspersion/Juxtaposition patch index	lsm_l_iji										x		x		x					3
Shannon's diversity index	lsm_l_shdi		x						x	x			x	x					x	6
Contagion	lsm_l_contag		x	x	x		x	x	x		x	x	x				x		x	11

1 – Armenteras et al., 2013
2 – Del Martinez Castillo et al., 2015
3 – Gergel & Turner, 2017
4 – Hargis et al., 1998
5 – Hermosilla et al., 2019
6 - Leitão & Ahern, 2002
7 – Li & Reynolds, 1993
8 – Lloret et al., 2002
9 – Mori & Lertzmann, 2011
10 – Kumar et al., 2018
11 – Riiters et al., 1995
12 – Haines-Young & Chopping, 1996
13 – Ryu et al., 2007
14 – Sabr et al., 2016
15 – Silva Junior et al., 2018
16 – Turner et al., 2001
17 – Vogt et al., 2019
18 – Viedma et al., 2006

Figure B1: Identified metrics to describe landscape or forest fragmentation within a literature review. The numbers refer to the respective study.

Appendix C: Fragmentation metrics normality

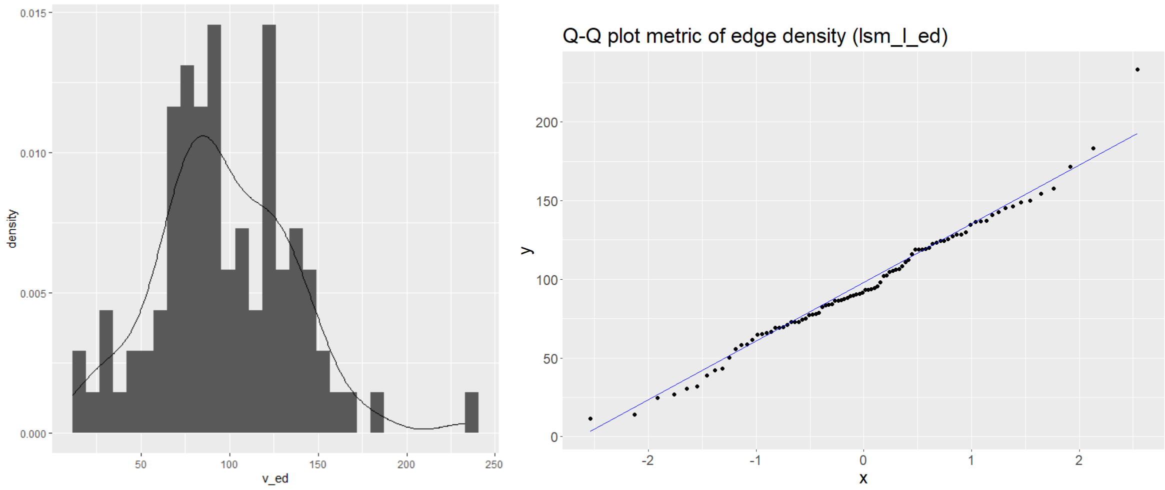

Figure C1: Distribution and density plot for the values of the metric edge density (lsm_l_ed; left) and the Q-Q plot for the same metric (right).

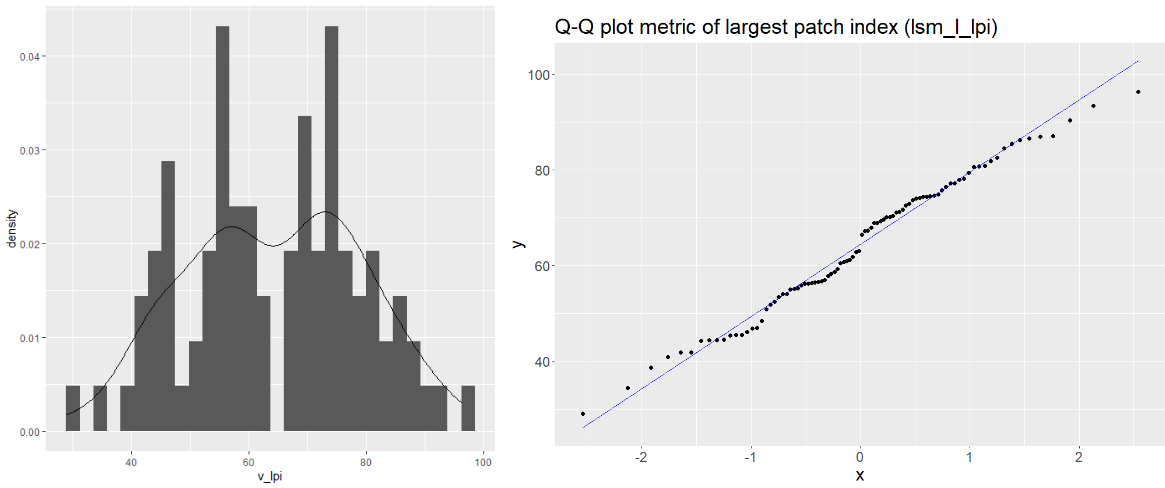

Figure C2: Distribution and density plot for the values of the metric largest patch index (lsm_l_lpi; left) and the Q-Q plot for the same metric (right).

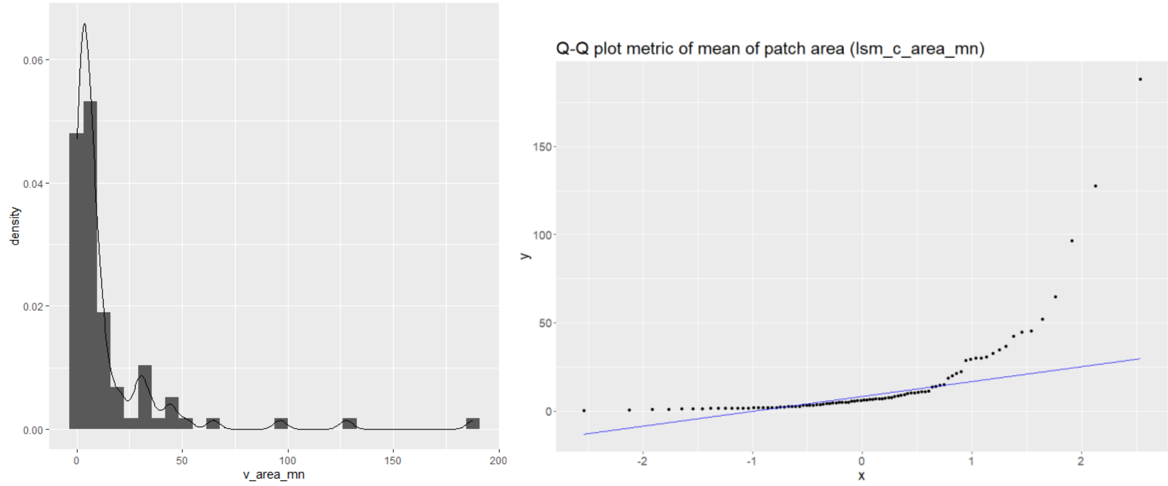

Figure C3: Distribution and density plot for the values of the metric mean of patch area (lsm_c_area_mn; left) and the Q-Q plot for the same metric (right).

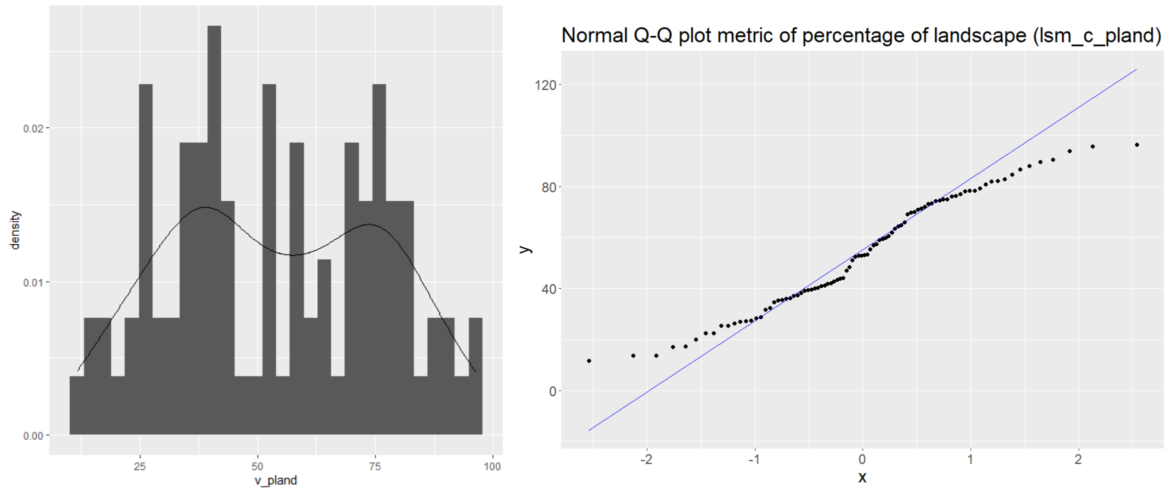

Figure C4: Distribution and density plot for the values of the metric percentage of landscape of class (lsm_c_pland; left) and the Q-Q plot for the same metric (right).

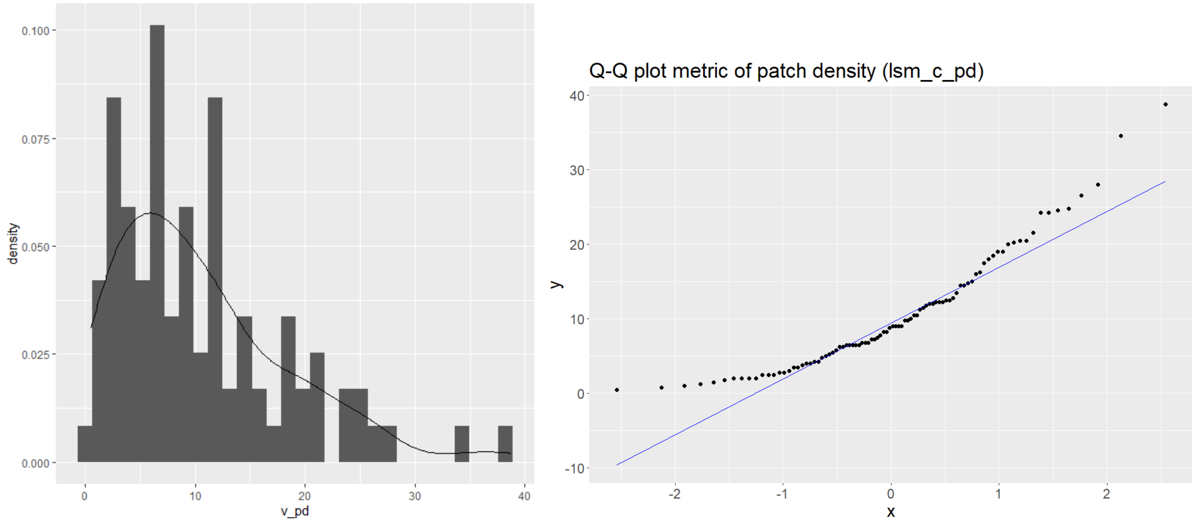

Figure C5: Distribution and density plot for the values of the metric patch density (lsm_c_pd; left) and the Q-Q plot for the same metric (right).

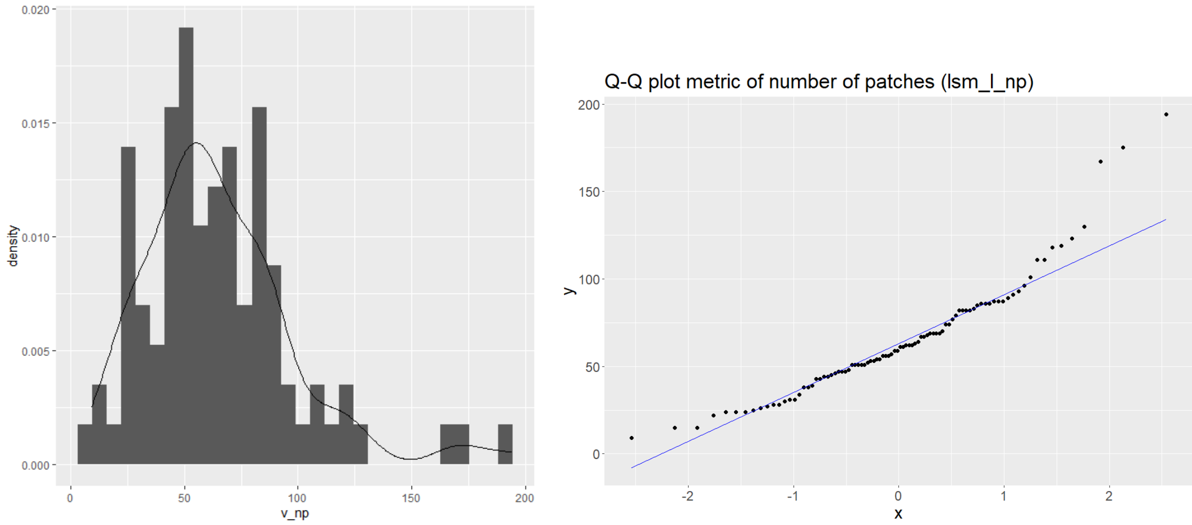

Figure C6: Distribution and density plot for the values of the metric number of patches (lsm_l_np; left) and the Q-Q plot for the same metric (right).

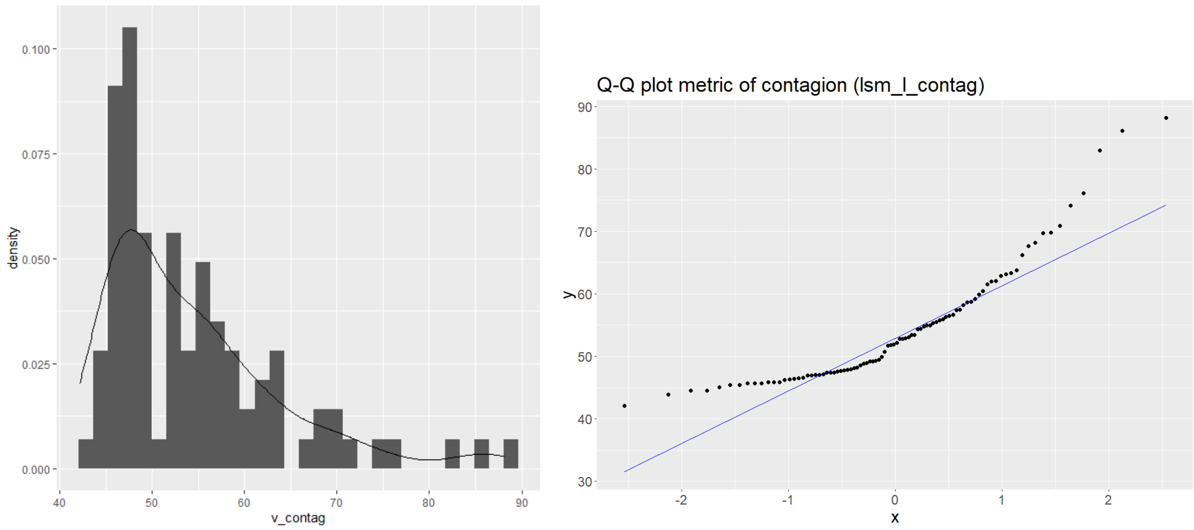

Figure C7: Distribution and density plot for the values of the metric contagion (lsm_l_contag; left) and the Q-Q plot for the same metric (right).

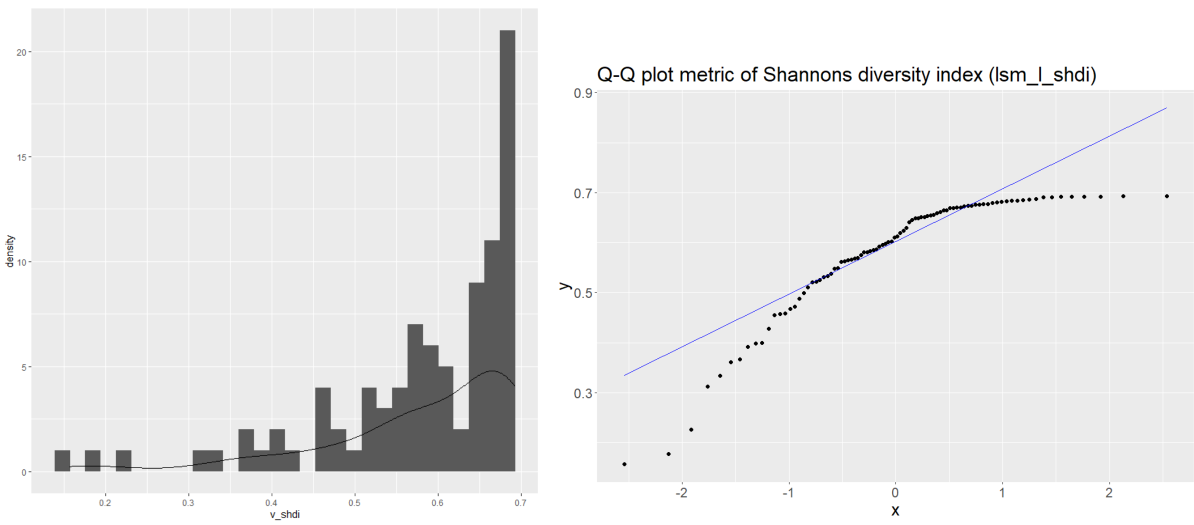

Figure C8: Distribution and density plot for the values of the metric Shannon’s diversity index (lsm_l_shdi; left) and the Q-Q plot for the same metric (right).

Appendix D: Fragmentation effects on fire spread

Linear regressions for the 8 fragmentation metrics to the **relative blocked path lengths**

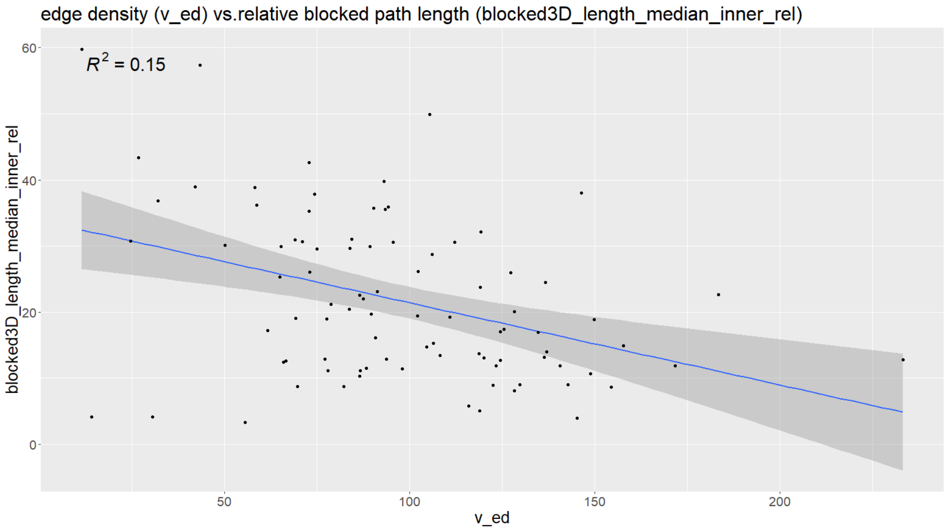

Figure D1: Metric of edge density to the relative blocked path length.

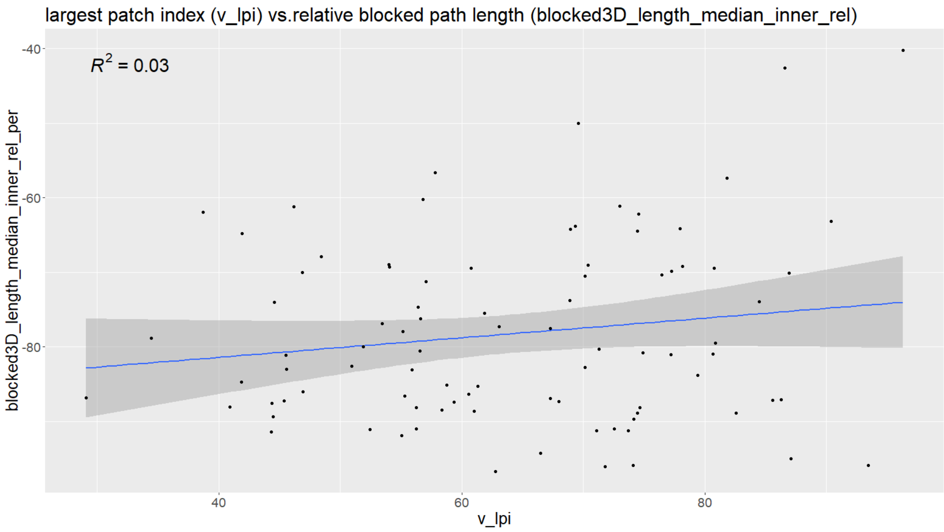

Figure D2: Metric of largest patch index to the relative blocked path length.

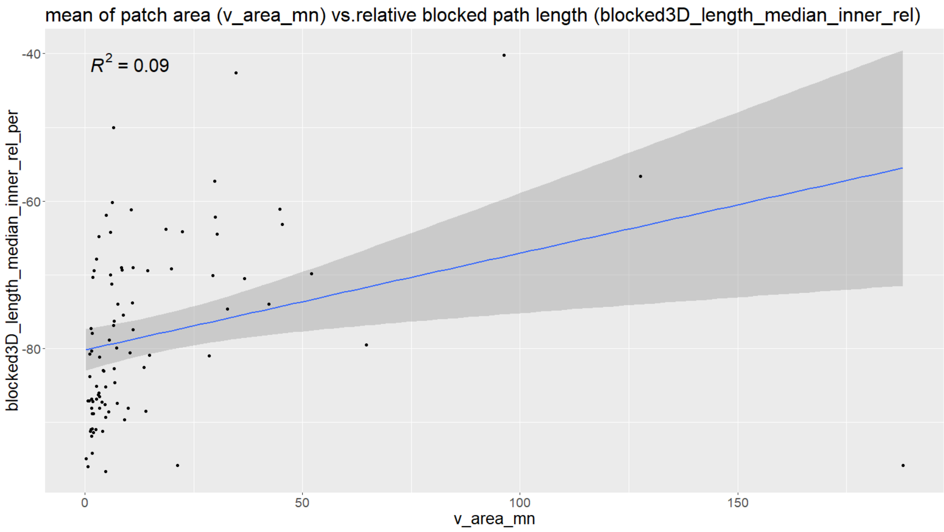

Figure D3: Metric of mean of patch area to the relative blocked path length.

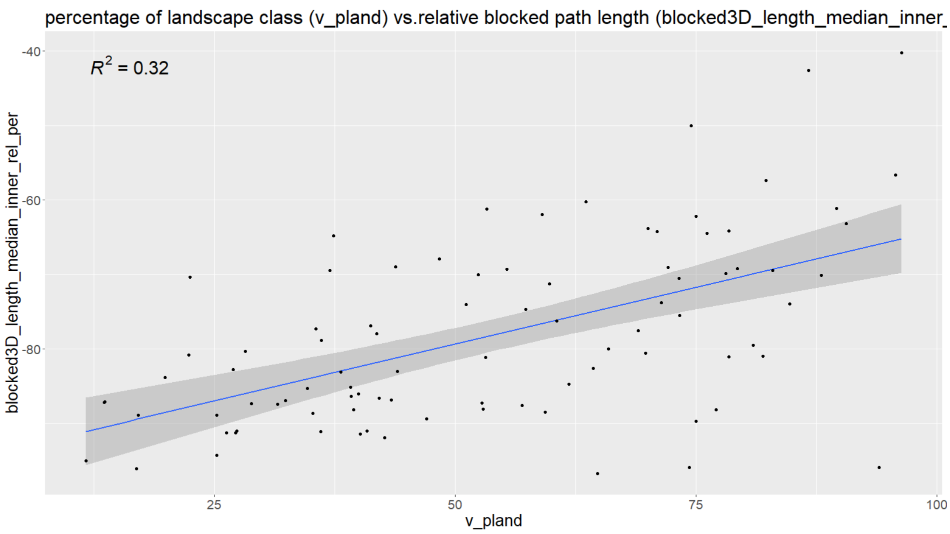

Figure D4: Metric of percentage of landscape to the relative blocked path length.

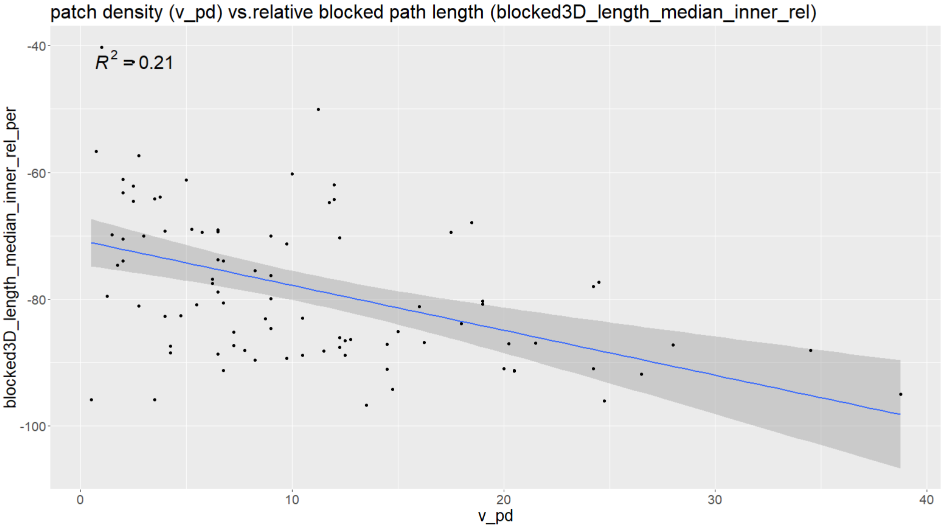

Figure D5: Metric of patch density to the relative blocked path length.

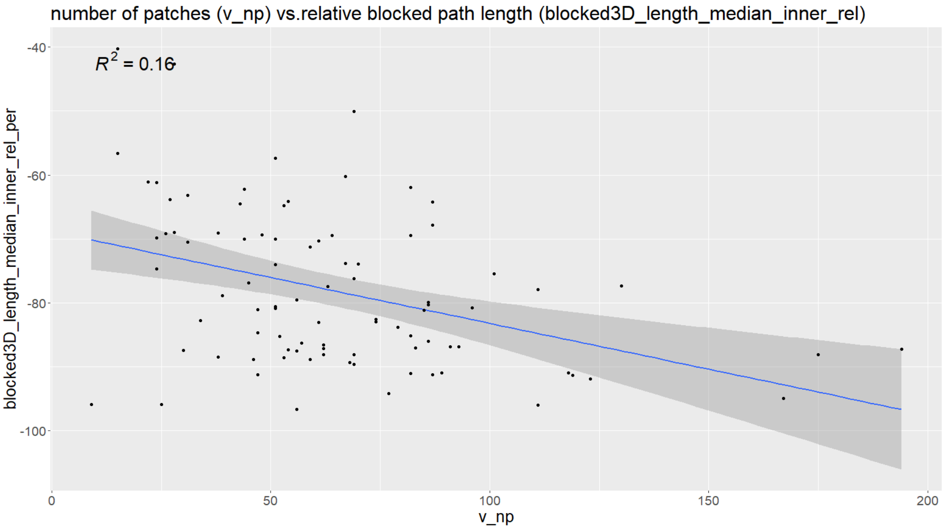

Figure D6: Metric of number of patches to the relative blocked path length.

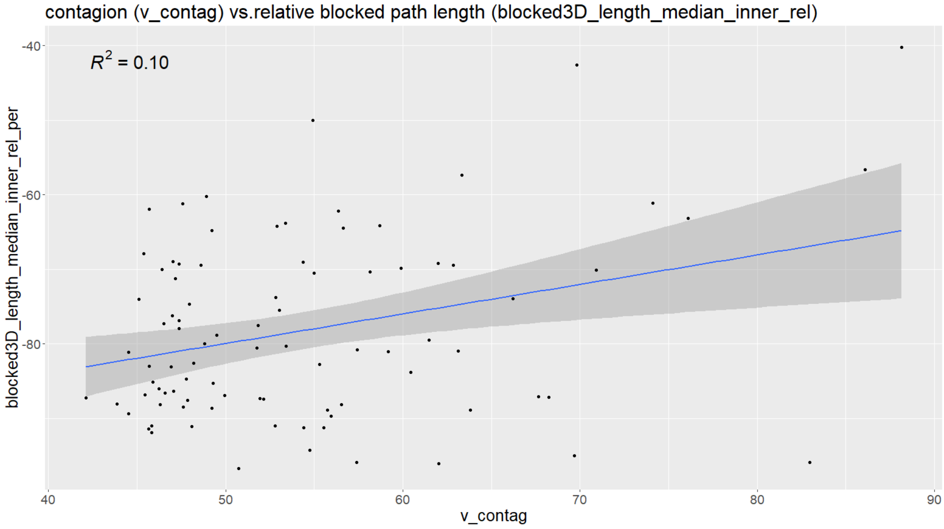

Figure D7: Metric of contagion to the relative blocked path length.

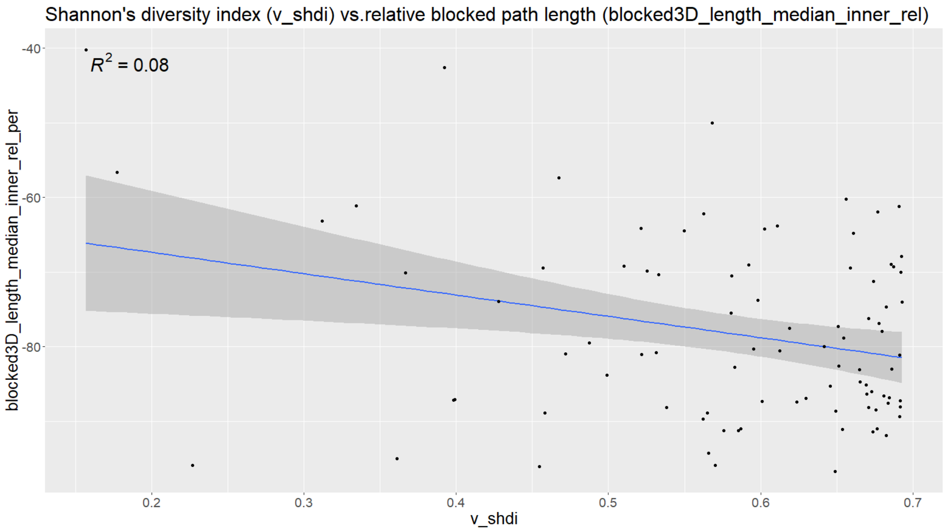

Figure D8: Metric of Shannon's diversity index to the relative blocked path length.

Linear regressions for the 8 fragmentation metrics to the **percentage of fire paths blocked**

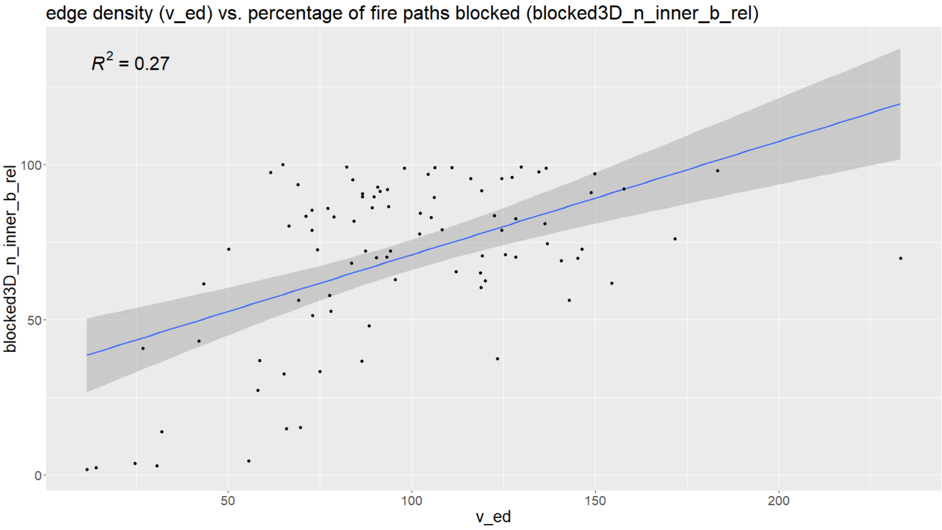

Figure D9: Metric of edge density to the percentage of fire paths blocked.

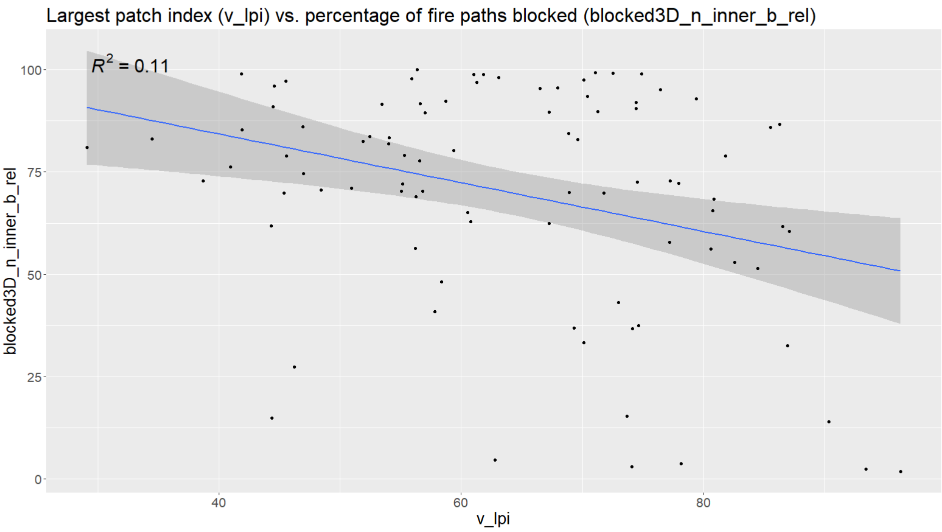

Figure D10: Metric of largest patch index to the percentage of fire paths blocked.

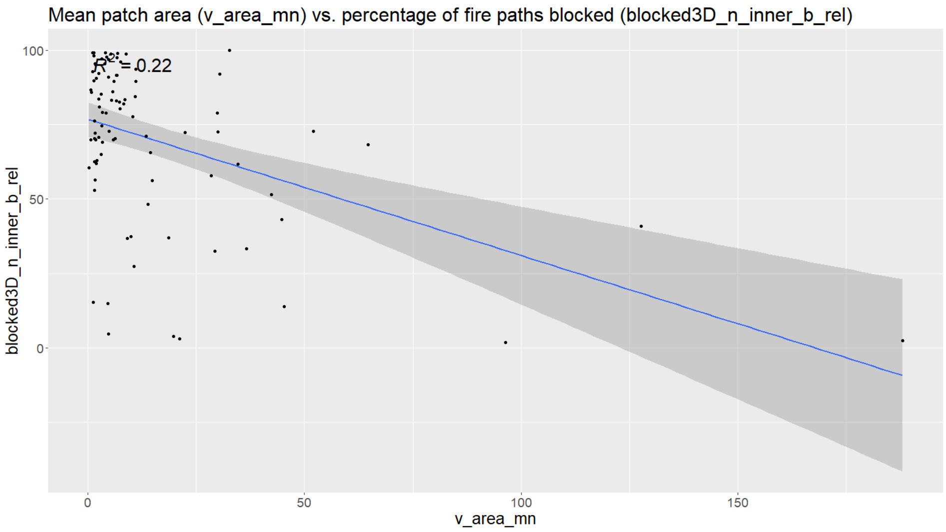

Figure D11: Metric of men of patch area to the percentage of fire paths blocked.

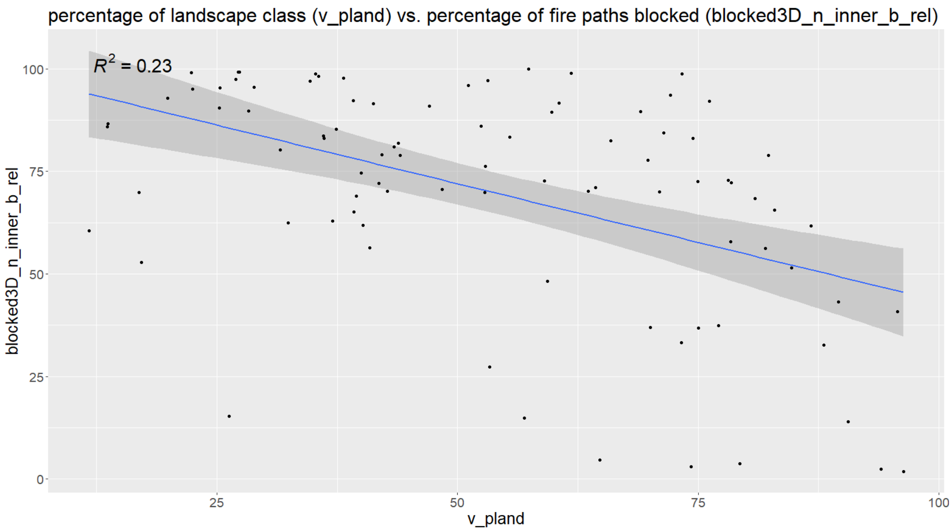

Figure D12: Metric of percentage of landscape to the percentage of fire paths blocked.

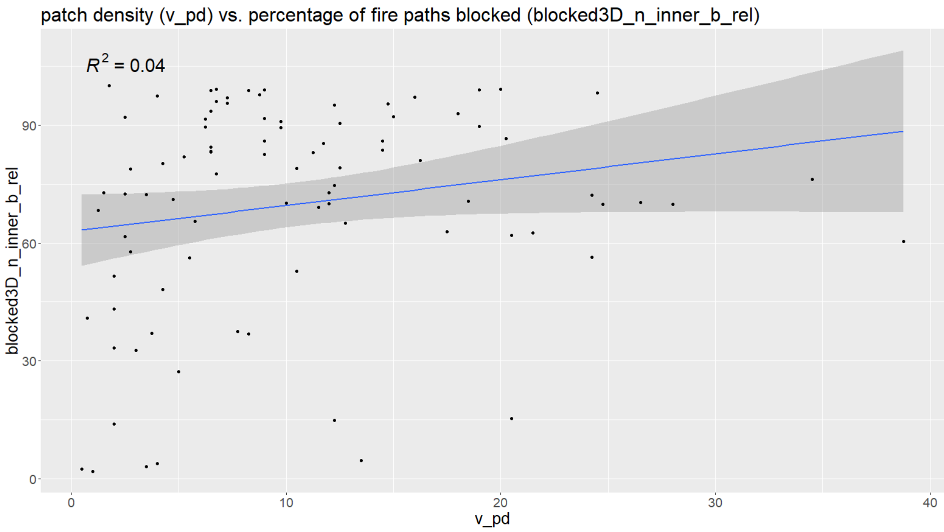

Figure D13: Metric of patch density to the percentage of fire paths blocked.

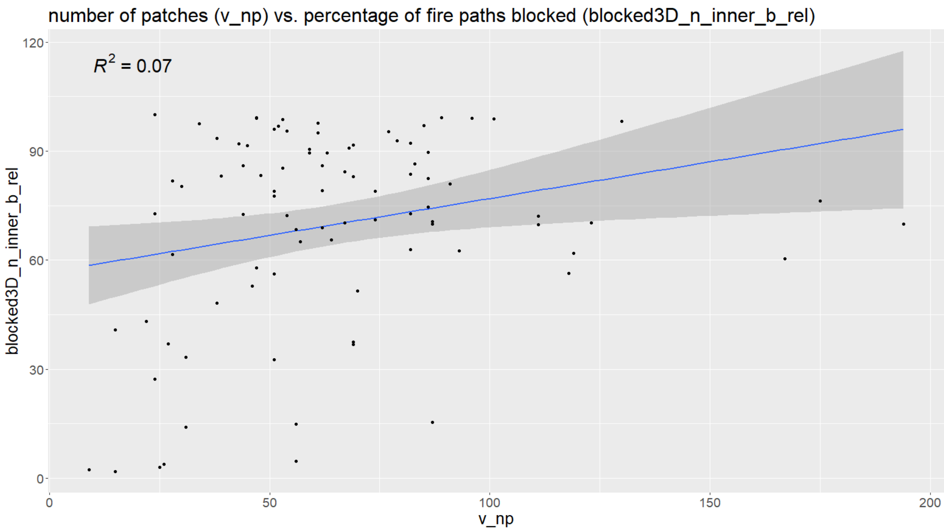

Figure D14: Metric of number of patches to the percentage of fire paths blocked.

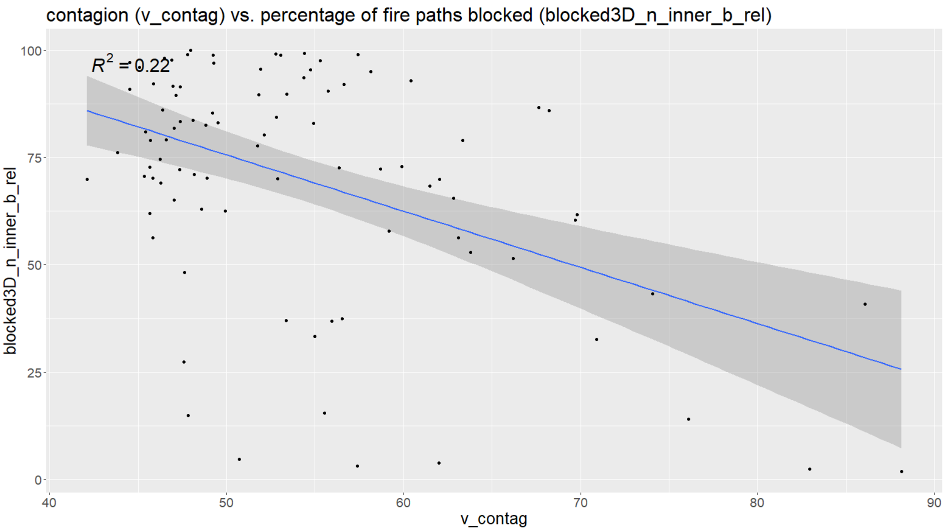

Figure D15: Metric of contagion to the percentage of fire paths blocked.

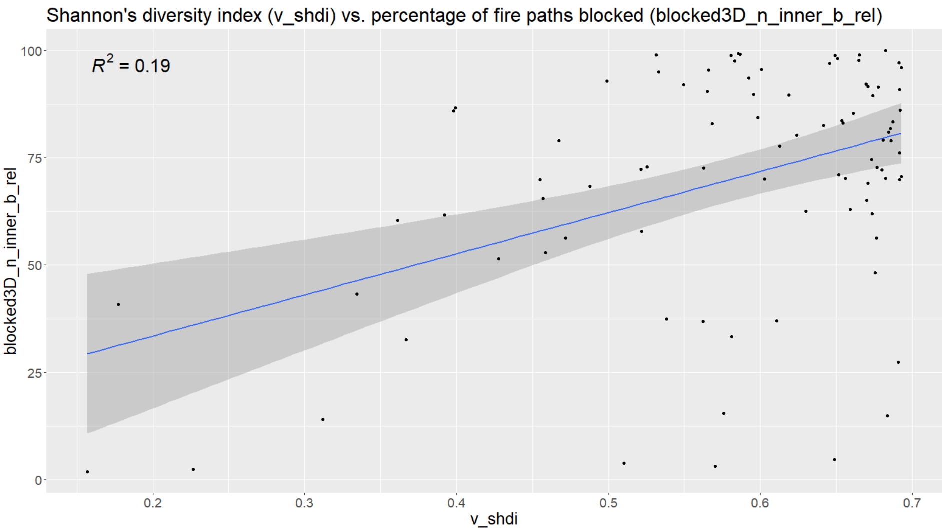

Figure D16: Metric of Shannon’s diversity index to the percentage of fire paths blocked.