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ORIGINAL PAPER

Linking the future likelihood of large fires to occur on mountain slopes with fuel connectivity and topography

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Abstract

In the long run, ongoing climate change is expected to alter fuel production as well as the frequency and severity of fire weather, which may result in an unprecedented frequency of extreme fire events. In this paper we propose a simplified and spatially explicit method to assess the probability of experiencing large fires, based on topography (slope length) as well as extent and aggregation of the forested area (fuel connectivity). We considered 21 homogeneous pyroregions covering entire Switzerland as a study case and computed the length of the upslope paths within the forested areas, simulating ignition points on a systematic 100×100 m square grid. We then compared the obtained path lengths for each pyroregion with selected historical large forest fire statistics (e.g., mean area of the largest 5% of fires, maximum burnt area per fire) collected over the course of the last 30 years. This resulted in rather high R^2 values, ranging from 0.558 to 0.651. The proposed approach was shown to allow for an easy identification and geo-localization of potential hotspots in terms of the likelihood for large fires to occur in mountainous regions, which is a prerequisite for a targeted planning of fire management measures aimed at preventing large fires and related post-fire gravitative natural hazards.

Keywords Steepest path · Slope-driven fires · Megafires · Fire behavior · Burnt area · Switzerland

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1 Introduction

On a global scale, the observed wildfire regimes largely depend on the prevalent climate and weather conditions, which in essence determine the requirements for a fire event to occur (i.e., vegetation and related fuel buildup, fire-conducive environmental conditions), sometimes also providing the cause of ignition through the presence of lightning (e.g., Krawchuk et al. 2009; Pausas and Ribeiro 2013). Human activity (land-use, ignition sources, and suppression activity) and the fire prevalence itself (feedback effects on the vegetation and post-fire fuel buildup dynamics) further modulate the resulting historical fire regimes (Bond and Keely 2005; Archibald et al. 2013; Kelley et al. 2019).

In the long run, however, ongoing climate change is expected to alter the fuel production as well as the frequency and severity of fire weather (Jones et al. 2022). For instance, in some areas such as the Mediterranean and the Amazon, a human-induced increase of the fire weather indices' values beyond the pre-industrial levels is already visible (Abatzoglou et al. 2019). In systems where biomass productivity is high and the fire activity is moisture limited, this may lead to a partial shift from a fire-resistant to a fire-sensitive landscape (e.g., McCarty et al. 2020) or to a significant increase in fire activity (e.g., Hanes et al. 2019) as postulated by the intermediate fire–productivity hypothesis (Pausas and Bradstock 2007). In these systems, severe fire weather combined with abundant fuel may in the future result in an unprecedented frequency of extreme fire events *sensu* Tedim et al. (2020), which completely overwhelm the firefighting resources and represent significant threats to people and infrastructure. Regarding these dynamics, recent evidence suggests that in systems without fuel limitations, bottom-up variables such as the fuel characteristics (i.e., load, connectivity, and diversity) and topography largely influence the difficulty of controlling the spreading fire in severe fire weather conditions, fundamentally influencing the final fire size (e.g., DeAngelis et al. 2015; Fernandes et al. 2016; Francis et al. 2023). Accordingly, even stationary fire–climate relationships that have remained largely unchanged over the past centuries may be altered, resulting in non-stationary dynamics with feedback loops which again involve vegetation, fuel load, and fuel connectivity, therefore potentially leading to an unprecedented relevance of these effects in determining future average fire sizes and burnt area on a regional scale (e.g., Williams and Abatzoglou 2016; Kitzberger et al. 2017; Littell 2018).

Despite marked differences in regional fire regimes (e.g., Conedera et al. 2018; Galizia et al. 2022), Central Europe—and the Alps in particular—are among the regions in which climate change is likely to exacerbate the frequency and magnitude of fires in the future (Wastl et al. 2012, 2013; Berčák et al. 2023). For instance, an increased frequency has already been reported for lightning-induced fires, especially during summer drought years (Conedera et al. 2006), although the burnt area has usually nevertheless remained of limited extent for the time being (e.g., Müller et al. 2013). Anthropogenic fire activity, on the other hand, has been mitigated by other factors such as land-use change (fuel type and connectivity across the landscape), legislation (ban of fire activities in the open), and fire suppression (e.g., Zumbrunnen et al. 2012; Pezzatti et al. 2013). As a general rule of thumb, human-induced fire activity has increased in the last postwar period due to the abandonment of the marginal rural areas, which subsequently underwent a transition to forest, intermittently becoming highly flammable fallow land (e.g., Gellrich et al. 2007). However, most fires remained rather small in size thanks to a significant improvement in firefighting strategies and the possibility of imposing fire bans in case of severe fire weather conditions (e.g., Pezzatti et al. 2013; Müller et al. 2020; Bardsley et al. 2021). Nevertheless, in recent times, intense fires of relatively large size have increased in frequency (Valese et al. 2014; Müller et al. 2020), raising concerns regarding the subsequent post-fire risks related to natural hazards such as increased surface runoff, erosion, rockfall, debris flows, and shallow landslides, and the threats to humans and infrastructures which these entail (e.g., Conedera et al. 2003; Vergani et al. 2017; Melzner et al. 2019).

In the future, the higher frequency of severe fire weather conditions combined with the increasing flammability of the landscape may reduce the effectiveness of the traditional fire management and suppression activities, further increasing the likelihood of large fires to occur. Therefore, forest and fire managers are expected to be prepared for such scenarios, despite the fact that the complexity of the interactions between the evolving climate, vegetation, and related fuel load, as well as possible management interventions will make a spatially explicit forecasting of such fire regimes highly non-trivial (e.g., Schoennagel et al. 2017; Jones et al. 2022).

The aim of this paper is to present a simplified and spatially explicit method to test the hypothesis that the likelihood of a region to experience large fires will to a large part depend on topography (i.e., the slope, which modulates the speed at which the fire spreads and induces an upslope convective heat flux) and fuel connectivity (i.e., the extent and aggregation of vegetation cover with significant fuel buildup). We in particular assume that future fire weather will be severe enough to sufficiently desiccate any type of fuel, making it highly flammable and prone to the contagious upslope evolution of the fire front.

For this purpose, we chose Switzerland as a case study which presents a remarkable variety of geographic environments (from the Plateau to the Alps) and related fire regimes. Based on fire statistics, topography, and dominant vegetation, we first divided the country into homogeneous subregions (pyroregions) for which we then calculated possible fire spread trajectories along the paths of steepest ascent. To validate the approach, the computed lengths of the fire paths contained within areas covered by forest-like vegetation (i.e., forest, open forest stands, and shrubland) were then compared to the observed historical fire activity within each pyroregion, such as the largest forest fires which occurred in the last 30 years (i.e., 1990–2022).

2 Material and methods

2.1 Study area

The study area is the entirety of Switzerland, which extends over 41,285 km^2 largely across the European Alps. The climate is strongly affected by the Alpine chain which acts as a natural divide for weather systems, with the northern slope mostly influenced by air masses from the Atlantic Ocean and the southern slope by those from the Mediterranean Sea. The average temperature in the lowlands ranges from 8 to 12 °C and decreases with altitude. In the summer months (JJA), long and intense heatwaves may occur, with maximum daily temperatures above 30 °C. Precipitation is usually higher in the summer than in the winter and reaches yearly amounts ranging from 800 to more than 2000 mm depending on the region and altitude. The highest amount of precipitation occurs in the Alps, in the Alpine foothills (in particular on the southern slopes), and in the western Jura. The driest region lies in the central part of the canton of Valais. Prolonged meteorological droughts interrupted by heavy thunderstorms may occur in summer in the whole country, whereas prolonged winter/spring dry periods take place mostly south of the Alps, where the desiccating effect of the drought may be additionally exacerbated by the dry katabatic foehn wind (Mofidi et al. 2015; MeteoSwiss 2023).

The forested area encompasses about a third of the territory (i.e., 13,271 km^2, 32.1%) and ranges from 200 to 2400 m asl depending on the region and the aspect (Abegg et al. 2023). Although strongly shaped by management, dominant forest vegetation is organized along an altitudinal gradient starting with mixed broad-leaved stands in the lowlands, followed by forests dominated by beech and silver fir at mid elevation, and coniferous forests (mainly spruce followed by European larch) at higher elevation (Conedera et al. 2017).

Taking into account this climatological and ecological heterogeneity, Gonseth et al. (2001) proposed a subdivision of Switzerland into five main biogeographic regions (Fig. 1).

Natural disturbances of the Swiss forests are mainly caused by wind (59%) and insects (16%) (which do sometimes also interact), followed by snow and avalanches (15%). At present, forest fires are responsible for a mere 1.2% of the disturbed forest area, a rate which is similar to drought-induced disturbances (1.6%), but less than the gaps caused by mass movements (5.7%) (Scherrer et al. 2022). In the last three decades (1990–2022), the average annual number of forest fires registered in Switzerland was ca. 1502, of which 12% are of natural origin (lightning-induced fires in the summer period). However, marked differences among bioregions can be observed (Table 1). The average total burnt area is ca. 260 ha per year, most of which (46%) is concentrated on the southern slope of the Alps, where fast-spreading winter surface fires greatly contribute to the total burnt area. As a consequence, overall average fire size keeps quite small (i.e., 2.9 ha), although again with significant regional differences as a function of prevalent climatological, vegetative, and topographic conditions (Table 1; Pezzatti et al. 2009). Based on this heterogeneity of pyrological conditions and resulting fire regimes, Pezzatti et al. (2016) proposed dividing the

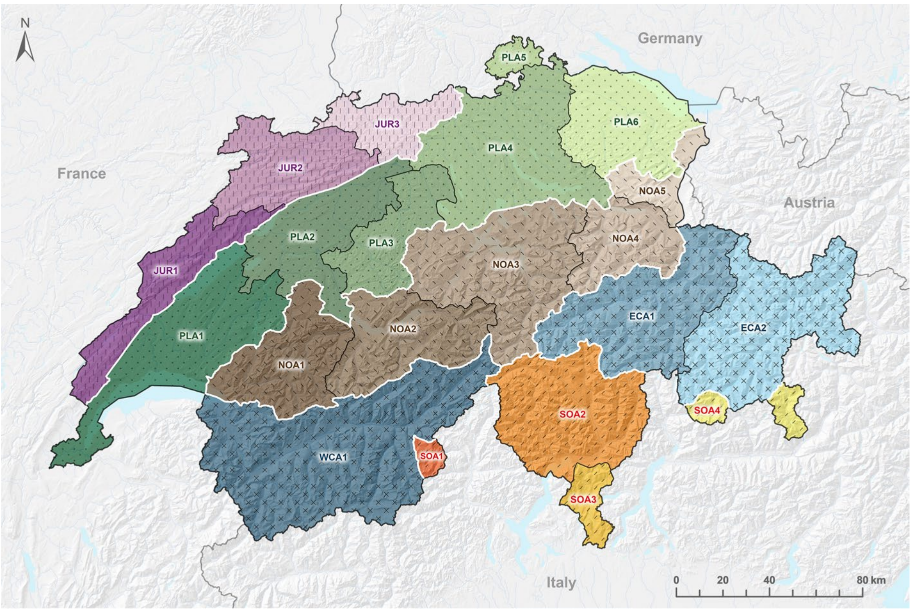


Fig. 1 Map of Switzerland showing the extent of the five main biogeographic regions (JUR = Jura; PLA = Plateau; NOA = Northern Alps; WCA, ECA = Western and Eastern Central Alps; SOA = Southern Alps) and pyroregions (progressive numbers)

Table 1 General annual fire statistics by Swiss biogeographic region for the period 1990–2022

Region	Winter fires		Summer fires				Total burnable area	Average fire size
	Human-induced		Human-induced		Lightning-induced			
	Number	Total area	Number	Total area	Number	Total area		
	N (± SD)	ha (± SD)	*N* (± SD)	ha (± SD)	*N* (± SD)	ha (± SD)	ha	ha (± SD)
JUR	3.85 (3.72)	1.17 (2.06)	4.15 (5.06)	0.64 (0.89)	0.12 (0.49)	0.01 (0.03)	4′131	0.40 (1.40)
PLA	6.33 (5.95)	1.04 (1.41)	8.18 (11.6)	0.96 (1.65)	0.18 (0.47)	0.00 (0.01)	9′750	0.31 (0.78)
NOA	4.70 (4.00)	1.60 (3.07)	7.97 (10.4)	1.24 (2.64)	1.33 (2.47)	0.14 (0.46)	8′077	0.28 (0.92)
WCA	4.61 (6.57)	13.3 (34.2)	7.39 (5.07)	13.1 (55.4)	1.97 (2.16)	0.17 (0.33)	3′303	0.18 (0.39)
ECA	2.97 (2.98)	2.49 (4.69)	7.00 (4.75)	1.40 (2.07)	2.15 (2.32)	0.10 (0.14)	4′648	5.39 (30.9)
SOA	28.3 (20.1)	192 (360)	20.8 (18.5)	28.6(65.4)	7.03 (8.15)	12.9 (36.0)	3′389	2.38 (19.0)

country in 21 homogeneous fire regions (hereafter refereed as pyroregions; Fig. 1). Existing differences in flammability among dominant forest species under normal fire weather conditions tend however to disappear in the case of extreme fire weather, when any type of forest become highly fire-conducive (e.g., Cruz et al. 2022; Conedera et al. 2023), allowing fires to become relatively large, especially on steep slopes in mountainous regions. Nearly all historical large-scale events in the last 30 years in Switzerland took place under severe drought conditions (snow drought with lacking snowpack in the mountains in winter, prolonged "hot" droughts in summer). Despite the windy conditions such as foehn, which usually exacerbates the rate of spread and partially influences the initial fire front direction, nearly all of these large events were slope-driven fires which rapidly spread along the forest and shrubland vegetation on steep topography (see Supplementary Material 1), making the suppression efforts highly problematic for the fire brigades (e.g., Krättli 2017; Pezzatti et al. 2017; Gerold 2019; Gauye et al. 2023). In most cases, these fires implied the need to employ sylvicultural and technical measures to avoid post-fire natural hazards and related damage, which nevertheless could not be completely averted (e.g., Conedera et al. 2003; Melzner et al. 2022). Therefore, fire management strategies have been developed in Switzerland at a federal (e.g., Reinhard et al. 2019) and cantonal level (e.g., Gerold 2019; Ghiringhelli et al. 2019) to avoid large fires and related post-fire risks.

2.2 Basic assumptions and methodological approach

Since it is expected that the frequency of extreme fire weather will increase, for this study we assume that in the future, topography (i.e., slope) and fuel connectivity (i.e., continuous forest and shrubland cover) will be the main limiting factors for successfully controlling fires, due on the one hand to the fast spread of the fire front on steep slopes with reduced accessibility and on the other hand to the upslope convective heat flux released by the fire (e.g., DeAngelis et al. 2015; Fernandes et al. 2016). Consequently, we conclude that the final size of a forest fire will be directly related to the length of the steepest path within an area covered by woody vegetation. Here we define a steepest path as the 3D polyline or linestring which starts at the point of ignition, proceeds up the slope following the direction of maximal elevation gradient (i.e., gaining the most elevation across the shortest possible horizontal distance), and stops where the path encounters large open areas which make it possible or easier for the fire brigades to stop the fire front and extinguish the flames (e.g., grassland, farmland, and rock faces).

Foehn winds usually blow with strong and irregular gusts, which only partially lead to a deviation of the main fire front from the upslope trajectory, contrary to the case in which winds exert a constant strong lateral pressure (see Supplementary Material 1, Fig. SM1.1 and SM1.18). In conclusion, we assume that the future likelihood for a region to experience large fires is positively correlated with the lengths of the steepest paths along a forested slope.

To test this hypothesis, we simulated fire ignitions at each forested point (at most 40 m away from the forest edge) on a systematic 100 × 100 m square grid and, for each point, computed the steepest path within the forested area. We then compared the resulting path lengths for each pyroregion with selected large fire statistics (e.g., total burnt area, mean area of the largest 5% of fires, and maximum burnt area per fire) of the last 30 years (i.e., 1990–2022) as documented in the forest fire database "Swissfire" (https://www.wsl.ch/swissfire; Pezzatti et al. 2019). Here, each fire record includes the date and time at which the fire was detected (i.e., when the fire was discovered) as well as the spatial coordinates and/or municipality within which the fire ignition point occurred, allowing us to assign each fire record to a pyroregion on the basis of the coordinates or the municipality of the ignition point. Note that all large fires which occurred in the study region during this period are registered in this dataset, i.e., including fires which did not occur entirely within the forest. However, as one can see from Supplementary Material 1, these large fire events were in nearly all cases associated with a forest-like vegetation cover and steep topographical conditions.

2.3 The steepest paths algorithm

Over the past decades, several techniques and applications have been implemented in GIS for the computation of vector features representing the lines of greatest slope both downhill and uphill (e.g., Moore et al. 1988; Mitasova et al. 1995; Zhou et al. 2011) and different terms are in use to indicate these particular terrain geometries (e.g., flow lines, flow trajectories, streamlines, fall line, steepest ascent lines, and surface flow path). Currently, flow lines are exploited in multiple scientific fields such as the study of water runoff (Freitas et al. 2016), the forecast of lava flow paths (Favalli et al. 2005), or the detection of ridges (Koka et al. 2011). To our knowledge, however, this type of vector data has never been intersected with forest cover distribution data for the purpose of estimating the likelihood of fire occurrence over vast territories.

The steepest paths algorithm represents a highly simplified approach for modeling the spread of a slope-driven fire front assuming the presence of a homogeneous and highly fire-conducive forest fuel bed. The input data for the algorithm are thus the topography (slope, as derived from a digital elevation model—DEM in raster format) and the fuel connectivity (joint vector map representing the forest, open forest stand, and shrubland cover).

The algorithm consists of a two-step approach (Fig. 2). In a first step, it determines the ignition points on a regular grid (in our case of mesh size 100 × 100 m). It then computes all steepest paths from these points along the slope until a summit (e.g., a mountain top)

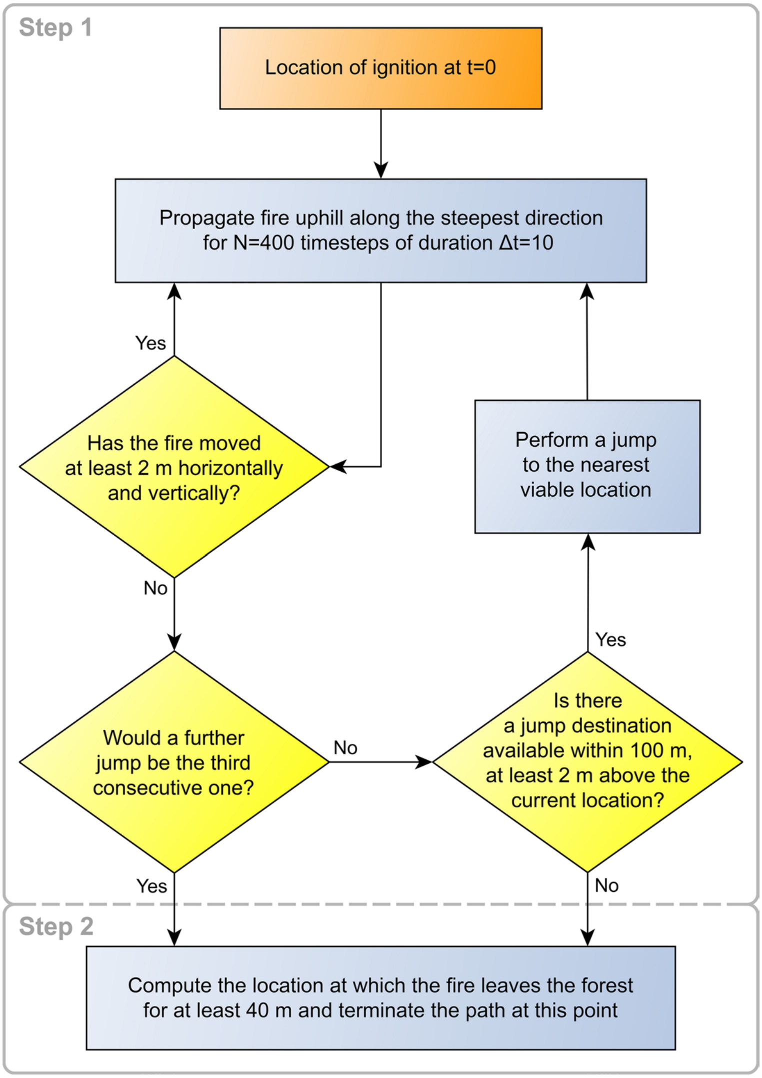


Fig. 2 Flowchart describing the steepest path algorithm

or a large flat region is reached. In a second step, the obtained lines are checked for fuel connectivity in order to stop the paths when crossing open areas or vegetation covers other than shrubs, open forest stands, and forests (see Supplementary Material 2 and Fig. SM2.1 for a detail explanation of the tool, including the precise parameters chosen for our study case).

The final output of the steepest path algorithm is a set of polyline features representing the computed steepest paths. In our case, we will use the following two sets of three-dimensional polylines:

– The "forest steepest paths," i.e., the steepest path lines within the forested area (i.e., forest, open forest stands, and shrublands) and truncated at the first point at which the

fire leaves the forested area for at least 40 m. Note that these lines can also start outside the forested area as long as the horizontal distance between the starting point and the woodland is less than this preset threshold value (Supplementary Materials 2, Fig. SM2.1a).
– The "full steepest paths," i.e., all computed steepest path lines truncated at 2500 m asl, i.e., assuming that the entire territory has transitioned to forested area (hypothetical totally forested landscape, Supplementary materials 2, Fig. SM2.1b).

A first release of the R script implementing the steepest path algorithm, accompanied by detailed instructions and further explanations concerning the multiple calculation procedures and usage options is available in a repository on GitHub (https://github.com/Insubric/steepest_paths_tool).

2.4 Statistical analysis

In order to provide a descriptive statistical overview of the steepest paths obtained, we visualized the three-dimensional length of these line features for each pyroregion in the form of a box plot. Regional differences were then assessed in terms of statistical significance using the unpaired Wilcoxon rank-sum test. On the other hand, the fire regime characteristics of each pyroregion were expressed by means of different metrics related to the total burnt area and to large fires in particular. Explicitly, the selected variables are the total burnt area summed across all fires, the mean burnt area of the largest 5% of fires, the mean burnt area of the 5 largest fires, and the maximal area of any fire within the pyroregion. In order to assess the relationship of the key parameters defining the current fire regime with the calculated steepest paths, the logarithm of each fire regime metric was linearly regressed on the median path length within each of the pyroregions, using the *geom_smooth* function from the *ggplot2* package (Wickham 2016).

3 Results

Figure 3 shows the dispersion of the obtained three-dimensional path lengths grouped by pyroregion and main biogeographic region. Clear and significant differences exist among the main biogeographic regions but also among most pyroregions. As expected, the southern regions display the largest three-dimensional path lengths, followed by the Central Alps, the mountainous regions of Jura and the Northern Alps. The lack of steep mountains in the Plateau region is reflected in the low median values reported in Fig. 3.

When considering the linear regressions obtained by regressing the logarithm of the selected fire metrics against the calculated medians of the steepest path lengths of each pyroregion, we always obtain highly significant relationships ($p < 0.001$) and rather high R^2 values ranging from 0.558 for the total burnt area between 1990 and 2022 at the pyroregion level (see Supplementary Materials 3, Fig. SM3.1) to 0.644 for the average area of the largest 5% of forest fires (Fig. 4), and to 0.651 for the area of the largest fire which occurred during the considered period (see Supplementary Materials 3, Fig. SM3.2). Based on these results, we define four likelihood classes for pyroregions with a similar propensity for large fires to occur, by applying a regular thresholding to the computed median three-dimensional length L of the forest steepest paths. Namely, we define a pyroregion to have a low propensity if $L < 150$ m, medium propensity if L is between 150 and 200 m,

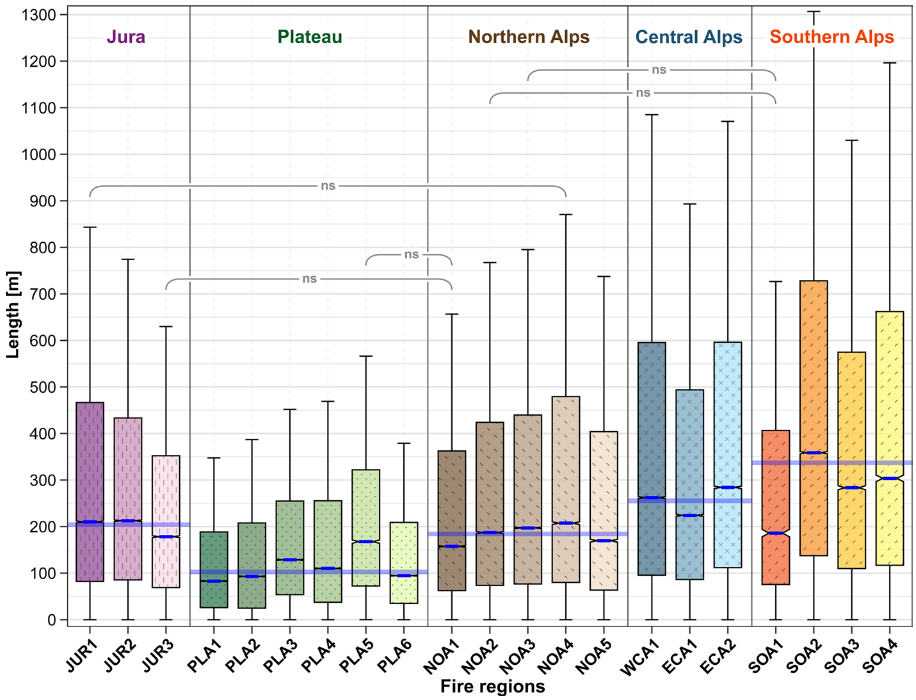


Fig. 3 Variability of each pyroregion in terms of the three-dimensional length of the forest steepest paths. Box plots span from the 25th (lower limit) to the 75th percentile (upper limit) of the data. Blue dashes and notches display the median values and the confidence intervals, respectively. Light blue lines represent the median values of the correspondent bioregion. Whisker extents have been set to one time the interquartile range. Only non-significant differences between pyroregions according to the unpaired Wilcoxon rank-sum test are indicated as "ns" ($p > 0.01$), while all others are highly significant ($p < 0.001$)

high propensity if L is between 200 and 250 m, and very high propensity if $L \geq 250$ m. When analyzing the so-defined classes with respect to the proposed regression, we obtain threshold maximum fire size values of 1.2 ha between the low and moderate classes, 4.0 ha between the moderate and high classes, and 13.5 ha between the high and very high classes (Fig. 4).

Figure 5 shows the geographic distribution of the considered pyroregions in terms of the propensity classes for large fires. As expected, low propensity classes are concentrated on the Swiss Plateau, whereas the Central Alps and Southern Alps mostly display a high propensity for large fires. The Northern Alps (mostly medium propensity) and Jura (mostly high propensity) take an intermediate position.

When analyzing the high-propensity class in detail, some regions such as the canton of Valais (WCA1) appear to display slightly higher maximum burnt area than the regression predicts (Fig. SM3.2), although they remain within the confidence interval range when considering the mean area of the largest 5% of fires (Fig. 4). Others, such as Bregaglia and Poschiavo (SOA4) or Engadina (ECA2), on the other hand, burn significantly less (Fig. 4).

Figure 6a highlights the increase in the path lengths when simulating a Swiss landscape which is completely forested up until 2500 m asl, e.g., due to a hypothetical suspension of all land use. Interestingly, when comparing the metrics of the current fire regimes to

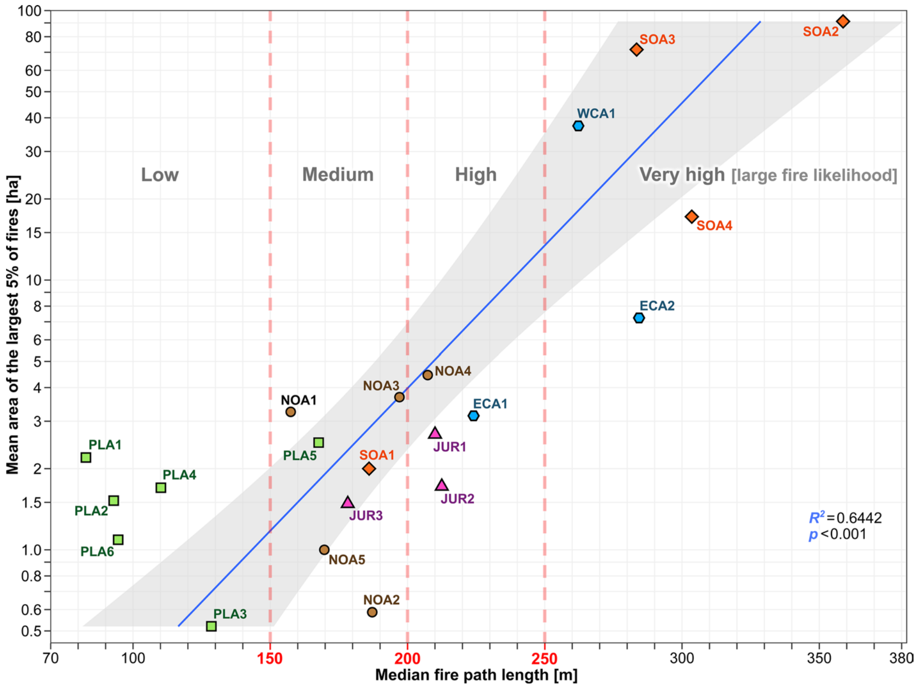


Fig. 4 Scatter plot showing the relationship between the mean area of the largest 5% of the fires which occurred between 1990 and 2022 within a given pyroregion and the median three-dimensional length of the forest steepest path lines. The gray area around the blue regression line represents the 95% confidence interval. Please note that the *Y*-axis has a logarithmic scale. Red vertical lines correspond to the threshold values for the path lengths *L* separating the four large fire propensity classes: $L = 150$ m for discriminating between low and medium (corresponding to a burnt area of 1.2 ha), $L = 200$ m for discriminating between medium and high (corresponding to a burnt area of 4.0 ha), and $L = 250$ m for discriminating between high and very high (corresponding to a burnt area of 13.5 ha)

the resulting steepest path lengths, the observed relationships become markedly weaker, both in terms of statistical significance ($p < 0.01$) and R^2 (0.301) (Fig. 6b). The very high-propensity class would however extend over 16 out of the 21 pyroregions (Fig. 6c).

4 Discussion

In this paper we applied a simplified and spatially explicit method for analyzing the possible influences of topography (slope length and steepness) and fuel connectivity (continuity and extent of the forested area) on the probability of large fires occurring in different subregions of Switzerland in the case of a future scenario with a higher frequency of extreme fire weather conditions.

The computed potential fire path lengths varied significantly among pyroregions within and among most of the main biogeographic regions. Interestingly, median values of the calculated path lengths highly correlate with the large fires' statistics over the last 30 years. The highest correlations are obtained when comparing with the recent largest fire events within each pyroregion (e.g., largest observed fire event; the largest 5% of forest fires),

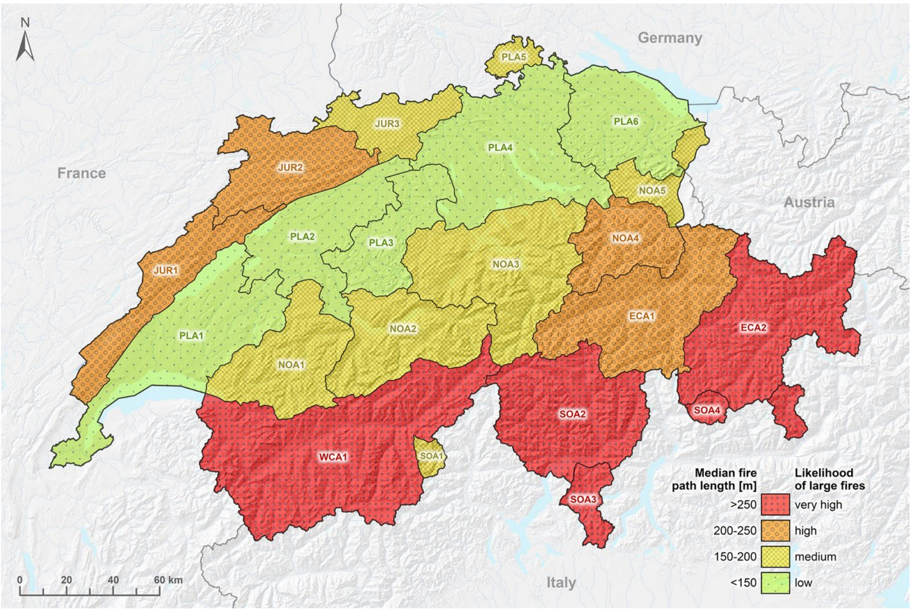


Fig. 5 Map representing the classification of the 21 Swiss pyroregions into four classes according to the current large fire propensity

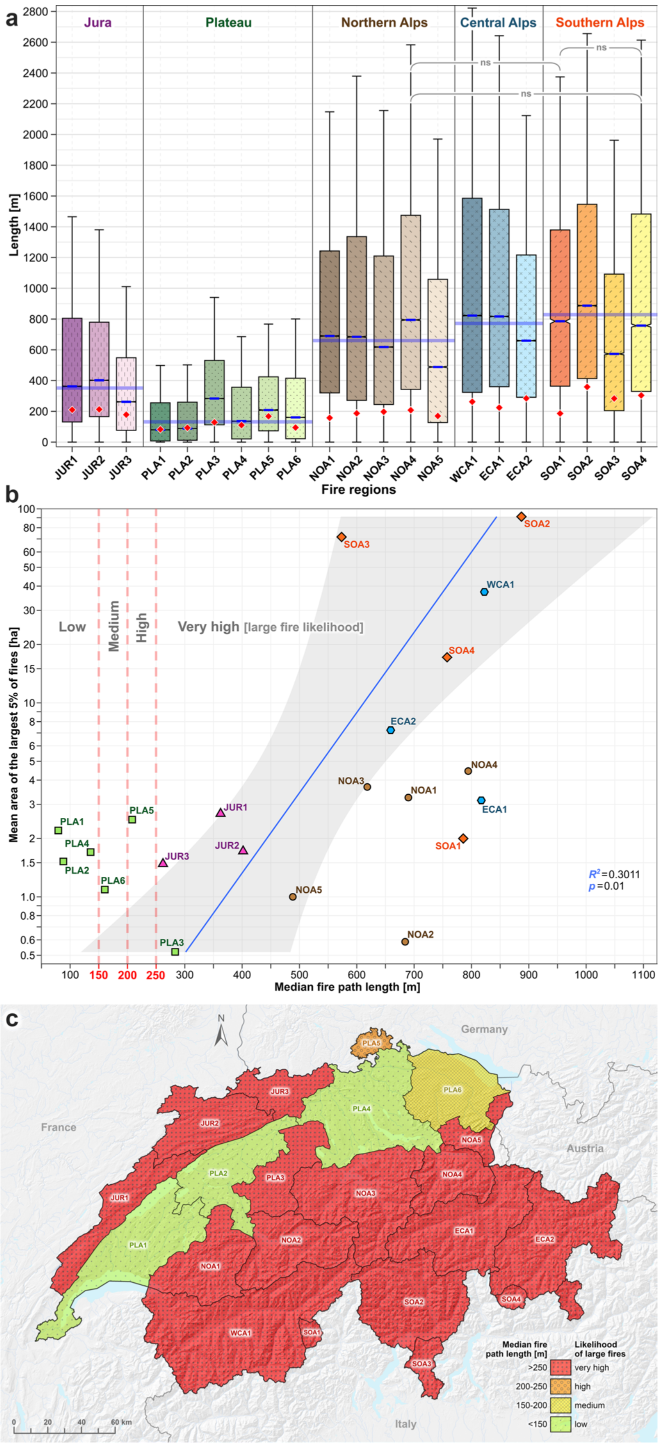
confirming the prominent role of topography and fuel connectivity in shaping the fire behavior, determining the difficulty of controlling a given fire event, and crucially influencing the final burnt area (Moreira et al. 2010; Fernandes et al. 2016; Beverly et al. 2021; Francis et al. 2023). According to our results, Switzerland can be subdivided into four distinct classes in terms of present and future likelihood of experiencing large fires. Here, the very high-propensity pyroregion corresponding to the canton of Valais (WCA1) already displays a maximal burnt area slightly surpassing the expected maximal burnt area as computed using a linear regression (although still within the confidence interval when considering the largest 5% of fires), whereas others such as Engadina (ECA2) and some southern valleys of Grisons (Bregaglia and Poschiavo, SOA4) are presently underrepresented in terms of burnt area. In fact, this behavior in the canton of Valais (WCA1) is to be expected, as even today, this is one of the driest regions of Switzerland (MeteoSwiss 2023). During extreme drought periods combined with days of strong wind, possible fires are very likely to spread into the crowns of the broadly diffused and dense coniferous forests, which often results in large final burnt areas (Supplementary Materials 1, Fig. SM1.2). Conversely, the mountain regions of the Engadina (ECA2) are currently characterized by a pronounced continental climate, and this combined with the area's high median elevation results in long periods of snow cover, which most likely prevents large fires from occurring so far, especially during the spring season. A similar effect of the generally high elevation of the territory, despite a marked influence of foehn winds, may be the reason for the current absence of large fires in the SOA4 pyroregion, especially in the case of the Poschiavo valley.

The very low correlation coefficients obtained when comparing the current fire regimes to the theoretical three-dimensional steep paths when supposing a transition to a total forest cover of the Swiss landscape indirectly highlight the paramount role of fuel-consuming and fuel-removing land uses in preventing large fires. Without such traditional agricultural or

Fig. 6 Large fire propensity in a hypothetical Swiss landscape which is completely forested up until 2500 m asl. **a** Variability for each pyroregion in terms of the three-dimensional length of the full steepest paths. Box plots span from the 25th (lower limit) to the 75th percentile (upper limit) of the data. Blue dashes and notches display the median values and the confidence intervals, respectively. Light blue lines represent the median values of the correspondent bioregion. Whisker extents have been set to one time the interquartile range. Only non-significant differences between pyroregions according to the unpaired Wilcoxon rank-sum test are indicated as "ns" ($p > 0.01$), while all others are highly significant ($p < 0.001$). The red dots represent the median path lengths when considering the present forested region (see Fig. 3). **b** Scatter plot showing the relationship between the mean area of the largest 5% of the fires which occurred between 1990 and 2022 within a given pyroregion and the median three-dimensional length of the full steepest paths. The gray area around the blue regression line represents the 95% confidence interval. Please note that the *Y*-axis has a logarithmic scale. Red vertical lines correspond to the threshold values for the path length *L* separating the four large fire propensity classes (see Fig. 4 for further details). **c** Map representing the classification of the 21 Swiss pyroregions into four classes of large fire propensity, resulting from our analysis of a hypothetical completely forested Swiss landscape ▶

pastoral activities on the mountain slopes, significant additional parts of Switzerland would transition to the very high-propensity class regarding the likelihood for large fires to occur.

From a methodological point of view, we propose a very simplified approach with respect to existing spatially explicit fire simulations models and techniques (see Miller and Ager 2013 for a short review). On the one hand, this prevents us from accurately simulating the fire growth dynamics through different fuel types as well as loads and the related local fire intensities, including possible effects of landscape and fuel management (e.g., Ager et al. 2012). On the other hand, our approach allows the estimation of fire spread potential using readily available GIS data and is particularly suitable for application even over vast areas. Furthermore, our main focus is on simulating the effect of extreme fire weather conditions which induce fast-spreading and intense fire fronts on slopes with continuous fuel cover. Details regarding the local fire intensity are not relevant in this context and omitting these makes the approach highly flexible. Depending to the characteristics of the landscape which is to be analyzed, one can add additional vegetation cover types that potentially support fast fires of high intensities (i.e., fallow lands of any type if a cartography is available), which were not considered in this study. Similarly, the parametrization of the tool (e.g., distance from the forested area before a fire can be stopped) can be adapted to future fire regime scenarios (e.g., high frequency and long-distance spotting during a fire). Finally, possible effects of fuel breaks or fuel management activities can easily be simulated by simply removing the target vegetation cover load where the interventions are planned.


a
Jura
Plateau
Northern Alps
Central Alps
Southern Alps
Length [m]
Fire regions
ns
JUR1 JUR2 JUR3 PLA1 PLA2 PLA3 PLA4 PLA5 PLA6 NOA1 NOA2 NOA3 NOA4 NOA5 WCA1 ECA1 ECA2 SOA1 SOA2 SOA3 SOA4
b
Low
Medium
High
Very high [large fire likelihood]
Mean area of the largest 5% of fires [ha]
Median fire path length [m]
R^2=0.3011
p=0.01
c
Germany
France
Austria
Italy
Median fire path length [m]
Likelihood of large fires
>250 very high
200-250 high
150-200 medium
<150 low
0 20 40 60 km

5 Conclusions

In mountainous regions, future fire management efforts should focus on preventing large fires and related post-fire gravitative natural hazards. Here we presented a simplified approach for identifying and mapping the areas with an elevated likelihood for large fires to occur within a defined region of interest. Despite obvious oversimplifications, the proposed spatially explicit approach yields results which are highly correlated with the current fire regime and allow for an easy identification and geo-localization of potential hotspots in terms of the likelihood for large fires to occur. This is a prerequisite for a targeted planning of fire management measures and costly fire pre-suppression infrastructures such as water points for aerial firefighting in particular.

The suggested approach can be implemented using readily available GIS data (namely a DEM and a vector map of the forested region) and is also relatively economical in terms of computational resources meaning that it is suitable for application even over vast areas. In addition, it can be integrated and combined with other approaches, considering further characteristics of the landscape (ignition probability, aspect, dominant forest vegetation and related fuel, post-fire susceptibility of the landscape, etc.) relevant for fire behavior, as such allowing any region (e.g., whole country, province, and district) to be analyzed.

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Declarations

Conflict of interest The authors have not disclosed any conflict of interest.

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