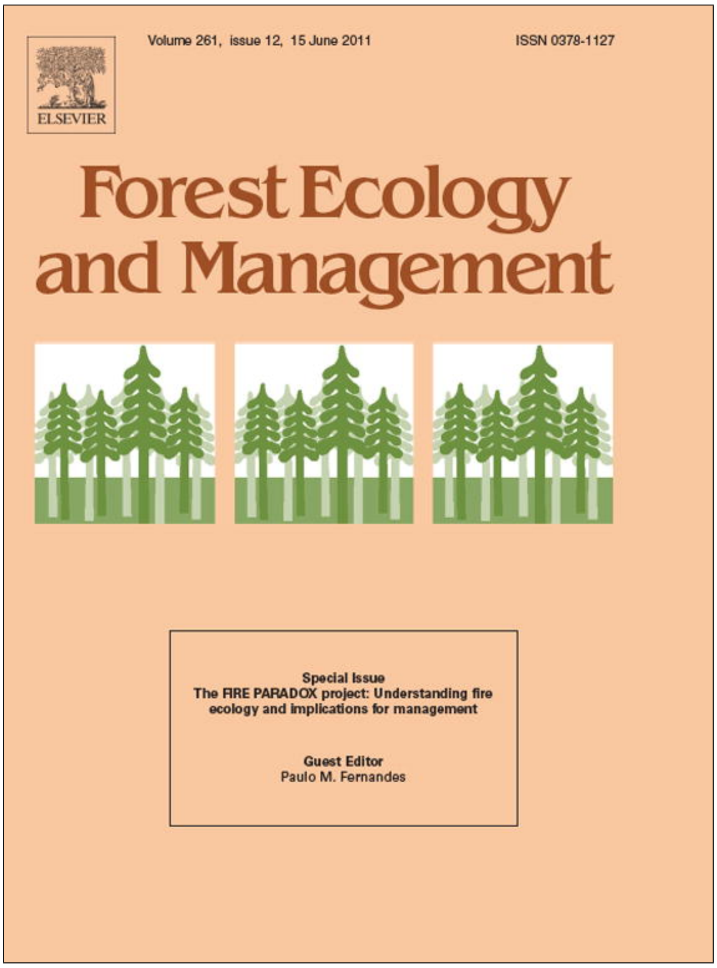
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Using Monte Carlo simulations to estimate relative fire ignition danger in a low-to-medium fire-prone region

Marco Conedera[a,*], Damiano Torriani[a], Christophe Neff[b], Carlo Ricotta[c], Sofia Bajocco[c], Gianni Boris Pezzatti[a]

[a] WSL Swiss Federal Research Institute, Insubric Ecosystems Research Group, via Belsoggiorno 22, CH-6500 Bellinzona, Switzerland
[b] Institut für Geographie und Geoökologie, Universität Karlsruhe (TH), Kaiserstr. 12, D-76128 Karlruhe, Germany
[c] Department of Plant Biology, University of Rome "La Sapienza", Piazzale Aldo Moro 5, I-00185 Rome, Italy

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ABSTRACT

A comprehensive assessment of fire ignition danger is nowadays a basic step towards the prioritization of fire management measures. In this study we propose performing a fire selectivity analysis using Monte Carlo simulations to statistically estimate the relative fire ignition danger in a low-to-intermediate fire-prone region such as Canton Ticino, Switzerland. We define fire ignition danger as the likelihood that at a given place a fire will be ignited. For each 25 m × 25 m pixel of the study area, landscape characteristics that may be related to the probability of fire ignition such as vegetation type, elevation, aspect, slope, urban–forest interface were first split into 9–12 categories. The selectivity of each category with respect to fire ignition was then statistically tested by means of Monte Carlo simulations. Finally, we proposed two different approaches for calculating the ignition danger index: cumulating the scores of the Monte Carlo simulations to a final index or producing synthetic scores by performing a principal component analysis of the Monte Carlo results. The validation of the resulting fire danger indices highlights the suitability of both proposed approaches. The PCA-option allows a slightly better discrimination between ignition and non-ignition points and may be of more general application.

1. Introduction

In last few decades, advances in fire ecology and the strong evidence of the unsuitability of a systematic fire suppression led most fire managers to a shift away from a fire control approach (i.e. concentration of the main effort on suppressing ongoing wildfires) towards a more comprehensive approach, where fire prevention, pre-suppression and suppression strategies as well as knowledge of local fire history and ecology are fully integrated in landscape management (Fries et al., 1997; Swetnam et al., 1999; Bengtsson et al., 2000; Bergeron et al., 2002; Castellnou et al., 2002; Vélez and Merida, 2002; Silva et al., 2010). Modern fire management strategies should, however, consider not only the complex interactions between past natural and anthropogenic forces, but also the present evolution of landscape structures (e.g. wildland–urban interface, WUI, Lampin-Maillet et al., 2010), forest ecosystem services (protection, economic and recreational) and the changing environmental conditions (climate change, pollution, invading alien species, etc.) that may cause unforeseen and unprecedented post-fire ecosystem reaction patterns (Alexandrian, 2002; Flannigan et al., 2000, 2005; Trabaud, 2002; Whitlock et al., 2003).

A basic step towards achieving management goals and minimizing intervention costs is to conduct a comprehensive and quantitative assessment of fire danger and fire risk. Different methodological approaches have been developed in recent times for assessing fire danger and risk (see EUFIRELAB, 2003, 2004; Amatulli et al., 2006; Catry et al., 2009 for a review on strengthens, gaps and drawbacks of the main existing methods) and for the prioritization of fire management measures (Alexandrian, 2002; Finney, 2005; Reynolds and Hessburg, 2005; Hessburg et al., 2007). Unfortunately in some regions where forest and wildfires are not very frequent or where they just start to become a problem as a consequence of the global change (Krawchuk et al., 2009), statistical data on fire frequency and distribution may be lacking or may be too scarce for allowing a statistical approach such as multiple linear regressions or logistic regressions. This may be the case for instance in the Alps (Schumacher and Bugmann, 2006), in selected areas of central Europe such as Germany (Neff and Scheid, 2003; Thonicke and Cramer, 2006) and the French Vosges (Neff et al., 2004), of the Balkans (Albania, former Yugoslav Republic of Macedonia), of the Maghreb (Neff et al., 2007) among others.

* Corresponding author. Tel.: +41 918215231; fax: +41 918215239.
E-mail address: marco.conedera@wsl.ch (M. Conedera).

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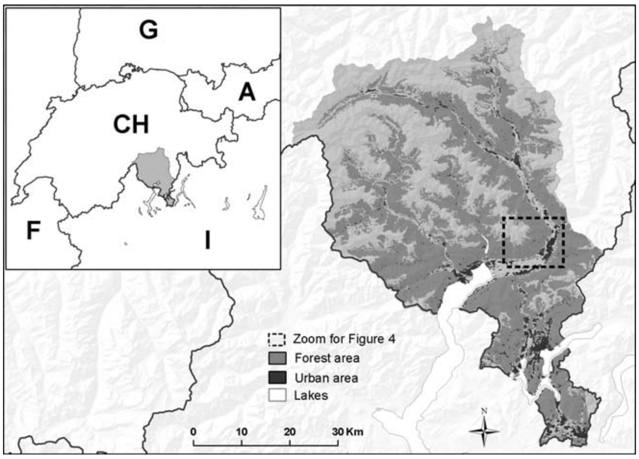

Fig. 1. The study area of the Canton Ticino. The inset refers to Fig. 4.

In this study we test the suitability of using Monte Carlo simulations to statistically estimate the fire selectivity of single landscape characteristics in a low-to-intermediate fire-prone region such as Canton Ticino, Switzerland. We then propose two different approaches for implementing the Monte Carlo results into a relative fire ignition danger index.

2. Material and methods

2.1. Defining the fire ignition danger

Fire management terminology has been constantly evolving and is not uniformly used in all countries and in all fire contexts. Hardy (2005) notes how the terms we use to characterize resource management, particularly fire management, appear to have become less concise over time, and provides examples of numerous inconsistencies in the use of most fire management terms. There are linguistic and cultural aspects behind this problem, partially due to different languages and partially due to the fact that fire is a complex phenomenon involving very different kind of people, e.g. fire fighters, foresters, ecologic lobbying groups, environmental NGOs, land owners, and scientists. These may not share the same vocabulary (Bachmann and Allgöwer, 1999).

A short review of the existing definitions of the terms "fire danger", "fire risk", and "fire hazard" shows that there are currently various definitions, interpretations, and implementations of such concepts in fire management (Hardy, 2005; EUFIRELAB, 2004). In this paper we define "fire ignition danger" as the likelihood that at a given place a fire will be ignited ("fire risk" according to FAO, 1986).

According to EUFIRELAB (2004) the most appropriate time scale for assessing such ignition danger is the long-term (10 years or more). Considering such a time span allows referring to almost static variables that is fire-relevant parameters that do not change along the period of reference. In this paper we therefore refer our estimates of "fire ignition danger" to structural and locational factors (e.g. topography, forest cover) that do not change or only change very slowly over time. This approach enables to describe the long-term relative fire ignition danger within the study area avoiding an explicit use of meteorological data, whose spatial and seasonal distribution is assumed to be similarly recurrent during the study period. This corresponds in practice to the assessment of the internal climatic gradient of an average fire season for which the mean ignition danger can be calculated using the historical fire data.

2.2. Study area

The Canton of Ticino is located on the southern slope of the Alps. It has a total area of 2812 km^2, with 320,000 inhabitants and represents the southernmost of the 26 Swiss Cantons, bordering on Italy (Fig. 1). Like the whole southern slope of the Alps, the area is characterized by a marked altitudinal gradient (from 200 to 340 m a.s.l.) and quite a heterogeneous geology, dominated by siliceous rocks originated in connection with the tectonics of the Alps. Depending on the elevation and the geographical location, the mean annual precipitation ranges from 1600 to 2600 mm, and the mean annual temperature from 3 to 12 °C. The high quantity of summer rain (800–1200 mm in the period June–September) contrasts with the low level of summer precipitation in the Mediterranean climate just south of Ticino. The climate is also characterized by dry and mild winters with some days (40 days a year on average) having strong gusts of a katabatic (descending) dry wind from the North (Foehn), which causes drops in the relative humidity to values as low as 20%. In summer long periods without rain or even of drought may alternate with thunderstorms and short, heavy spells of precipitation (Spinedi and Isotta, 2004).

Forest cover of the area is high (on average 50.5%). The forest vegetation is dominated at low elevations (up to 900–1100 m a.s.l.) by the chestnut tree (*Castanea sativa*), which was first cultivated (and probably first introduced) in the area by the Romans (Conedera et al., 2004). Chestnut forests are anthropogenic monocultures occasionally interrupted by the presence of other broadleaved species, such as *Tilia cordata*, *Quercus petraea*, *Quercus pubescens*, *Alnus glutinosa*, *Prunus avium*, *Acer* spp., or *Fraxinus* spp. At medium elevations (900–1400 m a.s.l.), the forests mostly consist of pure stands of *Fagus sylvatica*, followed by coniferous forests (*Picea abies* and, at higher elevations, *Larix decidua*). On the south-facing slopes the beech belt is sometimes completely missing. The presence of *Abies alba* has been reduced to small patches on north-facing slopes in the central part of the area, and pine forests are confined to very particular sites: *Pinus sylvestris* on dry south-facing slopes, and *Pinus cembra* on the most continental areas of the upper regions (Ceschi, 2006).

2.3. Forest fire data

Fire data have been collected in Ticino by the forest service since 1900. Although data recording has changed with time, some basic information such as the date, time, and cause of ignition, fire duration, area burnt, fire type, and forest type have been collected for the whole period. Thus it has been possible to organize the fire data in a relational database (Pezzatti et al., 2005). In addition, since 1969 geo-referenced perimeters of the burnt area exist for most forest fires.

Up to 2007, 5658 events are registered in the database, resulting in a long-term average of 52.4 forest fires per year. Since 1900, however, the general trend in forest fire frequency and burnt area has varied greatly with respect to this average value (Fig. 2). According to Conedera et al. (2004) and Conedera and Pezzatti (2005) a significant shift in burnt area took place starting in 1980s as a result from a major fire brigades reorganisation (1978) and from the start of systematic use of helicopters for both transport of the fire fighters and aerial fire fighting. Concerning the fire frequency, a relevant drop in anthropogenic induced fire ignitions without a correspondent change in the precipitation regime took place in 1990 as a consequence of two preventative legal acts (Conedera et al., 2004): the prohibition of burning garden debris in the open (Cantonal decree approved on October 21, 1987, but operational with the corresponding penalties since January 1, 1989) and the prohibition against fire works and celebration fires on the Swiss National Day of August 1st in case of high fire ignition danger (Cantonal

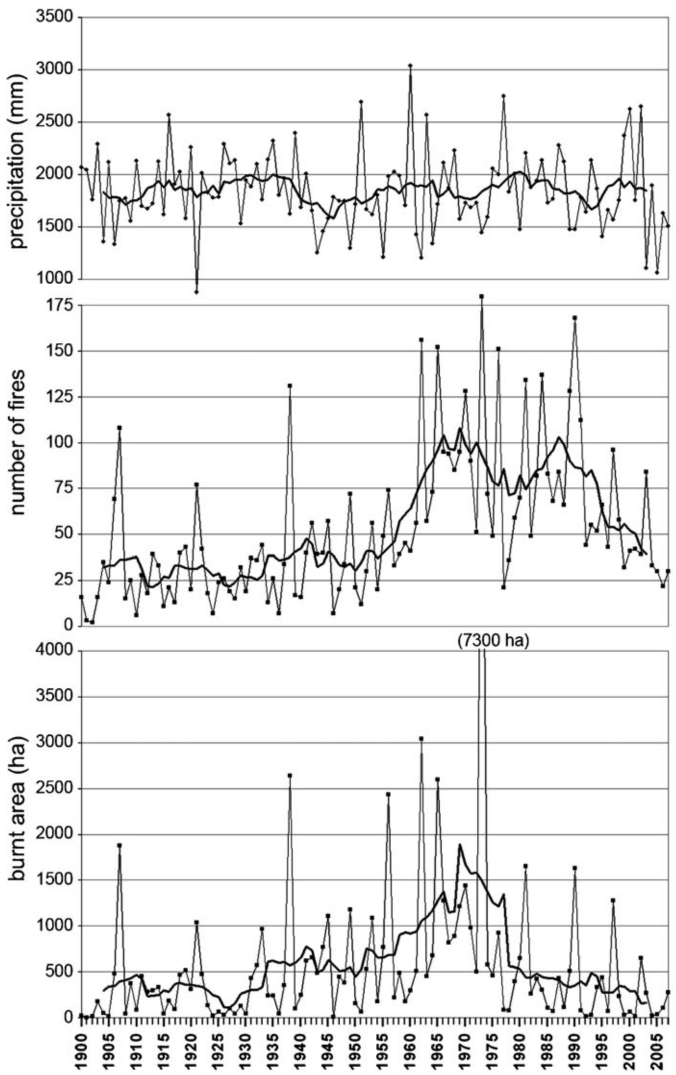

Fig. 2. Annual precipitation (Locarno-Monti), number of fires and burnt area in Canton Ticino for the period 1900–2007 (source: Swiss forest fire database, WSL Bellinzona; MeteoSwiss Locarno-Monti). The lines in bold represent a 9 years running mean.

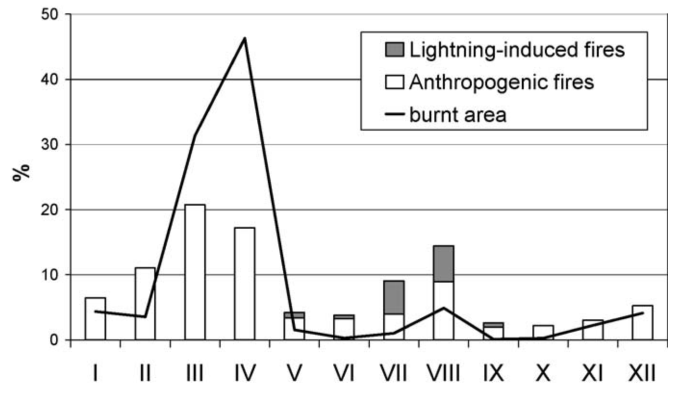

Fig. 3. Monthly distribution of number of fires (anthropogenic and lightning-induced) and total burnt area in Canton Ticino for the period 1990–2007.
Swiss forest fire database, WSL Bellinzona.

Table 1
Fire data considered in this study.

Fire regime	Period of reference	Total number of events
Anthropogenic winter fires (AWF)	1990–2007	569
Anthropogenic summer fires (ASF)	1990–2007	197
Natural summer fires (NSF)	1980–2007	138

decrees of July 11, 1990). Present pyrologic conditions last therefore since 1980 concerning the burnt area and 1990 concerning the anthropogenic fire ignitions.

Current monthly distributions of fires highlight the existence of three different fire regime patterns (Fig. 3). During the vegetation rest period (December–April) fire events are mostly rapid spreading (surface) fires of anthropogenic origin with a major peak in March–April. During the vegetation season and, in particular, in the summer months of July–August, a mixed pattern dominates with slow spreading fires of both natural (lightning-induced) and anthropogenic origin. According to Conedera et al. (2006) summer fires display two distinct geographic distribution: the lightning-induced fires are concentrated in the coniferous forests at higher altitudes and on steeper slopes than the human-caused events.

In conclusion, a reliable assessment of present fire regime of the study area may be achieved considering homogeneous data sets for each of the three fire regime patterns, that is 1990–2007 for both winter (AWF) and summer anthropogenic fires (ASF) and 1980–2007 for the natural summer fires (NSF). In this latter case, extending the period of natural forest fire back to 1980 represents a compromise between the consistency (homogeneity) and the representativeness (quantity) of the data, being lightning-induced fire ignitions of course not influenced by the preventive legislation. Table 1 summarizes the available data according to these selection criteria.

2.4. Fire ignition-relevant parameters

Based on existing literature, own previous studies, local expert knowledge and data availability, we selected the five landscape characteristics reported in Table 2 as the most relevant in relation to fire ignition in the study area. Fuel composition and related flammability may change according to the different vegetation type, which

Table 2
Landscape characteristics and categories considered.

Landscape characteristics	Categories	
	Nr	Description
Vegetation cover	12	Non-forest, buffer 0–50 m, buffer 50–100 m, chestnut stands, beech stands, spruce stands, larch stands, fir stands, pine stands, other broadleaved forests, mixed forests (broadleaves-conifers), other coniferous forests
Elevation class	10	Categories of 250 m each from 0 to 2500 m a.s.l.
Aspect	9	N, NE, E, SE, S, SW, W, NW and flat
Slope	10	Categories of 8.25° each
Urban–forest interface (for anthropogenic fire regimes only)	9	Forest within 100 m of an urban area; non-forest within 100 m of an urban area, forest areas located in doughnuts of 100–200, 200–300 or 300–400 m around the urban area, non-forest areas located in doughnuts of 100–200, 200–300 or 300–400 m around the urban area, remaining area (no interface)

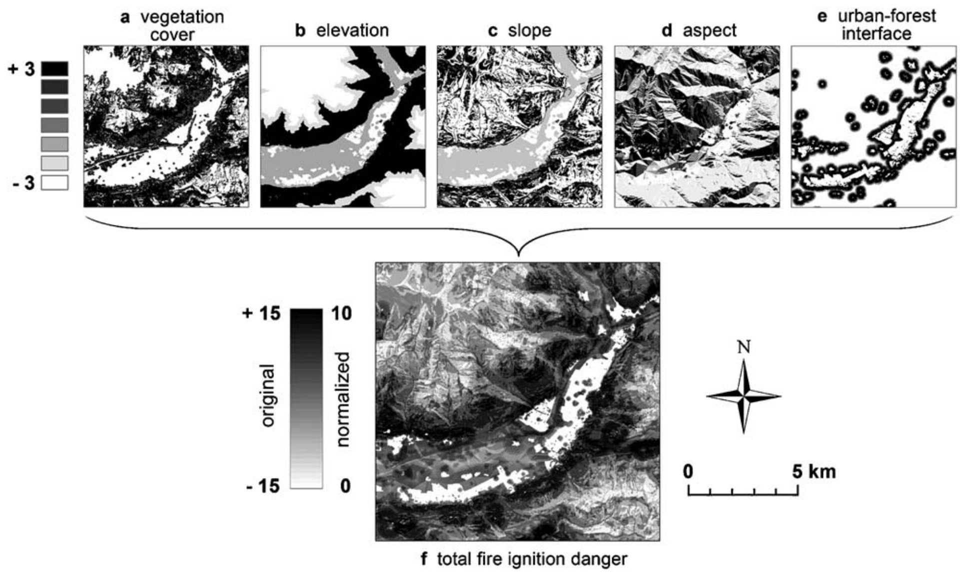

Fig. 4. Example of a cumulated total fire ignition danger map referring to the anthropogenic winter fires. Figures (a)–(e) show the selectivity scores of each landscape characteristics considered with respect to the fire ignition. Figure (f) shows the total fire ignition danger scores obtained as the sum of the single-layer values and as the correspondent rescaled values in the range 0–10.

on turn may vary as a function of the site (elevation, aspect, and slope). Similarly, fuel moisture may vary according to the elevation (e.g. different snow cover), aspect, and slope (different drying out effect of the soil irradiation). Urban-forest interface may increase the likelihood of contact between potential human ignition sources and fuel.

In order to perform the statistical analysis, we handled each landscape characteristics of Table 2 as a separated GIS layer, producing spatially explicit thematic maps with a resolution of a 25 m × 25 m raster grid. The lakes, the urban area outside the urban–forest interface and the territories above 2500 m a.s.l. were excluded from the analysis. The topographic characteristics (elevation, aspect and slope) were derived from the Swiss digital elevation model DHM25. The urban–forest interface was constructed by intersecting the forest area with buffers of the urban area from the Swiss digital landscape model VECTOR25 (see http://www.swisstopo.ch/). For the definition of the vegetation cover within the forest area, we considered the nine categories and related maps provided by Pezzatti et al. (2009). In order to account for forest fires originating outside the forest area or trespassing forest gaps we considered two additional vegetation cover types consisting of two buffer zones (0–50 m and 50–100 m) from the forest edge. The remaining territory was classified as non-forest (Table 2).

Beside the 12 vegetation classes, all other variables were split in 9–10 categories of equal range (Table 2) in order to avoid data dispersal and to assure the statistical significance of the analysis. Each fire was assigned to a category of the selected landscape characteristics by overlapping the ignition points of each fire with corresponding 25 m × 25 m landscape pixel.

2.5. Performing Monte Carlo simulations

The contribution of each landscape characteristic to the fire ignition danger was assessed by testing its fire selectivity for the tree fire regime patterns (AWF and ASF 1990–2007 and NSF 1980–2007) separately. This approach was originally designed by zoologists to determine if specific habitats are positively or negatively selected by animals. That is, used more or less than availability (Manly et al., 1993; Alldredge et al., 1998). Other authors have added a pyrologic application to this basic idea stating that fire may be considered as a kind of 'herbivore' exerting variable pressure on different kind of vegetation or forest types as a function of their differential fuel load (Moreira et al., 2001; Nunes et al., 2005; Bajocco and Ricotta, 2008; Pezzatti et al., 2009). In fact, if the different forest types were equally prone to fire ignition, fires would occur randomly across the forest with an equal proportion of available and burnt forest types. In this sense, fire is considered selective when fuels are burnt disproportionately to their availability (Moreira et al., 2001; Nunes et al., 2005). In this study, we developed this idea further, using Monte Carlo simulations to test fire selectivity of each ignition-relevant landscape characteristic listed in Table 2.

For each fire regime pattern, all fire events were randomly reassigned to the different categories of a specific landscape characteristic, such that the probability of assignment of each fire to a given category was kept equal to the relative extension of that category. The null hypothesis is that forest fires ignite randomly across the different categories, so that there is no significant difference between the relative abundance of fire ignitions in a given category and the correspondent relative abundance of that category within the analyzed landscape. The actual number of fires in each category was then compared with the results of 9999 random simulations. For each category, p-values (two-tailed test) were computed as the proportion of Monte Carlo-derived values that were as low or lower (or as high or higher) than the actual values.

We finally assigned the relative fire ignition danger to each category of the considered landscape characteristics by converting the significance levels resulting from the Monte Carlo simulations into integer scores according to the following ordinal scale: ±3 for all categories that are either positively (+3) or negatively (−3) selected by fire with a significance level of $p < 0.001$, ±2 for all categories that are significantly selected by fire with $p < 0.01$, and ±1 for all categories that are significantly selected by fire with $p < 0.05$. All categories that do not show any significant association to fire ignition at $p < 0.05$ receive a score of zero.

As an example, dealing with expositions, if the south-facing slopes (157.5–202.5°) correlate very positively ($p < 0.001$) with the occurrence of anthropogenic winter fires, each raster cell displaying a south-facing exposition will receive a score of +3 as the result of the fire ignition selectivity for the anthropogenic winter fires provided by the Monte Carlo simulations.

2.6. Assessing relative fire ignition danger

We first tested possible redundancies among the selected landscape characteristics by performing a Spearman pairwise correlation matrix on the obtained Monte Carlo scores for each fire regime pattern considered.

We then evaluated the suitability of two different approaches for assessing the final fire ignition danger scores. In a first option we applied a cumulative approach without considering any weighting procedure and assuming that correlations lower than 0.6 among the selected variables reveal an acceptable level of redundancy. The overall fire ignition danger score of each raster cell is in this case calculated for each fire regime pattern separately by adding the single scores obtained from the analysis of each landscape characteristic listed in Table 2 (see Fig. 4 for an example). According to this procedure, the overall fire ignition danger associated to each fire regime pattern potentially ranges from −15 (−12 for NSF) if all landscape characteristics of a given raster cell display a highly significant negative association to fire ignition, to 15 (12 for NSF) if all landscape characteristics of a given raster cell display a highly significant positive association to fire ignition.

The second option consisted in first performing a principal component analysis (PCA) on the scores of the Monte Carlo simulations for each fire regime pattern separately. The overall fire ignition danger score was then determined using the projection of each point on the first axis of the PCA. Doing so, we maximized the overall variance, eliminating existing redundancies among the landscape characteristics considered.

For both approaches, the final relative ignition danger was calculated by normalizing the obtained scores into a range between 0 and 10 (see Fig. 4 for an example). In addition, for the summer season a synoptic fire ignition danger map was obtained by considering for each raster cell the highest value between the anthropogenic and natural summer fires only.

All the computing procedures were performed using the R statistical computing package (R Development Core Team, 2010).

2.7. Data validation

Unfortunately, the exiguous data set available does not allow validating the results using a totally independent data set for all fire regimes in the period considered. We therefore used both the period of the analysis (1990–2007) and the previous period (1969–1989). In doing so, we split the original dataset (1980–2007) for natural summer fires over the two periods. Apart from possible changes in the anthropogenic fire ignition behaviour due to the new legislation, we assumed that the vegetation cover, the morphological components (slope, elevation and aspect) and the urban–forest interface did not change dramatically during the two periods considered.

We then verified within each period the suitability of the results obtained with the cumulative and the PCA approach by comparing separately for winter and summer the fire ignition danger of raster cells with fire ignitions with a random selection of cells without ignitions during the corresponding season. By the selection procedure we enforced a minimum distance between randomly selected grid points of at least 100 m. We then tested the differences in the distributions of the fire ignition danger values by means of a non-parametric Wilcoxon rank-sum test.

Table 3
Monte Carlo results for the selectivity to the fire ignition frequency.

Vegetation cover	Cover types	Non-forest	Other coniferous forests	Mixed forests	Other broadleaved forests	Chestnut stands	Beech stands	Spruce stands	Fir stands	Larch stands	Pine stands	Buffer 0–50 m	Buffer 50–100 m
	AWF	−−−	−−−	+++	+++	+++	−−−	−−−	−−−	−−−		+++	
	ASF	−−−				+++	−−		−−−			+++	
	NSF	−−−		+			−	+++				++	−−
Elevation	(m a.s.l.)	<250	251–500	501–750	751–1000	1001–1250	1251–1500	1501–1750	1751–2000	2001–2250	2251–2500		
	AWF		+++	+++	+++	+	−−−	−−−	−−−	−−−	−−−		
	ASF		+++	+++	++		−−	−−	−−−	−−−	−−−		
	NSF	−−−	−			+	++	+	−−	−−−	−−−		
Slope	(°)	<8.35	8.25–16.50	16.50–24.75	24.75–33.00	33.00–41.24	41.24–49.48	49.48–57.73	57.73–65.98	65.98–74.23	>74.23		
	AWF		++	+++	+++	−−−	−−−	−−−	−−−	−−−	−−−		
	ASF				+		−−			−−−	−−−		
	NSF	−−−	−−	−−−			+	+++	+++		−−−		
Aspect	(g)	flat	337.5–22.5	22.5–67.5	67.5–112.5	112.5–157.5	157.5–202.5	202.5–247.5	247.5–292.5	292.5–337.5			
	AWF	−−−	−−	−−−	−	++	+++	+++		−−			
	ASF	−−−						+					
	NSF	−−−	−−					++					
Urban–forest interface	Interface types	No urban–forest interface	Urban–forest <100 m	Urban-non-forest <100 m	Urban–forest 100–200 m	Urban-non-forest 100–200 m	Urban–forest 200–300 m	Urban-non-forest 200–300 m	Urban–forest 300–400 m	Urban-non-forest 300–400 m			
	AWF	−−−	+++	+++	+++	+++	+++	++	+				
	ASF	−−−	+++	+++	+++		+++						
	NSF												

AWF = anthropogenic winter fires; ASF = anthropogenic summer fires; NSF = natural summer fires. +++/−−− correspond to significance values $p < 0.001$ (two-tailed test); ++/−− = $p < 0.01$; +/− = $p < 0.05$; no symbol = non significant at the $p = 0.05$ level (The signs +/− refer to positive or negative selectivity to fire ignition).

Table 4
Spearman pairwise correlation matrices.

Fire regime pattern	Landscape characteristics	Vegetation	Urban	Slope	Aspect
AWF	Urban	0.257			
	Slope	0.040	0.127		
	Aspect	0.075	0.089	0.001	
	Elevation	0.412	0.495	0.078	0.014
ASF	Urban	0.205			
	Slope	−0.011	0.081		
	Aspect	0.055	0.029	−0.015	
	Elevation	0.382	0.507	0.043	0.029
NSF	Slope	0.099			
	Aspect	0.013		0.008	
	Elevation	0.526		0.144	0.022

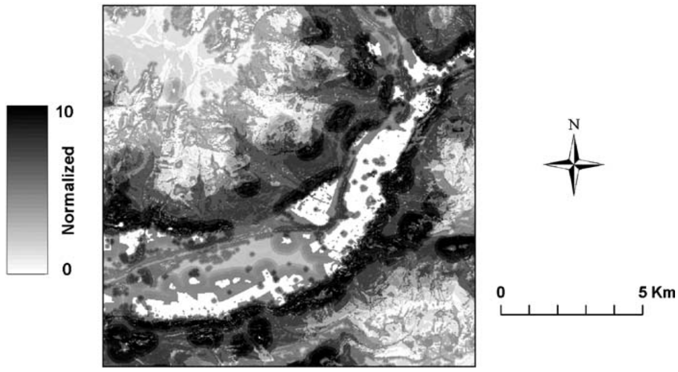

Fig. 6. Example of a fire ignition danger map referring to the anthropogenic winter fires resulting from the PCA approach. The fire ignition danger scores are rescaled in the range 0–10.

3. Results and discussion

3.1. Monte Carlo simulations

Results of the Monte Carlo simulations for the landscape characteristic considered are reported in Table 3. AWF frequency was significantly higher (overrepresented) in chestnut stands, mixed forests, other broadleaved forests, and the area next to the forest edge (50 m buffer) as expected according to the relative abundance of these vegetation cover categories. Fire frequency was significantly lower (underrepresented) in beech, spruce, fir, and larch stands, as well as in other coniferous forests. Outside the forests, fires are underrepresented in the non-forest category and in the 50–100 m buffer area from the forest edge. Pine stands were the only vegetation type without any significant pattern in fire ignition frequency. In most cases, ASF displayed similar patterns (preference for buffer area 0–50 m, chestnut stands; avoidance of beech stands, fir stands and non-forest), albeit with a lower statistical significance. NSF were clearly prevalent in spruce stands but less significant in mixed forests. NSF tend to be rare in the 50–100 m buffer area, beech stands, and in the non-forest area.

Altitudinal distribution of ignition frequency clearly follows two contrasting patterns: significant overrepresentation of the lower altitudes (<1000 m a.s.l.) for both anthropogenic fire regimes (AWF and ASF) and overrepresentation of lightning-induced fires (NSF) at altitudes between 1000 and 1750 m a.s.l. Similarly, NSF are more frequent on steep slopes (50°–66°), whereas AWF develop more frequently on the gentler slopes (8–33°). Fire ignitions are clearly overrepresented on south-facing slopes during the winter season, but not during summer. This is because during summer the drying effects of sunshine do not appear to differ greatly according to main exposition, with the exception of the NW sector. The interface between settlements and forest is greatly overrepresented in fire frequency up to 300 m, with a still significant effect up to 400 m for AWF. In contrast, the effects of the interface between settlement area and open areas (non-forest) extend up to 300 m in winter and 100 m in summer.

Selectivity to fire frequency for NSF is very similar to what Conedera et al. (2006) reported for lightning-induced fires in the Alps: fires are very frequent on the relatively steep slopes of high mountains at elevations where spruce stands dominate. On the other hand, the selectivity for both anthropogenic fire regime patterns (AWF and ASF) tends to match the distribution of the local population and of the human activities which reach their maxima at low elevations, on gentle south-facing slopes, and close to the urban–forest interface (see also Pezzatti et al., 2009). During the main fire season (December–April), this relationship tends

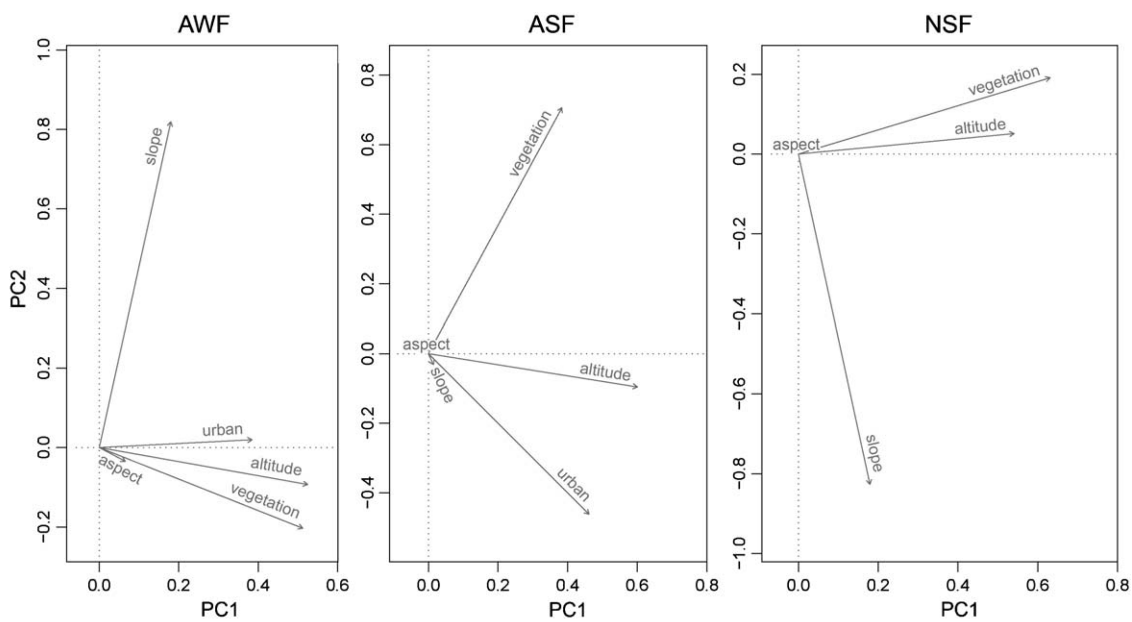

Fig. 5. Result of the PCA on the scores of the Monte Carlo simulations for the three considered fire regime patterns: AWF, anthropogenic winter fires; ASF, anthropogenic summer fires; NSF, natural summer fires.

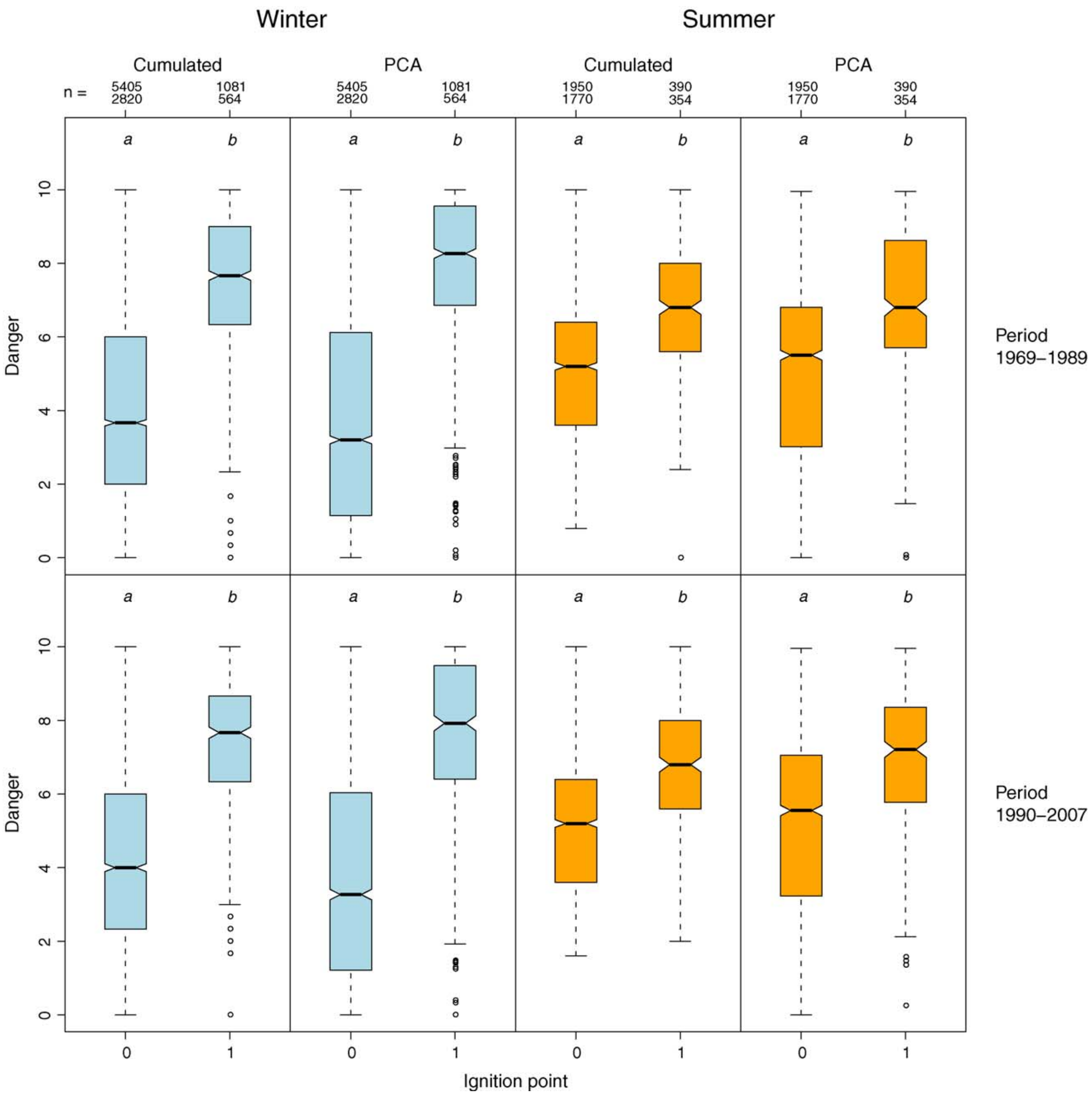

Fig. 7. Box-plot distributions of winter and summer fire danger values for points with and without fire ignitions in the periods 1969–1989 and 1990–2007 for the cumulated and the PCA approaches. Distributions with different letters are significantly different ($p < 0.05$, non-parametric Wilcoxon rank-sum test).

to be stronger because fire-related human activity tends to be more concentrated at low, snow-free elevations close to residential areas.

Table 4 reports the Spearman pairwise correlation matrices for the three fire regime pattern considered. The correlation coefficients are generally low with only two cases of values exceeding 0.5 that is the correlation between urban and elevation in the anthropogenic summer fires (ASF; 0.507) and between elevation and vegetation in the case of natural summer fires (NSF; 0.526).

3.2. Relative ignition danger assessment

Fig. 4 shows a map of fire ignition danger for the anthropogenic winter fires (AFW) in a sub-area of the study region (see Fig. 1) as resulting from the cumulative approach consisting in summing up the scores of according to the fire selectivity of the single landscape characteristics (a–e) to a final score representing the total fire ignition danger (f). The results of the PCA for the three fire regime patterns considered and the resulting fire ignition danger map for the anthropogenic winter fires (AFW) are reported in Figs. 5 and 6, respectively. As expected from the correlation matrices reported in Table 4, the first axis of the PCA reveals evident overlapping for the vectors urban and elevation (correlation factor of 0.495, see Table 4) as well as vegetation and elevation (0.412) for the AWF, urban and elevation (0.507) for the ASF, and vegetation and elevation (0.526) for the NSF (Fig. 5). As a general result, the PCA strongly reduces the effect of the aspect and the slope on the relative ignition danger. As reported by Reineking et al. (2010) for the same study region, in case of fires of anthropogenic origin humans usually provide enough ignition energy. This may explain the high priority given by the PCA-model to the presence of settlements as a proxy for ignition source that masks the effect of slope and aspect in particular. This can be also optically verified by comparing the final fire ignition danger maps for AWF as resulting from the two different approaches. With respect to the cumulative approach (Fig. 4f), in the PCA-option the main influence on the map is given by the presence of settlement patches (Fig. 6).

Concerning the summer time, on contrary, the general high temperature and irradiation level reduces the importance of the aspect and slope effects in relation of the fuel drying processes.

Fig. 7 reports the frequency distributions of fire ignition danger values for the winter and summer fire regimes for cells with and without ignition points during the period 1990–2007 and 1969–1989, respectively. Both approaches display statistically significant differences in the fire ignition danger scores between cells with and without fire ignitions ($p < 0.05$, non-parametric Wilcoxon rank-sum test) for the periods considered.

Although connected with a much higher computing effort, the PCA-approach reaches a slightly higher discrimination power between ignited and non ignited cells, especially for anthropogenic winter fires (Fig. 7). On contrary, due to the empirical approach without any attempt of weighting the single variables, the suitability of the cumulative approach in terms of discrimination capability between sites with and without fire ignitions of the final ignition danger model may highly depend on the degree of correlation existing among the explanatory variables considered in the study area.

4. Conclusions

In this study we propose testing the fire ignition selectivity of different landscape characteristics by using Monte Carlo simulations. Starting from the selectivity pattern obtained with the Monte Carlo simulations, two different approaches are proposed for assessing the relative fire ignition danger of the study area: cumulating the scores of the Monte Carlo simulations to a final index and producing a synthetic scores by performing a principal component analysis (PCA) of the Monte Carlo scores.

The statistical verification of the resulting fire danger indices showed that both proposed approaches are suitable for producing a fire ignition danger map of a low-to-intermediate fire-prone region such as Canton Ticino. The PCA-option allowed a slightly better discrimination between ignition and non-ignition points. On contrary, the cumulative approach is simple and may even be operated with a relatively small amount of fire data and/or on coarser scales, but it is subjected to limitations in case of high degree of correlation among the explanatory variables considered. In such cases the PCA approach should be privileged.

The approaches we describe here for assessing relative fire ignition danger may effectively assist forest and landscape management authorities in developing better fire management plans in areas of low-to-medium fire frequency. For instance it should support managers to select appropriate preventive and pre-suppression activities, to locate helicopter water points, to plan fuel management interventions, as well as to simulate different fire scenarios with different fire-fighting tactics. Local discrepancies between the theoretical fire danger index provided by the method and existing fire hot-spots are mainly due to permanent (structural) ignition sources such as military areas, steep railway sections, and electroducts that were not considered in the general model. Such specific hot-spots can be however easily identified and considered when implementing fire management measures. Furthermore, by combining the fire danger with the vulnerability to fire (ecological and economic fire impact) of each cell considered the resulting fire risk (combination of fire danger and vulnerability to fire) can be assessed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2010.08.013.

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