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Effects of human-related and biotic landscape features on the occurrence and size of modern forest fires in Sweden

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ABSTRACT

The influence of landscape features on the occurrence and size of forest fires in Northern Europe has not been well-studied. In this paper, we analyzed the impact of human-related landscape properties (road and human population density), biotic features (amount of firebreak area and vegetation zone) and fire weather indices (Buildup Index, BUI and Initial Spread Index, ISI) on the occurrence and size of forest fires in Sweden from 1998 to 2017. To analyze the environmental controls of fire occurrence and fire size under different levels of climatological fire hazard, we divided the data into two subsets: (1) large fire years (LFY), defined as the years with the total amount of burned area being higher than the dataset-wide average (2002, 2003, 2006, 2008 and 2014), and (2) the remaining years (nLFY). Our analytical approach was based on spatial models using Integrated Nested Laplace Approximations (INLA). Models built on both LFY and nLFY subsets suggested a strong human influence on fire occurrence: road density, the number of firebreaks, and population density, all were positively associated with fire occurrence, suggesting an important role of human-related ignitions. The southernmost vegetation zones in Sweden (boreo-nemoral and nemoral) exhibited the highest fire occurrence (LFY), a pattern potentially related to a higher population density in combination with weather more conducive for fires in this part of the country. The patterns that emerged from the fire size models pointed to the climate as the main factor controlling fire size, irrespective of the type of years analyzed. Road density, number of firebreaks and population density showed a negative association with fire size, possibly indicating higher efficiency of fire suppression in the areas with higher human presence. Vegetation zones were selected as an informative predictor, indicating that the fire activity varies across the zones, with those in mid-Sweden being the most prone to large events. The ISI correlated strongly and positively with fire size in both subsets (LFY and nLFY), pointing to the role of weather conditions favorable for fire spread, primarily that of surface fires. The BUI showed a weak negative correlation to fire size, indicating that dryness of organic horizon, specifically its deeper layers, is less relevant for predicting fire size. Contemporary fire activity in Sweden is driven by a combination of human-related ignitions, and weather conditions controlling fire spread with a moderate effect of vegetation composition and generally efficient fire suppression. Human-related landscape features (roads and population density) play a major role in shaping ignition patterns, whereas climate (ISI) and vegetation properties appear informative as predictors of fire size, even under a modern fire suppression effort.

1. Introduction

Forest fire is a major disturbance factor in boreal landscapes that is mainly driven by climatic conditions (Stocks et al., 2002; Drobyshev et al., 2012, 2016; Flannigan et al., 2013). Prolonged droughts precondition forest fuels and make increasingly larger portions of the forest landscape conducive to fires. Forest age and forest composition largely control the distribution and abundance of forest fuels, creating variability in fire risks across the landscape (Larsen, 1997) and affecting the spatial patterns of fire spread (Larsen, 1997; Niklasson and Granstrom, 2000; Hellberg et al., 2004). Under natural conditions, fuels are ignited by lightning strikes

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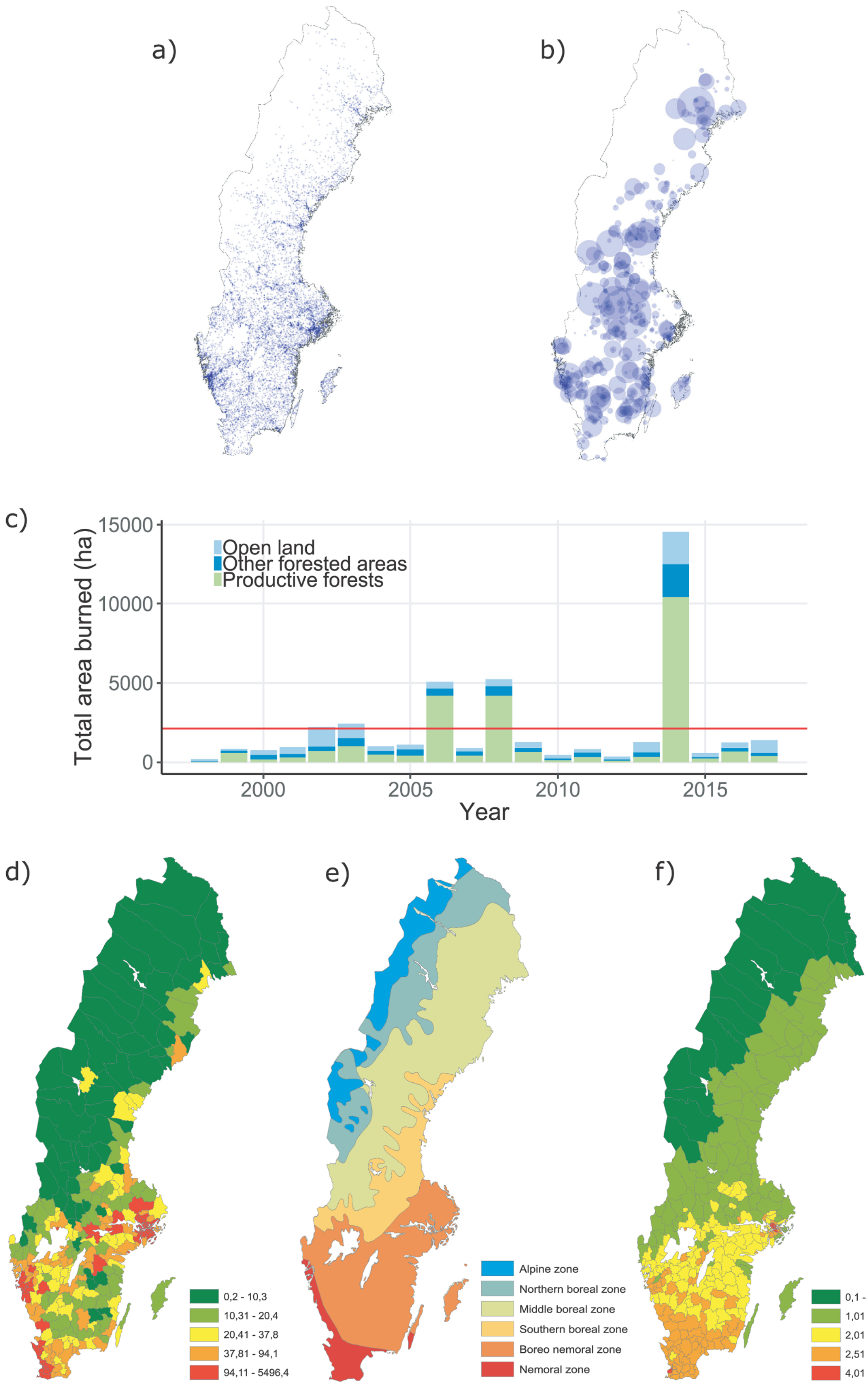

Fig. 1. Forest fires in Sweden during 1998–2017 (a) drawn at the linear scale and (b) location of fires larger than 10 ha's, drawn at the logarithmic scale (log (fire size)). (c) The total amount of area annually burned by forest fires in Sweden for three land cover categories, in ha. The red line is the dataset-wide mean (1998–2017). Large fire years (LFYs) are the years with the annually burned areas being above the mean (years 2002, 2003, 2006, 2008 and 2014). Maps of selected variables: (d) population density (inhabitants/km^2) county-wise; (e) Swedish vegetation zones; and (f) road density (km/km^2) county-wise. Note: the variability in fire sizes was accommodated in Fig. 1b by using the logarithmic scale.

(Granström, 1993), whereas in populated areas, humans may contribute with additional ignition sources.

Throughout history, humans altered forest fire regimes either through providing additional sources of ignition or by actively suppressing fires (Granström and Niklasson, 2008). Human ignitions currently account for the majority of forest fires in temperate and boreal regions of the Northern Hemisphere (Stocks et al., 2002). These ignitions are facilitated by the modern infrastructure, such as road networks that provide public access to the forests. In some regions of the USA and Western and Central Europe, human activity has been identified as a main source of fire ignitions (Ubysz and Szczygieł, 2006; Catry et al., 2009; Martínez et al., 2009; Syphard et al., 2017; Adámek et al., 2018; Sjöström et al., 2019), considerably exceeding natural ignition frequencies (Ubysz and Szczygieł, 2006; Syphard et al., 2017). In Northern Europe, however, the understanding of human-related modern controls of forest fire activity remains limited to studies of recent fires that are primarily focused on the effects of climate variability (Drobyshev and Niklasson, 2004; Drobyshev et al., 2012).

Since 1996, the annual burned area of the forest in Sweden ranges between 1 000 and 5 000 ha (MSB, 2019). This proves that there was an efficient application of fire suppression policies. However, two recent events questioned the ability of the modern fire suppression in Sweden to effectively manage fire risks under periods of extreme fire hazard. In 2014, a fire in the vicinity of Sala town in the Västmanland County of central Sweden burned ~ 14 000 ha and in 2018, several fires cumulatively burned ~ 21 000 ha. The size of the Sala fire exceeded the size of the previous largest fire in recent times, by nearly a factor of ten (the Bodträskfors fire in the county of Norrbotten in 2006 burned around 1900 ha) (Bodens kommun, 2006). The Sala fire exemplified an interplay of human and climatic factors: the ignition source of that fire was related to forestry operations, although its spread was greatly favored by a prolonged drought period in combination with high winds. Although they are of critical importance in shaping modern fire activity, these relationships remain largely unstudied in Northern Europe.

Aiming to reduce this knowledge gap, we quantified the effects of selected road density and population density and biotic landscape features (firebreak area and vegetation zone) and fire weather indices (Buildup index, BUI and Initial Spread Index, ISI) on the occurrence and size of modern fires in Sweden. We hypothesized that: (H1) road and population density positively affect fire occurrence but negatively affect fire size; (H2) increasing amount of firebreaks negatively affects fire occurrence and fire size and; (H3) the patterns suggested in H1 and H2 do not depend on climatological fire hazard over a fire season. The H1 assumed a higher density of human ignitions in more accessible parts of the forested landscapes and also higher suppression efficiency, due to reduced initial attack time (Hansen, 2003). The H2 assumed a negative effect of firebreaks on fire occurrence and spread due to reduced fuel amount, lower conductance and spread possibilities in the parts of the landscapes with a higher proportion of non-burnable areas. H3 assumed that in years characterized by extreme weather conditions, such as prolonged droughts (e.g. 2014), the impacts from H1 and H2 on fire activity remain consistent in relation to years with normal weather conditions.

2. Methods

2.1. Study area

Sweden lies between 55° and 70°N, with a total land area of 40.7 million ha (Skogsstyrelsen, 2014). The North Atlantic westerlies have a strong influence on the Swedish climate, resulting in a relatively mild maritime climate in the south (Rohli and Vega, 2008). Winter temperatures show a strong north-south gradient with January means at around 0 °C in the south, to around −14 C° in the north. Due to the continental influence in the north and maritime influence in the south, summer temperatures are less variable, with only minor deviations from a July mean of 14–16 °C. Annual precipitation shows a pronounced east-west gradient in the southern part of the country with 500–600 mm in the east up to 1100 mm in the west. The build-up of high-pressure cells over Scandinavia during summer diverts the Atlantic westerlies towards the lower latitudes, eventually creating periods of dry weather (Wastenson et al., 1995), which drives the forest fire hazard during the fire season.

The country's productive forest land is 23.2 million ha, which covers around 57% of the total land area (Skogsstyrelsen, 2014). The standing volume of the productive forest is dominated by *Picea abies* (42%), *Pinus sylvestris* (39%) and *Betula pendula* (12%) (Skogsstyrelsen, 2014). Swedish vegetation is divided into six biogeographical zones (Fig. 1e): alpine, northern boreal, middle boreal, southern boreal, boreo-nemoral and nemoral (Ahti et al., 1968; Wastenson et al., 1996).

Fire has been a part of the Swedish landscape, since the establishment of forest vegetation in the early Holocene, around 10 000 years ago (Carcaillet et al., 2007; Bradshaw et al., 2010). Over the last five centuries, the dynamics of forest fire activity has been responding to variability in climate (Drobyshev et al., 2016) and human land use patterns (Granström and Niklasson, 2008). At the end of the 19th century, fire activity declined in the most of the country's forests, as a result of fire suppression policies and less fire-prone weather in the post-Little Ice Age period (Niklasson and Granstrom, 2000; Drobyshev et al., 2012, 2015). During the 20th and 21st centuries, the levels of fire activity remained low with 3 000 to 4 000 fires burning around 2 000 to 5 000 ha annually (Granström, 1993; Drobyshev et al., 2012; National Knowledge Centre for Climate Change Adaptation, 2016).

2.2. Fire data

We used official forest fire data in Sweden containing information on date, location and area burned between 1998 - 2017 from the Swedish Civil Contingency Agency (*in Swedish* Myndigheten för Samhällsskydd och Beredskap, MSB, 2017) (Fig. 1). The raw dataset contained information on 88 982 fires. It was filtered to exclude fire locations with coordinates inside urban areas and water bodies (6553 fires), as mapped by the CORINE dataset (EEA, 2017). We also removed the data with missing or dubious observations on fire date, size or location (25 740 fires), as well as duplicated records (1851 fires). We classified records as duplicated, when they referred either to two or more entries of a fire that occurred in a 4.9 hectare area within a two-day period. We considered that those fires were either multiple reports or re-ignitions of the same fire. In such cases, we used the larger fire size estimate among all estimates for assumingly the same fire event. The size of the area used to identify duplicated records (4.9 ha) was the median of the fire size distribution in our dataset. Datasets fed to fire size models also excluded fires (5540 fires) that were dated outside the fire season, i.e. from April to October. The total number of fires analyzed in the fire occurrence models was 54 838 and in the fire size models was 49 298.

2.3. Landscape data

We analyzed two aspects of fire activity: fire occurrence and fire size. To analyze fire occurrence, we used a circle with a radius of 100 m (3.14 ha, latter referred to as *buffer area*) centered on the geographical coordinates of each fire, as recorded in the database. The size of that buffer was intended to make our variables capture local fine-scale conditions, where the initial ignition took place. To analyze fire size, we used a circle with a 1000 m radius (314 ha). The size of the area aimed to characterize the landscape context relevant for the fire spread.

For both buffer sizes, we quantified two human-related and two biotic landscape variables: length of roads (later referred to as roads), human population density, proportion of the area occupied by firebreaks, and vegetation zone (Table 1). Roads were the sum of the length

Table 1
Variables used in the models. For each variable, we extracted data for a circle centered on the fire coordinates. To model fire occurrence, the size of the circle was set to 3.14 ha and to model fire size 314.15 ha.

Independent variable	Dependent variable modeled with that variable	Data description	Resolution	Reference
Vegetation zone	Fire occurrence; fire size	Polygons representing vegetation zones	Vector data	(Ahti et al., 1968; Wastenson et al., 1996)
Population	Fire occurrence; fire size	Mean of population density in inhabitants/km^2 from a pixel grid, 2012 data	100×100 m^2	(Gallego, 2010; EEA, 2012)
Roads	Fire occurrence; fire size	Sum of road length in km, 2016 data	Vector data	(Lantmäteriet, 2016)
Firebreak	Fire occurrence; fire size	Sum of pixels that contained firebreak structures (urban areas, water) from a pixel grid, 2012 data	100×100 m^2	(EEA, 2017)
BUI	Fire size	Buildup Index calculated using BioSIM 11 for each fire location	index	(Régnière et al., 2017)
ISI	Fire size	Initial Spread Index calculated using BioSIM 11 for each fire location	index	(Régnière et al., 2017)

of all roads and railroads (km) within the buffer areas. Road data originated from the Lantmäteriet database (Lantmäteriet, 2016). The class 'poorer class road' (*sämre bilväg* in Swedish) was excluded, since it is generally not accessible by car and mainly used by tractors for timber harvesting. The variable "population density" was the log of the mean of inhabitants/km^2 from the population density raster dataset, with a 100×100 m resolution, from the European Environment Agency (EEA, 2012) within the buffer area for occurrence and size. We defined firebreaks as urban areas and water bodies, as represented in the CORINE raster dataset, with a 100×100 m^2 resolution (EEA, 2017). Although firebreaks could be both natural and human-related, we considered this variable as a natural landscape feature as the amount of water pixels that surpassed the amount of urban area pixels (85% and 15%, respectively). The value for firebreaks was the count of firebreak grid cells within the respective buffer areas. Finally, we placed each fire within one of the six vegetation zones.

Representation of vegetation cover from the CORINE dataset was potentially subject to a loss in resolution. The reason for that was the size of the minimum mapping unit (MMU) in CORINE data (25 ha), i.e. the minimum size which an area is mapped accurately (Knight and Lunetta, 2003). However, it was unlikely that this accuracy loss had a tangible effect on the results, since the CORINE dataset has a user accuracy for urban areas and water bodies over 90% (EEA, 2017). A minor loss in accuracy, which we did not quantify precisely, seemed acceptable for a Sweden-wide analyses.

To portray weather conditions during fires, we considered fire weather indices as potential predictors in the fire size models: Buildup Index (BUI) and Initial Spread Index (ISI). Both indices are components of the Canadian Fire Weather Index (FWI, Lawson and Armitage, 2008). The BUI is a proxy of fuel available for combustion, derived from middle-term (weekly to monthly) temperature and rainfall and relative humidity of deeper organic layers (Van Wagner, 1987; Lawson and Armitage, 2008). ISI is a measure of fire spread potential, derived from short-term (hourly to daily) temperature and rainfall, relative humidity of litter and fine surface fuels and wind speed (Van Wagner, 1987; Lawson and Armitage, 2008). We calculated the BUI and ISI for each individual fire point with the BioSIM 11 software (Régnière et al., 2017), using data from the four nearest meteorological stations. In case of missing fire weather indices due to the fire occurring outside the fire season, we used the indices from the closest day for which indices were available. In total, there were 809 fires with missing weather data distributed throughout the months of October to December. The difference between the day a fire brigade reported the fire and the nearest date with available BUI and ISI had the mean of 24.3 days and median of 20.4 days. We considered these data gaps of having a minor effect on the overall results, as they represented only 1.3% of all fires analyzed. Further, the weather indexes allocated to those missing days were in general low (mean ISI of 1.55 and median of 1.16; mean BUI of 14.04 and median BUI of 4.41), reflecting the fact that these dates were commonly outside the regular fire season.

For the study of fire occurrence, we created a control dataset of 158 000 points randomly placed within Swedish borders, excluding locations falling inside urban areas and water bodies, as mapped in the CORINE dataset (EEA, 2017). For each random point, we collected information on human-related and biotic landscape features, using a 100-meter buffer centered at each point (Table 1). To obtain information on the properties of these points, we used the same protocol as for the collection of data around actual fire locations (see above). The random points were generated by the *Create random points* tool in ArcGIS 10.4.1 (ESRI, 2015).

2.4. Statistical analysis

The fire occurrence analysis used a binary response variable, with 0 indicating a random point and 1 indicating a fire. The fire size analysis used the total area burned as the response variable. To analyze the predictive skill of our explanatory variables to the changes in the levels of climatically controlled fire hazard in the fire occurrence and fire size models, we considered two different subsets of data: large fire years (LFY) and non-large fire years (nLFY). LFY were defined as the years where the total amount of area burned was higher (2002, 2003, 2006, 2008 and 2014) than the 1998–2018 average (Fig. 1c). The remaining years were classified as nLFY. The total sample size in the subset used to study fire occurrence was 16 526 in the LFY and 38 312 in the nLFY. The total sample size for analyses of fire size were 15 033 in the LFY and 34 265 in the nLFY.

To support the analysis of fire occurrence, we obtained a dataset of random points placed within the country borders. The number of random points used was 41 315 for the LFY subset and 95 780 for the nLFY subset. These amounts corresponded to 2.5 times the number of actual fires in each analyzed subset of years. The total number of points (random points and fires) analyzed in the fire occurrence models were 57 841 in the LFY subset and 134 092 in the nLFY subset.

To facilitate the inclusion of a spatial component dealing with residual spatial autocorrelation (Dormann et al., 2007; Hoeting, 2009), fire occurrences and fire sizes were both modeled using the Integrated Nested Laplace Approximation (INLA) (Rue et al., 2009). INLA provides an alternative to MCMC (Markov Chain Monte Carlo) for estimating latent Gaussian models in a Bayesian framework. It is especially suited for estimating spatial models (Bakka et al., 2018), since spatial components can be added through the Stochastic Partial Differential Equation (SPDE) approach (Lindgren et al., 2011). This approach allows the approximation of certain types of Gaussian random fields through an explicit link with Gaussian Markov Random Fields (GMRF) (Lindgren et al., 2011; Bakka et al., 2018).

Prior specification was done with the intent of providing weakly informative priors that could (a) avoid unrealistic parameter values on the scale of the linear predictor and (b) ensure reasonable parameter estimates (Lemoine, 2019). Whenever possible, we used penalized-complexity (PC) priors as they are easy to interpret and they tend to reduce model complexity unless supported by the data (Simpson et al., 2017). Considering the amount of available data, we, however, expected that priors would have only a weak influence on our analysis.

We assessed fire occurrence, by modeling the probability of a location being an actual fire (1) or not (0) using a logit link and a binomial error structure. Fires sizes were modelled using the generalized Pareto distribution (GPD), as parameterized in INLA (Krainski et al., 2018). Specifically, the INLA parameterization allows the modeling of a selected quantile of the distribution of fire sizes through a log link and the linear predictor, assuming that this distribution is described by the GPD. We chose to model a high quantile (here, 0.99), instead of the mean or the median of fire sizes, since the vast majority of fires are relatively small and are not as important as larger fires, in terms of the damage caused (Holmes et al., 2008). The INLA parameterization also allows the estimation of the shape parameter controlling the tail behavior of the distribution. Values of the shape parameter over 0.5 are associated with infinite variances and values over 1 are associated with infinite means (Krainski et al., 2018).

We used the same prior specification for parameters of the spatial field for both fire occurrence and fire size models. The PC prior used for the range parameter controlling the extent of spatial dependence represented a probability of 0.1 that the range is below 50 km. The prior used for the standard deviation (SD) of the spatial field represented a probability of 0.1 that the SD is over 3. The shape parameter of the Matérn covariance function was set to the default value 2. Other values produced very similar results. The maximum side length of triangles in the mesh was set to 10 km, which is much smaller than the expected extent of spatial dependence.

INLA uses a log-gamma prior for the shape parameter of the GPD that approximates a PC prior for the parameter (Krainski et al., 2018). We chose values of 1 and 3.25 for the prior specification, which represents an approximate probability of 0.1 that the shape parameter is over 0.5. We avoided constraining the value of the shape parameter too much, since values consistent with heavy tails and infinite variances have been observed in other wildfire studies (Pereira and Turkman, 2018).

For both fire occurrence and fire size models, default priors were used for the intercept and all explanatory variables, except for categorical variables for which more realistic priors were used. The default Gaussian priors of INLA for fixed effects parameters are centered on 0 with a SD of ∼ 32, which could potentially be informative on the logit (Seaman et al., 2012) or the log scale. Instead, Gaussian priors with mean 0 and SD 5 were used for all categorical variables. This represents a relatively large range of possible values on the logit or the log scale.

We analyzed all subsets for both fire occurrence and size models using the same protocol. We run a set of 11 different models for each subset, where each model had a different combination of explanatory variables. In order to have both anthropogenic and natural influences on fires, we kept at least one human-related variable and one natural landscape variable in different combinations in all models. The climate data was only added to the fire size models, because of the difficulty in generating weather data across and within years for the random points in the fire occurrence models. The fire size analysis had models either with or without climate variables.

Models were compared using the Watanabe-Akaike information criterion (WAIC; Gelman et al., 2014; Watanabe, 2010). Compared to alternatives, such as DIC (Deviance Information Criterion), WAIC uses the entire posterior distribution, instead of relying upon the posterior means of parameters (Vehtari et al., 2017). The probabilities resulted from the fire occurrence models are not a probability of a fire to occur but a probability of a point being a fire or not proportional to the density of our observations (Aarts et al., 2012).

Both analyses run the same set of 11 models and the model with the lowest WAIC value was selected. The analyses differed by (a) the type of dependent variables (a binary variable in fire occurrence models and a continuous variable in fire size models), and (b) the presence of climate data in models operating on fire size variable.

3. Results

3.1. Fire occurrence

The fire occurrence models showed strong correlations of human-related landscape features with fire occurrence (Figs. 2 and 3). The model selection algorithm chose a similar set of variables for each data subset analyzed (LFY and nLFY), with similar relationships to fire occurrence. The fire occurrence models developed on both subsets contained a nearly identical list of variables: roads, population density and firebreaks, whereas the model fed with LFY data also selected the vegetation zone variable.

Length of roads showed a strong positive correlation with the probability of a point being a fire (∼0.2-∼0.9 for both LFY and nLFY subsets). Population density (∼0.2–0.5 for both LFY and nLFY subsets) and firebreak density (∼0.2–0.5 for both LFY and nLFY subsets) had similar effects on fire occurrence. We observed an increase in the credible interval (CI) along the gradients of these variables. Both variables also revealed wider CI in the analyses done on nLFYs, in comparison to the LFYs. During LFY the nemoral and boreo-nemoral zones had a higher probability of a point being a fire (∼0.2), in comparison to other vegetation zones.

3.2. Fire size

The fire size models selected the same set of variables for both subsets of years analyzed (LFY and nLFY, Figs. 4 and 5). Irrespective of the data subset analyzed (LFY or nLFY), we observed similar relationships between fire size and the predictors selected by both subsets (Figs. 4 and 5). Fire size negatively correlated with road length,

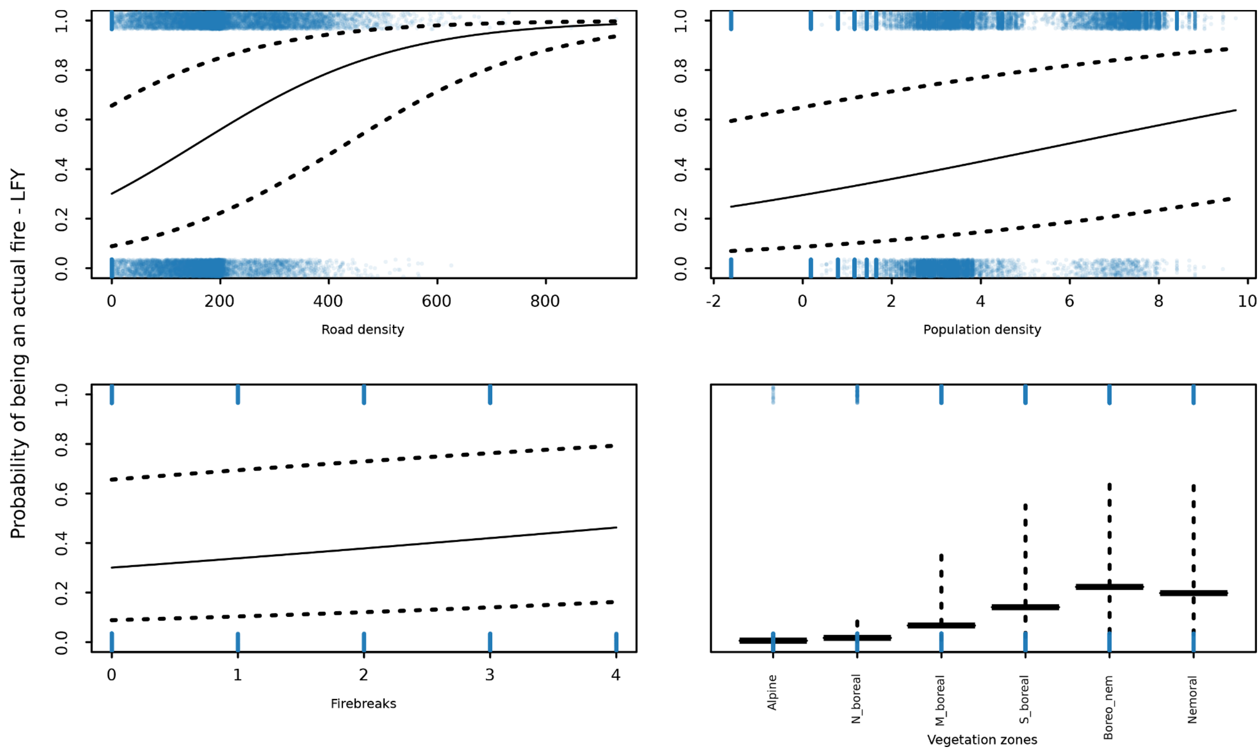

Fig. 2. Relationship between fire occurrence and factors selected by the best model operating on the subset of data representing large fire years (LFY). Units: road density, meters; population density, log (mean of inhabitants/km^2), firebreaks, pixel count within the buffer area; and vegetation zones, predefined classes. The y-axis shows the probability of a point being a fire proportional to the density of our observations (random points (probability of 0) and fire points (probability of 1)). Each blue point represents either a random point or a fire and the dotted lines represent the credible interval (CI).

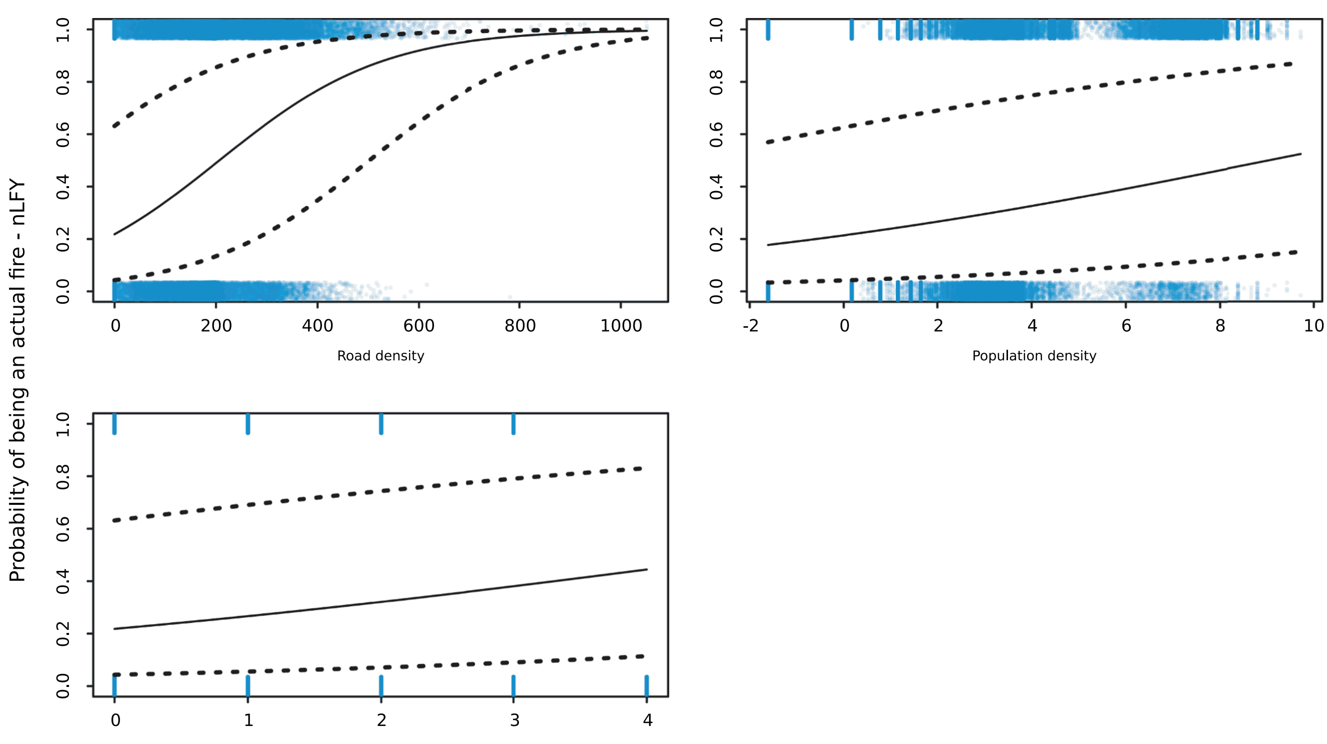

Fig. 3. Relationship between fire occurrence and factors selected in the model operating on the subset of data representing non-large fire years (nLFY). Units: road density, meters; population density, log (mean of inhabitants/km^2), firebreaks, pixel count within the buffer area; and vegetation zones, predefined classes. The y-axis shows the probability of a point being a fire proportional to the density of our observations (random points (probability of 0) and fire points (probability of 1)). Each blue point represents either a random point or a fire and the dotted lines represent the credible interval (CI).

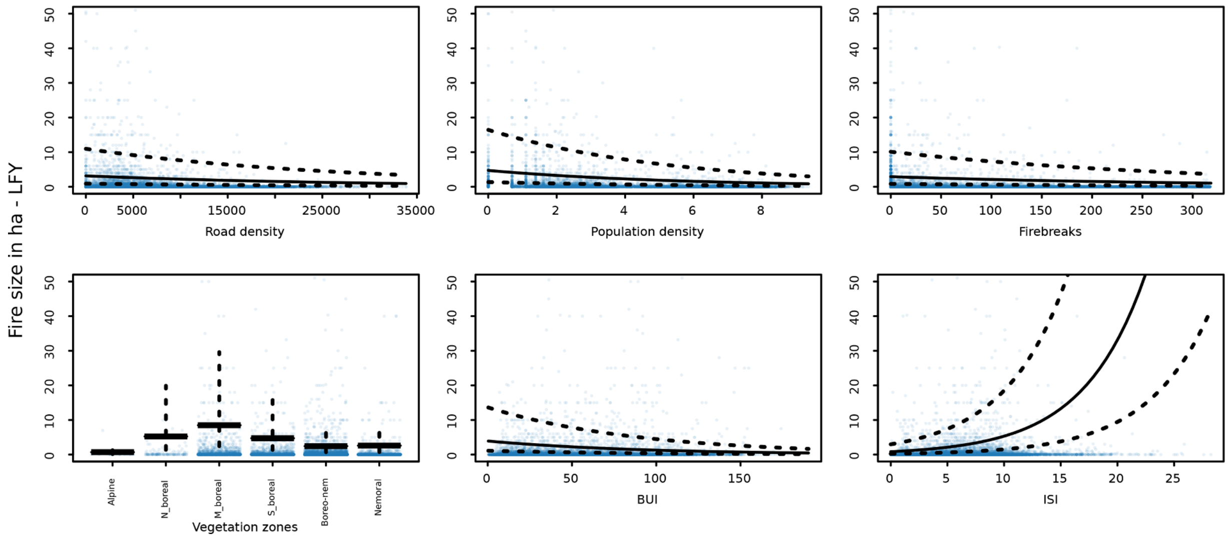

Fig. 4. Relationship between fire size and factors selected in the model operating on the subset of data representing large fire years (LFY). Units: road density, meters; population density, log (mean of inhabitants/km^2), firebreaks, pixel count within the buffer area, vegetation zones, predefined classes; BUI and ISI - index values. Each blue point represents a fire and the dotted lines represent the credible interval (CI).

population density and firebreaks in both subsets, with the CIs becoming narrower along the gradient in predictor values.

All variables selected by the fire size model presented stronger associations with fire size operating on the LFY subset (Fig. 5), when compared to those observed in the model operating on the nLFY subset (Fig. 4). The middle boreal zone was associated with higher fire size than the other vegetation zones during LFY, although the pattern was characterized by large CI. The vegetation zones in the nLFY subset presented similar but weak correlations with fire size (Fig. 5). ISI showed a very strong positive correlation with fire size, while BUI revealed a weak negative correlation with fire size on both subsets.

4. Discussion

4.1. Fire occurrence models

Fire occurrence was driven by human-related landscape properties and, during years with increased fire hazard, also by vegetation properties, likely due to fuel composition. The selection of a nearly identical set of variables and similar patterns revealed by them in the models operating on LFY and nLFY subsets indicated consistency of the observed effects along a gradient in climatological fire hazard. Road density revealed a positive effect on fire occurrence, a pattern predicted by H1. Road density has been shown to influence fire activity, by the facilitation of human access to forests and thereby an increase in human-related ignitions (Feltman et al., 2012). The high accessibility of Swedish forests, due to a dense network of small roads, apparently contributes to the observed pattern.

In line with H1, population density showed a positive correlation with fire occurrence. This is consistent with other studies showing that higher population density leads to higher human-related ignitions (Syphard et al., 2007; Catry et al., 2009; Martínez et al., 2009). At the same time, a positive correlation between population density and the amount of urban area also implies that fuel availability should decline with an increase in population, a trend which should ultimately lead to fewer possibilities for fires to ignite and spread (Syphard et al., 2007;

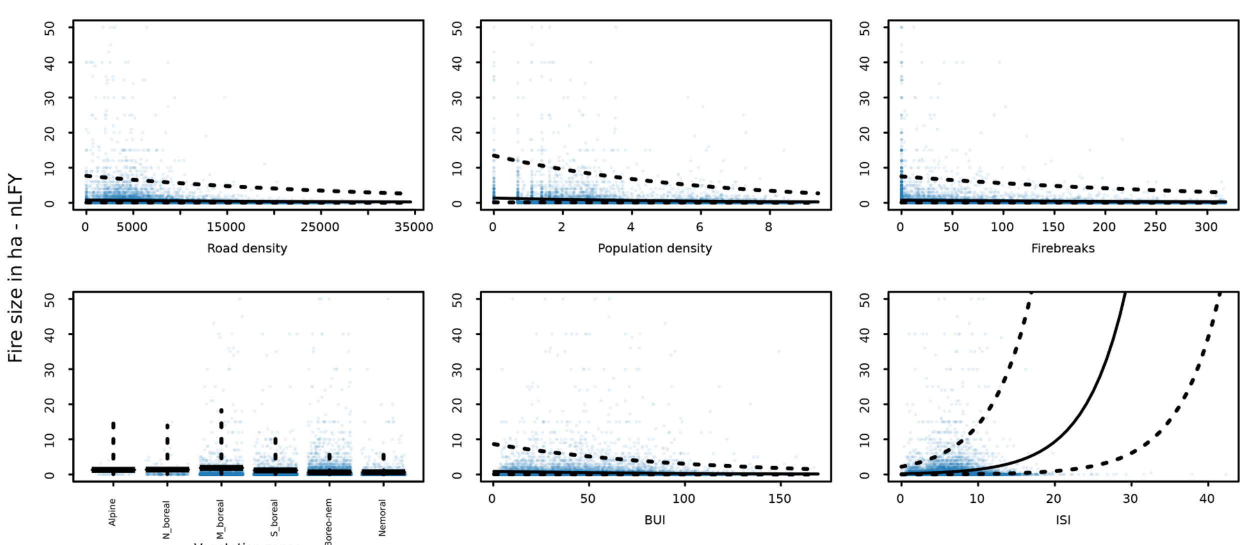

Fig. 5. Relationship between fire size and factors selected in the model operating on the subset of data representing non-large fire years (nLFY). Units: road density, meters; population density, log (mean of inhabitants/km^2), firebreaks, pixel count within the buffer area, vegetation zones, predefined classes; BUI and ISI - index values. Each blue point represents a fire and the dotted lines represent the credible interval (CI).

Table 2
Spearman correlation showing the strong correlation between population density and the number of firebreaks in the whole dataset and both LFY and nLFY subsets.

	All dataset		LFY		nLFY	
	r	*p-value*	r	*p-value*	r	*p-value*
Fire occurrence	0.296	< 2.2e-16	0.333	< 2.2e-16	0.274	< 2.2e-16
Fire size	0.480	< 2.2e-16	0.502	< 2.2e-16	0.464	< 2.2e-16

Feltman et al., 2012). These considerations and a positive relationship between fire occurrence and population density, as revealed in this study, suggest a parabolic relationship between population density and fire activity. Our data, however, did not provide the possibility fully parameterizing such a relationship, possibly due to the small scale at which fire occurrence was assessed.

Firebreaks presented a surprisingly positive correlation with fire occurrence, contradicting H2. In our study, firebreaks included not only water bodies but also urban areas. Areas with abundant firebreaks and high population density have been shown to have a positive effect on fire occurrence, due to the high recreational value of forest patches in forest-water interfaces (Stenseke and Hansen, 2014; Modugno et al., 2016; Sirca et al., 2017). In fact, firebreaks in our study showed a strong and positive correlation with population density (Table 2) and could possibly be viewed as a proxy for human presence in the modern Swedish forest landscape. Although being a non-burnable area, firebreaks appeared to "attract" fires due to higher human densities associated with them and further studies should better separate the role of natural properties vs. humans in shaping the observed pattern.

Boreo-nemoral and nemoral zones exhibited a higher probability of fire occurrence than other bioclimatic zones in years with increased fire hazard (LFYs). The longer summer in these zones (Wastenson et al., 1995) possibly contribute to this. However, since 85% of the Swedish population lives in this part of the country, the human contribution to total number of ignitions must have been considerable, possibly overriding the effect of climate.

4.2. Fire size models

Road density revealed a negative effect on fire size, a pattern predicted by our hypothesis H1. This is also consistent with Hansen (2003), who showed that higher road density positively influence fire suppression, reflecting the shorter "attack time" (i.e. the time between ignition and the onset of fire suppression efforts) due to the higher accessibility of a fire. Road surfaces may also possibly act as firebreaks, limiting fire spread under non-extreme conditions (Guyette et al., 2002).

Population density showed a negative correlation with fire size, which was in line with our hypothesis H1. The pattern (similar to road density) potentially indicates a higher efficiency of fire suppression in more populated areas (Granström and Niklasson, 2008), worse possibilities for fire spread in such areas (Guyette et al., 2002) or a combined effect of both factors. Suppression of forest fires in Sweden is commonly initiated by a local fire brigade. These brigades are present in 98% of Swedish municipalities which have, on average, three fire stations (Lantmäteriet, 2019). A possible increased presence of fire brigades in populated areas, together with a dense road network would suggest that areas with high population density have generally shorter distances between burning stands and fire brigade locations that reduce the initial attack time. This pattern can be observed, since larger fires occur more often in regions with lower population density and sparser road networks (Supp. Material 1). A positive correlation between fuel fragmentation and human infrastructure, such as roads, railways and urban areas, may be at play here (Syphard et al., 2007; Feltman et al., 2012)). However, our study did not test statistically this hypothesis.

Firebreaks presented a negative correlation with fire size (Fig. 4 and 5), consistent with our hypothesis H2. An increase in the amount of non-flammable areas surrounding burning forests limited the fire spread. This effect was more pronounced in the LFY than in the nLFY subset (Fig. 4), indicating its importance in years with more fire-prone conditions. In the fire size model, the effect of firebreaks reflected therefore the non-burnable nature of this landscape feature.

Fires in the middle boreal zone were larger than in all other zones (Fig. 5). The middle boreal zone had a higher occurrence of extra-large fires (>100 ha) during the analyzed period (Suppl. Material Fig. 1). Two main factors may contribute to the observed result: (a) a change in the forest composition from mixed forests in the south to mostly coniferous in the north, paralleled by (b) a decrease in human population density. The dominance of coniferous trees produces higher quantities of burnable fuels. In addition, in the northern part of the country the forests are generally less fragmented which favors the fire spread. A decrease in population and road densities towards the North possibly contributed to a less efficient suppression effort (Fig. 1d, f), supporting our hypothesis H1.

The dynamics of BUI and ISI showed divergent correlations with fire size. ISI showed a strong positive correlation with fire size, indicating an increased probability of large fires with ISI values exceeding 20. ISI is a proxy of fire spread, since it combines the dryness of fine fuels and wind. The association between ISI and fire size reflected primarily the dynamics of surface fires, the dominant type of fire event in Sweden.

A negative correlation between fire size and BUI was an unexpected result. Since BUI assesses the availability of combustible fuels and the moisture content of compact organic layers, its negative correlation with fire size suggested that larger fires occurred with generally less severe drought conditions. The pattern, seemingly counterintuitive, may be explained by the fact that southerly located parts of the country had higher BUI values, due to the higher temperatures, and possibly also due to a longer fire season. A number of factors make fires generally small in this region. This includes: (a) a denser road network, facilitating fire suppression activity, (b) higher forest fragmentation, and (c) a considerable proportion of deciduous fuels, which are generally not as good in supporting fires as coniferous fuels (Krawchuk et al., 2006; Hély et al., 2010; Terrier et al., 2013). By contrast, northern Sweden features larger fires and generally lower levels of BUI. The three above-mentioned factors potentially promote increase in fire size in that region. Indeed, the nemoral and boreo-nemoral zones are the regions with the largest number of recorded fires (~74% of all fires in the dataset), with the mean fire size of only 0.35 ha. In the southern, middle and northern boreal zone, which contributes to ~26% of all fires, the mean fire size increases to 2.17 ha. Constraining the analyses to the northern boreal zone showed a positive correlation between BUI and fire size, supporting our interpretation (Suppl. Material Fig. 2).

4.3. Differences in controls of fire activity between LFY and nLFY

We observed a high degree of similarity in the list of variables selected by the models developed on the LFY and nLFY subsets. The models with the lowest AIC contained all human and landscape variables, with the exception of the fire occurrence model operating on the nLFY subset that did not select the vegetation zone variable. This pattern suggested a consistency in the impact of the studied variables on fire activity under a gradient of climatological fire hazard, consistent with our hypothesis H3. The presence of human-related variables in models operating on both LFY and nLFY strengthens the notion that humans modify fire activity during the periods of both high and low fire hazard, a result also reported in California and in Europe (Catry et al., 2009; Martínez et al., 2009; Syphard et al., 2017; Adámek et al., 2018). However, since the analyzed period is just 19 years in length, it possibly underestimates the variability in climate forcing upon fire activity which, in turn, may override the role of other factors during the periods

Table 3
Summary of the minimum, maximum and quantiles for BUI and ISI for two periods (1950–2017 and 1998–2017).

	BUI		ISI	
	1950–2017	1998–2017	1950–2017	1998–2017
Min.	0.0	0.0	0.0	0.0
1st. Q.	8.4	16.1	1.8	3.1
Median	19.5	33.8	2.8	5.2
Mean	24.5	39.4	3.0	5.3
3rd. Q.	35.1	56.8	4.0	7.2
Max	220.1	190.3	18.8	42.2

of extreme fire hazard.

For the fire occurrence models, there were positive correlations between the dependent variable and the road, population and firebreak densities, consistently observed on both subsets (nLFYs and LFYs). During LFYs, the vegetation zone variable was additionally selected as a meaningful predictor of fire occurrence, with more southerly located regions exhibiting higher levels of fire occurrence. Higher population densities in the southern part of the country, possibly along with a higher level of climatological fire hazard are possibly behind the observed pattern. This interpretation is in line with the positive effects of population and road density on fire occurrence (Fig. 1d and f).

For fire size models, the similar predictors were selected for both LFY and nLFY. The presence of a stronger correlation between fire size and the vegetation zone variable during LFY, suggested that the differences in the fuel conditions become more important in years with an increased climatological fire hazard.

4.4. Methodological considerations

Our analyses included a relatively short period (1998–2017) as fire data outside that period were absent or lacking required spatial resolution. The limited time period analyzed could be a potential drawback of our analyses as the studied period might not be representative over a wider range of climate conditions. This scenario was however unlikely as climate indices showed a higher variability for the analyzed period than in a long-term period 1950–2017 (Table 3, Suppl. Material Fig. 3). Although we did not analyze the nature of these differences statistically, we note that the observation warrants the use of the recent climate data for parameterizing interactions between climate, landscape properties and fires.

To benefit from the consistency of the climate data observations inputs we relied exclusively on the BioSim models to calculate fire weather indexes, which were available for the period April to October. Only 1.3% of fires occurred outside this period. Although currently the contribution of these fires to the annual fire activity is negligible, the use of the indices calculated for the days of the actual fires will be desirable for the future analyses.

5. Conclusion

Forest fire activity in modern Sweden is driven by a combination of climate, human-related ignitions, and a moderate effect of vegetation composition. Forest fires are largely associated with human presence. However, their ecological and economic effects, as approximated by their size, appear to increase with the distance from populated areas. Climate variables were present in all fire size model formulations, with the higher values of ISI indices being associated with higher fire size. This pattern supports the view of modern fire activity as a process driven, at least partially, by natural climate variability. Such variability is particularly important during the years with increased fire hazard, potentially overriding the effects of other factors (Drobyshev et al., 2015). As a direct result of suppression policies initially introduced in the mid-1800s (Granström and Niklasson, 2008), the current state of Swedish forests is characterized by extremely long fire cycles of 10 000 to 20 000 years (Drobyshev et al., 2012). Although they are highly effective today, fire suppression does not eliminate significant effects of other proxies of the human activities to be manifested in respective models. Our study indicates that such proxies can be instrumental in improving fire risk assessment in the Swedish forests.

In this study, we considered the number of firebreaks as a natural feature of the landscapes, although it may also be a proxy of human occupational activities. In a country that relies heavily on forestry, it is a challenge to differentiate human-related from purely natural features of vegetation cover. Further research is warranted to disentangle the impact of firebreaks on fire occurrence and size. The high degree of transformation of Swedish forest cover and the universally high levels of access to forest land, create the possibility of integrating fire risks into the management of forest cover. Since the fire size could be viewed as a proxy of the economic impacts of forest fires, we argue that the focus of the work to estimate fire-related risks should be primarily directed towards parameterization of environmental controls of fire size, rather than of ignition frequencies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2020.108084.

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