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A Combination of Human Activity and Climate Drives Forest Fire Occurrence in Central Europe: The Case of the Czech Republic

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Abstract: Central Europe is not a typical wildfire region; however, an increasingly warm and dry climate and model-based projections indicate that the number of forest fires are increasing. This study provides new insights into the drivers of forest fire occurrence in the Czech Republic, during the period 2006 to 2015, by focusing on climate, land cover, and human activity factors. The average annual number of forest fires during the study period was 728, with a median burned area of 0.01 ha. Forest fire incidence showed distinct spring (April) and summer (July to August) peaks, with median burned areas of 0.04 ha and 0.005 ha, respectively. Relationships between the predictors (climate data, forest-related data, socioeconomic data, and landscape-context data) and the number of forest fires in individual municipality districts were analyzed using Generalized Additive Models (GAM) on three time scales (annually, monthly, and during the summer season). The constructed GAMs explained 48.7 and 53.8% of forest fire variability when fire occurrence was analyzed on a monthly scale and during the summer season, respectively. On an annual scale, the models explained 71.4% of the observed forest fire variability. The number of forest fires was related to the number of residents and overnight tourists in the area. The effect of climate was manifested on monthly and summer season scales only, with warmer and drier conditions associated with higher forest fire frequency. A higher proportion of conifers and the length of the wildland–urban interface were also positively associated with forest fire occurrence. Forest fire occurrence was influenced by a combination of climatic, forest-related, and social activity factors. The effect of climate was most pronounced on a monthly scale, corresponding with the presence of two distinct seasonal peaks of forest fire occurrence. The significant effect of factors related to human activity suggests that measures to increase public awareness about fire risk and targeted activity regulation are essential in controlling the risk of fire occurrence in Central Europe. An increasing frequency of fire-conducive weather, forest structure transformations due to excessive tree mortality, and changing patterns of human activity on the landscape require permanent monitoring and assessment of possible shifts in forest fire risk.

Keywords: Central Europe; climate; fire risk; human activities; wildfires

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1. Introduction

Although fire is as much a part of the ecosystem as rain, sun, and soil, wildfires represent forest disturbances, accounting for 24% of total forest disturbance in Europe from 1950 to 2019 [1]. While annually burned area in Europe showed a moderate decrease in recent decades, the severity of large singular events increased [2]. Moreover, large fires are now occurring in areas such as Sweden, Germany, and the Czech Republic, which have not previously experienced large wildfires [3,4].

The geographical pattern of forest vulnerability to fires emerges from the interplay between forest structure and composition and climate. High biomass levels are typically associated with higher fuel loads [5], with warmer and drier climates increasing the vulnerability [6]. At the scale of Europe, fire vulnerability hotspots in the period 1979 to 2018 were found in Sweden, Finland, European Russia, the Iberian Peninsula, and Turkey [7]. However, this distribution of fires changes due to land use changes and increased fire-conducive weather conditions [8,9]. These factors also affect forest structure and composition, which can alter future forest fire risk [10–13]. These developments highlight the importance of improved forest fire monitoring, modeling, prediction, and firefighting resource allocation systems, which are being increasingly implemented across Europe (e.g., [14–17]).

Forest vulnerability to fire [18] is dependent upon interactions between climate, fuel availability (fuel load and moisture content of the vegetation), and ignition sources [19–24]. Ignition sources are both natural (predominantly lightning) and anthropogenic (resulting from human activity on the landscape; [25]). In Europe, roughly 90 to 98% of forest fires are human-caused, and only a small percentage are caused by lightning [23,26–28]. Human-caused fires mainly result from activities related to recreation (e.g., camping, hiking, and hunting) and industry (e.g., timber production, railway and highway transportation, and oil and gas exploration) [29].

Forest fires in the European temperate forest zone are mainly associated with human activities, while climatic effects are less distinct [30–35]. Despite the recognized importance of anthropogenic effects, little attention has been paid to their quantitative assessment, with human activity data in forests being surprisingly scarce [36–38]. This makes assessing the human contribution to wildfire ignition and predicting the fire risk challenging [25,39].

Central Europe is not a typical wildfire region; forest fires account for a negligible proportion of the total forest area disturbed annually. Wildfires are typically small, predominantly ignited by human activity, and quickly extinguished in most cases, thanks to the high human population density (detection) and developed infrastructure (suppression). However, the frequency of forest fire increased by 70% during the periods from 1971 to 1990 and from 1991 to 2015, probably due to the increasingly hot and dry weather [40]. The danger of forest fire is expected to further increase not only due to increasingly conducive fire weather [41], but also due to intensifying human activity at the wildland–urban interface; growing numbers of visitors in the forests; and the increased fire danger associated with elevated forest mortality induced by drought, insects, and diseases. Large-scale forest mortality due to bark-beetle (Coleoptera: Curculionidae: Scolytinae) infestations in Central Europe [42] is of particular concern due to the large amounts of fuels that accumulate [43,44]. Heavy machinery operations conducting salvaging and wood transportation are another factor potentially increasing fire risk in the region [45].

Understanding regional patterns and drivers of forest fire that emerge from the interaction of climatic and social factors is essential for mitigating future fire risk and identifying fire-prone areas. We aimed to identify drivers of forest fire ignition in the Czech Republic (Central Europe) in the period 2006 to 2015, placing equal emphasis on landscape, social, and climatic drivers. Contrary to most previous studies, which mainly addressed the effect of climate [41,46], we sought to reach more profound insights by considering factors such as population density, tourism, and wildland–urban interface, which are hypothesized to be associated with fire ignition and spread in the region. This information will allow for a more robust fire danger assessment and forecasts by considering the coupled effects of climate change and ongoing socio-ecological transformations.

2. Materials and Methods

2.1. Study Area and Data

The Czech Republic (Central Europe; Figure 1a) has a mild four-season climate that is between oceanic and continental climate types. The country's climate is characterized by prevailing westerly winds and intense cyclonic activity. The average daily temperature ranges from 3 °C in January to 17 °C in July, and the average annual precipitation ranges from 600 to 800 mm in most of the country [47]. The altitude ranges from 115 to 1603 m a.s.l., with a median of 430 m a.s.l. The predominant relief is hills and highlands. The average population density is 133 inhabitants km^{-2} [48]. Additional information about the country is presented in Appendix A.

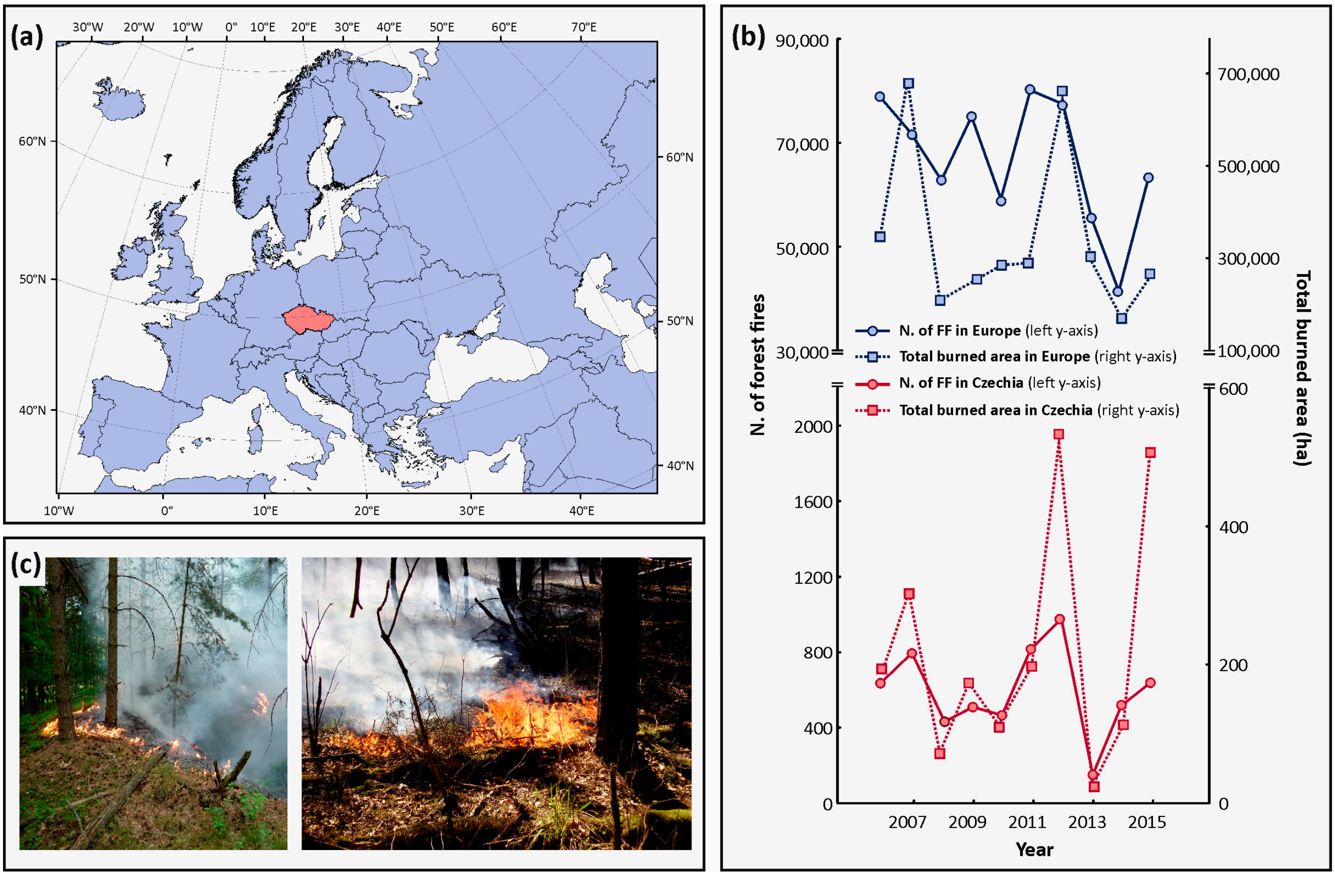

Figure 1. (**a**) Position of the Czech Republic in Europe; (**b**) a comparison of trends in the number of forest fires and burned areas in Europe and the Czech Republic in the study period 2006 to 2015; and (**c**) typical forest fires occurring in the Czech Republic. Source of the forest fire data for Europe: [3]; source of the forest fire data for Czechia: General Directorate of Fires Rescue Service of the Czech Republic; photographer credit: Jan Vaněk, 2018.

In the absence of humans, mixed beech (*Fagus sylvestris* L.) forests would dominate most of the Czech Republic, with oak (*Quercus* L.)-dominated deciduous forests in the lowlands, and coniferous forests with spruce (*Picea* L.) at higher altitudes [49]. Because of the intensive forest management practiced since the nineteenth century, the current forest composition consists predominantly of *Picea abies* L. (Karst.) (52%), *Pinus sylvestris* L. (17%), *Fagus sylvatica* L. (7%), *Quercus* spp. (7%), *Larix decidua* Mill. (4%), *Betula pendula* Roth (3%), and *Abies alba* Mill. (1%). Other deciduous species (e.g., *Carpinus betulus* L., *Acer* L. spp., *Fraxinus* L. spp., *Populus* L. spp., *Salix* L. spp., and *Tilia* L. spp.) occupy about 8% of the forested area [50]. Forests cover 33.9% of the country. The disturbance regime predominantly consists of windthrows triggering bark beetle outbreaks, which are further modulated by drought. This sequence of events has recently shifted toward the dominance of drought-driven processes [42]. Forest fires have accounted for a negligible proportion of total forest damage and are not considered in national forest damage reporting. Interestingly, the inter-annual pattern of forest fire numbers and burned areas in the Czech Republic was similar to that found throughout all of Europe, suggesting a large-scale synchrony (Figure 1b).

Fores fire data were obtained from the General Directorate of Fire Rescue Service of the Czech Republic [51], which keeps statistics on all fires in the country that required intervention. The database covers the whole area of the Czech Republic from 2006 to 2015 (except for military areas, which represent <5% of the area). From 2006 to 2010, the database indicated only the administrative districts where forest fires occurred. The data after 2010 included the exact geographical locations of almost every fire. Causes of the fire were indicated for only ~50% of all cases. For example, the cause of fire might have been recorded if private property was affected, if an intentional ignition with possible criminal implications was suspected, or if the cause of fire could have been unambiguously identified on the spot. Because the information about the causes of fire is highly incomplete, it was not considered in our analyses.

Because of problems with the clear identification of some forest fires, all records (roughly 10,000) were manually checked for misclassification; based on the descriptive information provided for each fire, the fire was included in or excluded from the final database [52,53]. Forest fires that occurred between January and March, and in November and December, were not considered in the study (around 100 forest fires in total), because these forest fires were mostly associated with events such as accidental fuel leaks or fireworks. In addition, due to minimal forested area, forest fires from the administrative district of the capital city (Prague, with more than 1,500,000 inhabitants) were removed from the analysis. In total, the dataset contained data on 7279 forest fires, with an average of 728 forest fires per year over the 10-year reporting period (2006 to 2015). Most of the burned areas were up to 0.16 ha (80% of the fires from 2006 to 2015 were less than 0.16 ha). Fires larger than 5 ha represented ~1% of all fires in the dataset.

Using burned areas as a characteristic of the fire regime in the Czech Republic has limitations as most fires are small (5 to 95% of the fires from 2006 to 2015 were between 0.0001 and 1.00 ha; Figure 1c), and their size is strongly affected by the time it takes for firefighters to respond (the duration of free fire development) [52]. Therefore, we focused on identifying the drivers of forest fire ignition, which were expected to be more closely associated with predictors such as climate and human activity. We used the number of forest fires in individual municipality districts (n = 76) ([54], see Appendix A) of the Czech Republic rather than accurate spatial coordinates of the forest fires. Data for 2006 through 2010 lacked coordinates; only forest fire occurrence within districts was available. Socio-economic data (population size, tourism, etc.) were available only on a municipal district scale. Because the size of forested area highly varied between districts, the number of fires per forest hectare (FF ha^{-1}) was used as a response variable in the statistical models.

2.2. Predictor Variables

We considered several predictors that are known to act as forest fire risk drivers in temperate forests, including climate data, forest-related data, socio-economic data, and landscape context data (Appendix B, [15–17,19–23,25,30–34,55–59]).

Monthly air temperature, monthly rainfall, average annual air temperature, annual total rainfall, and their differences from long-term means (from 1961 to 1990) together with the number of days with snow cover per year represented the climatic predictors (Czech Hydrometeorological Institute, Prague, Czech Republic, http://portal.chmi.cz/ (accessed on 1 January 2020).

Forest-related predictors were total forest area, percentage of forest area, percentage of conifers, and percentage of pine (*Pinus* L. spp.) within each district [50]. Pine was considered the most flammable tree species in the study area [60]; it usually grows under dry conditions, produces resinous and easily combustible debris, and older stands have a relatively thin canopy that allows debris to dry and easily ignitable grasses to appear [61]. The values for these variables were constant throughout the study period.

The interface between forest and urban areas and between forest and agricultural areas was used as a proxy of human activity on the landscape, which was found to be related to fire incidence in previous studies (e.g., [35,62]. The district-related values of these variables were calculated using the seamless Corine LandCover data containing major land cover categories for Europe [63]. The analysis was conducted using GIS by analyzing the spatial adjacency of different classes. These variables were standardized by the area of the forest in a district (m.ha^{-1}). These values also stayed constant throughout the study period.

The two variables related to human population density were the number of residents per forest area (inhabitants ha^{-1}), represented by the mean number of inhabitants in the district in the period 2006 to 2015, and the number of overnight tourists per forest area, represented by the mean annual number of overnight guests in recreational facilities (overnight guests $ha^{-1}yr^{-1}$; Czech Statistical Office (Prague, Czech Republic), https://www.czso.cz/ (accessed on 15 July 2016).

Although factors related to human activity on the landscape are related to fire ignition risk, and factors related to climate and forest structure are more related to fire spread, we collectively referred to all predictors as "fire ignition drivers." This term corresponds with the fact that fire occurrence (number of forest fires), rather than the size of burned areas, was analyzed.

2.3. Analyses

Relationships between the predictors and the number of forest fires were analyzed using Generalized Additive Models [64]. This model predicts values of the dependent variable based on a linear combination of predictor variables that are approximated by the so-called smoother functions. The degree of smoothness of the function (the number of nodes, k) is determined separately for each predictor variable by cross-validation to avoid overfitting (over-adaptation of the function to data and loss of ability to generalize). The main results of the analysis are the deviance explained by the model; the statistical significance of the individual predictor; and the shape of the smooth function along with the effective degrees of freedom, which reflect the degree of non-linearity of a curve. The mgcv library [65] of the statistical program R 4.0.0 [66] was used for the analysis.

Given the high number of candidate predictor variables (Appendix B), their mutual substitutability (concurvity) was evaluated, and redundant variables were discarded. Subsequently, several models involving different predictor variables were iteratively tested, and only the variables that had a statistically significant association with the number of forest fires were used in the final model. The influence of first-order interactions among the variables were also tested. The quality of the created model was assessed based on the percent of deviance explained, distribution of residuals, their autocorrelation, and the correlation of predicted and measured data.

The analysis addressed three time scales by using different subsets of forest fire data: a monthly scale that contained monthly sums of forest fire data; a summer scale that included forest fires from June, July, and August; and an annual scale that included yearly forest fire sums. A separate statistical model was constructed for each time scale.

3. Results

3.1. Temporal Forest Fire Patterns

On a monthly basis, forest fire numbers showed distinct spring and summer peaks occurring in April and in July to August, respectively (Figure 2). Although differences between the years were substantial, these seasonal patterns stayed the same throughout the study (Appendix C). The summer peak was most pronounced in 2015, which was particularly warm and dry, and had an especially dry June to August (Appendix C; Figure 3). The bi-modal pattern was not present in 2008, which did not show any deviations from the average climate conditions in the study period. In 2012 and 2007, which ranked second and third in the number of forest fires, respectively, a high number of forest fires occurred in the spring season (Appendix C). The spring of 2007 was the driest and hottest in the study period (Figure 3).

The size of burned areas showed a similar pattern, although the summer peak was less distinct (Figure 2b). Specifically, the median burned area was 0.04 ha during the spring peak, while it was ~0.005 ha in the summer peak. The smallest burned areas (and forest fire numbers) were recorded in 2008. The most distinct spring peaks of burned areas occurred in 2007, 2009, 2012, and 2014, while the dominant summer peak occurred in 2015 (Appendix C).

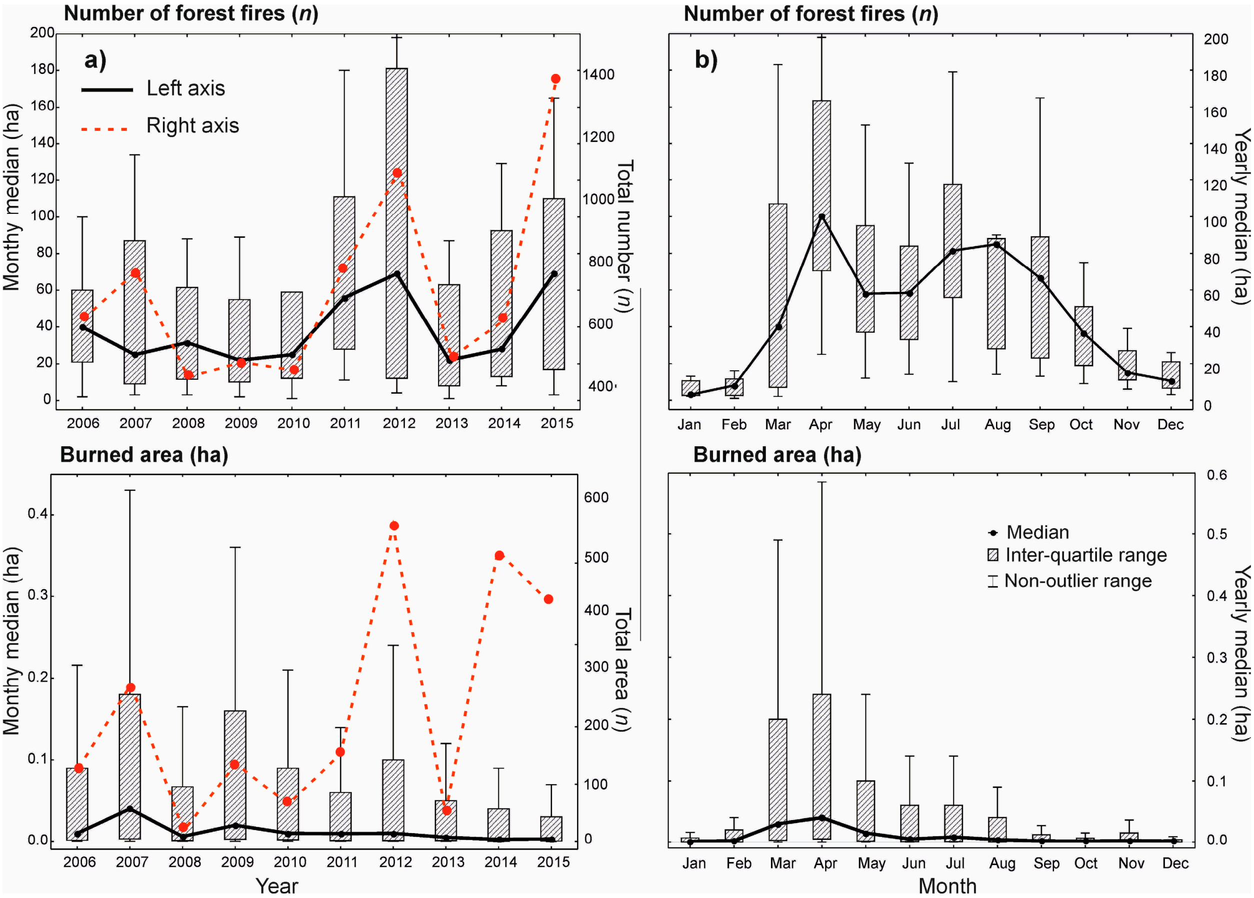

Figure 2. (**a**) Inter-annual and (**b**) monthly pattern of forest fire numbers and burned areas during our study to assess drivers of forest fire occurrence in the Czech Republic during 2006 to 2015. Medians (boxplots, left axis) and totals (red dotted line, right axis) are shown for the yearly values. Outliers beyond 1.5 of the inter-quartile range were removed for clarity.

3.2. Fire Ignition Drivers

The regression models indicated the significant effect of several predictors; however, these effects differed depending on the time scale (annual, monthly, during summer season). Our chosen predictors explained 48.7 and 53.9% of the variability in forest fire numbers on a monthly scale and summer season scale, respectively, and 71.4% of the variability on an annual scale (Table 1).

On annual, summer season, and monthly scales, the percentage of conifers and the wildland–urban interface were positively related to the occurrence of forest fires; the relationship with the wildland–urban interface was particularly strong (Table 1; Figures 4–6). On an annual scale, the number of forest fires was not significantly related to any of the climate variables. On the other hand, factors such as human population density and the number of overnight tourists per forest hectare were significantly associated with the number of forest fires. Although forest fires were positively related to population density (except for the most densely populated areas), forest fires were negatively related to the number of overnight tourists (Table 1; Figure 4c).

The number of forest fires was significantly related to climatic variables on a monthly scale (Table 1). The occurrence of forest fires increased as the monthly air temperature increased above 20 °C (Figure 5c) and decreased as total monthly rainfall increased (Figure 5d).

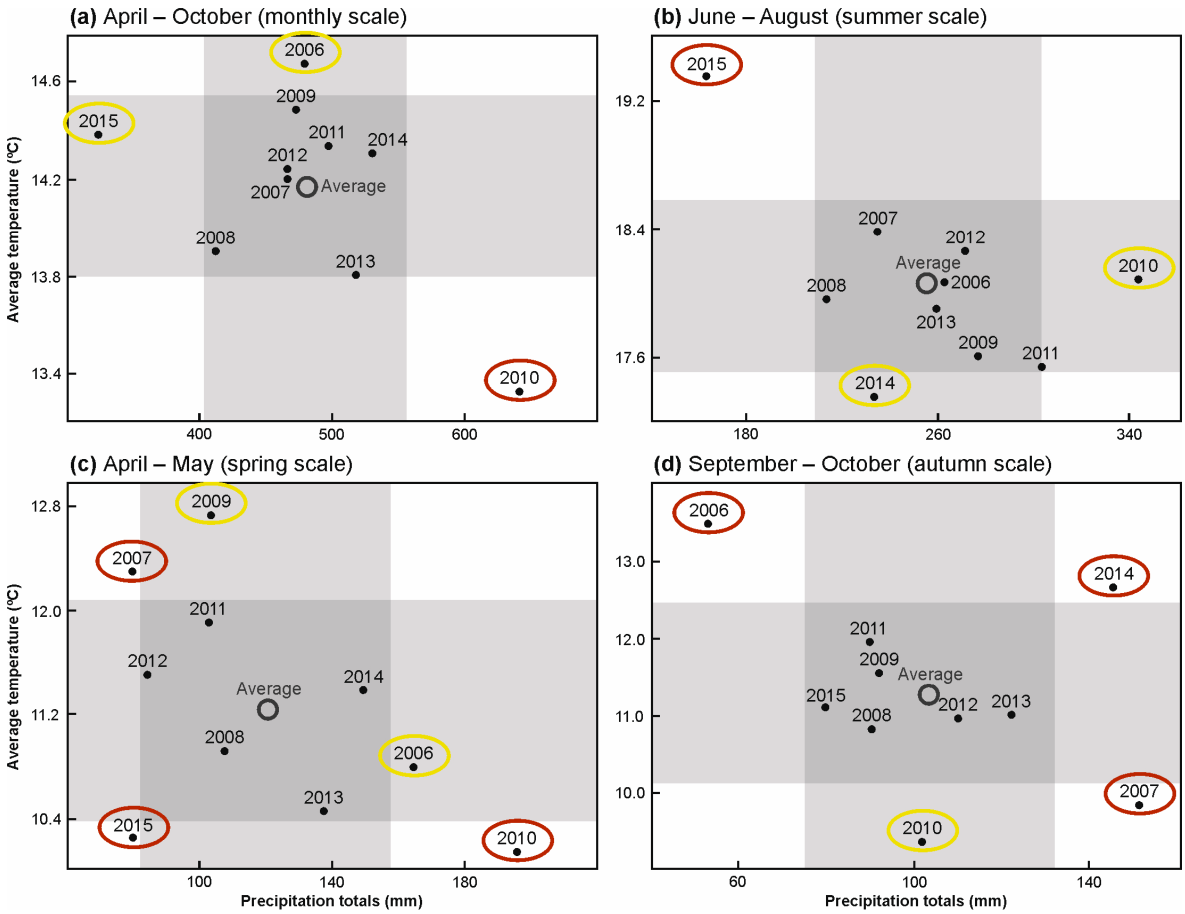

Figure 3. The position of years of the studied period in temperature–precipitation spaces characterizing different parts of the year: (**a**) April to October, (**b**) June to August, (**c**) April to May, and (**d**) September to October. Black circles indicate the average position of the 2006 to 2015 period. Dark gray rectangles represent the standard deviation of the two variables. Ellipses indicate years outside standard deviation ranges for one (yellow) and both (red) climatic variables.

Table 1. Results of regression models describing the relationships between the number of forest fires per forest area (the dependent variable) and various predictors characterizing climate, land cover, and human activity factors in the Czech Republic between 2006 and 2015, at the three time scales investigated in this study (monthly, summer season, and annual). The values indicated for predictor variables are estimated degrees of freedom. ** indicates $p < 0.01$, *** indicates $p < 0.001$, and n.s. indicates not significant ($p > 0.05$).

Predictor Variable	Time Scale		
	Monthly	Summer Season	Annual
Wildland–urban interface	3.39 ***	4.22 ***	3.55 ***
Overnight tourists	n.s.	3.03 ***	1.0 ***
Population density	n.s.	n.s.	2.558 **
Conifer cover	1.84 ***	3.60 ***	2.94 ***
Precipitation	1.272 ***	n.s.	n.s.
Temperature	3.7 ***	3.202 ***	n.s.
Temperature × Precipitation	11.28 ***	n.s.	n.s.
Deviation explained (%)	48.7	53.9	71.4

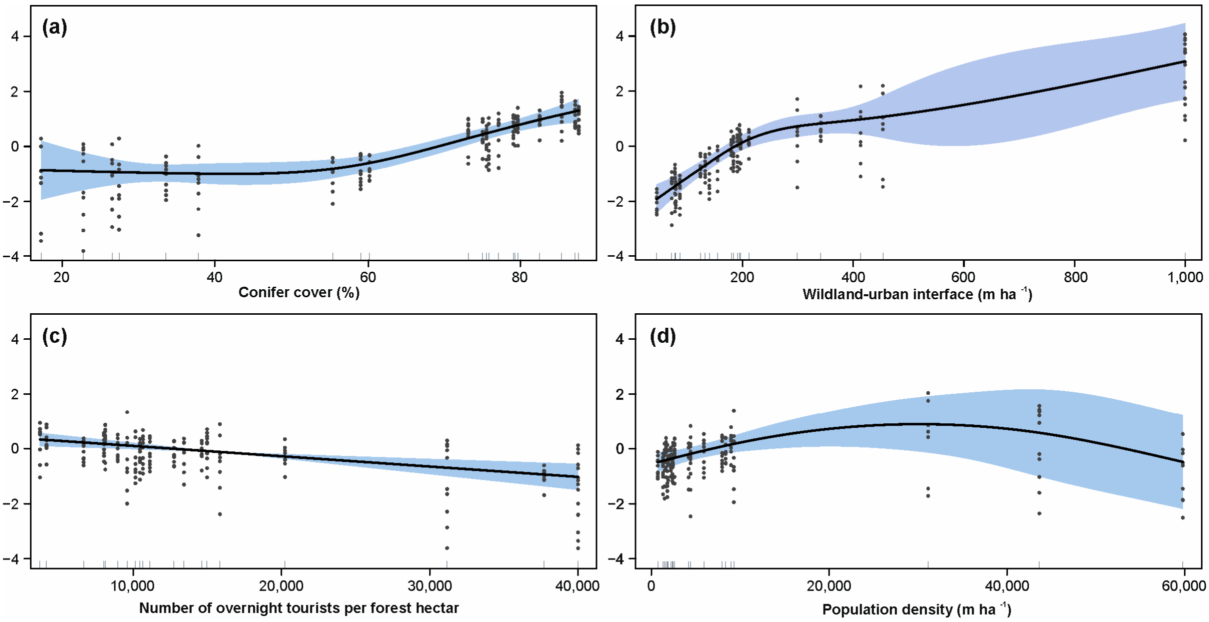

Figure 4. Responses of the number of forest fires per forest area (n ha^{-1}) that occurred in the Czech Republic during 2006 to 2015 to predictor variables with statistically significant effects. Results of analysis conducted on an annual scale are presented. Smoother functions fitted by Generalized Additive Models (line), 95% confidence interval (blue shaded area), and residuals (points) centered at a zero mean value are indicated. Forest fire responses to the (**a**) percentage of conifers, (**b**) length of the wildland–urban interface, (**c**) number of overnights, and (**d**) number of residents are displayed.

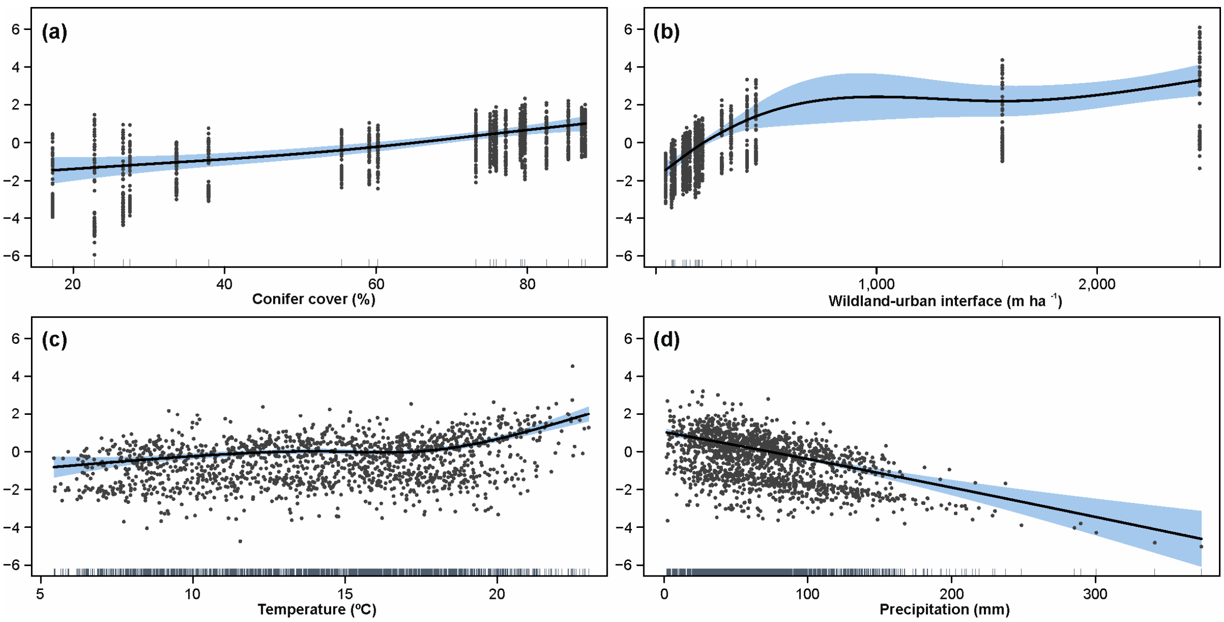

Figure 5. Responses of the number of forest fires per forest area (n ha^{-1}) that occurred in the Czech Republic during 2006 to 2015 to predictor variables with statistically significant effects. Results of analysis conducted on a monthly scale are presented. Smoother functions fitted by Generalized Additive Models (line), 95% confidence interval (blue shaded area), and residuals (points) centered at a zero mean value are indicated. Forest fire responses to the (**a**) percentage of conifers, (**b**) length of the wildland–urban interface, (**c**) air temperature, and (**d**) precipitation are displayed.

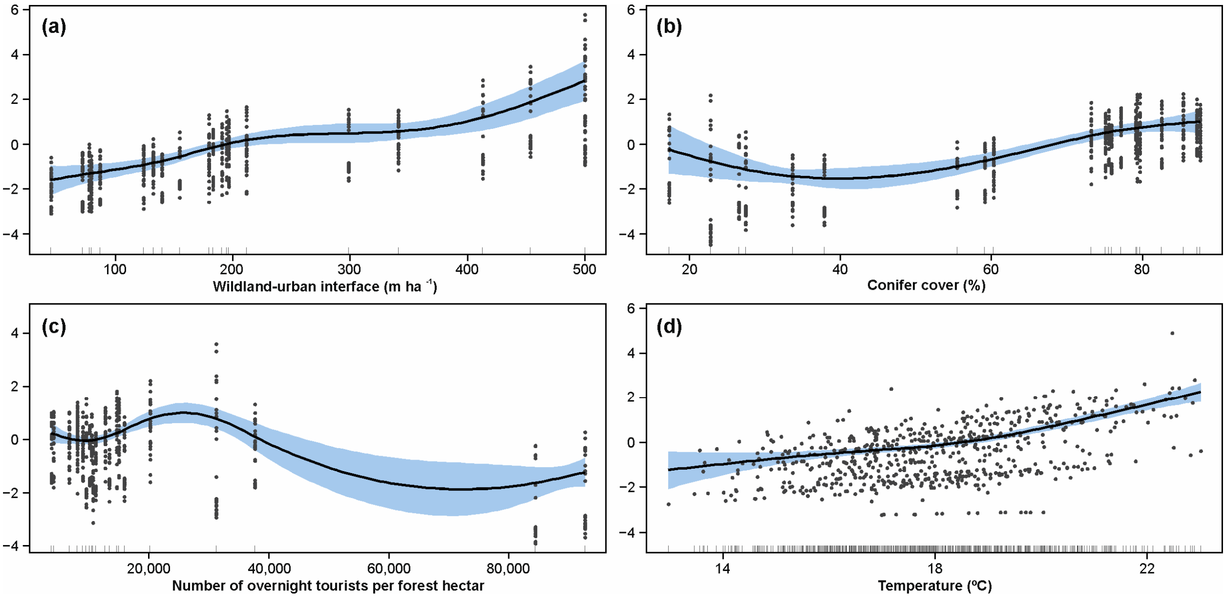

Figure 6. Responses of the number of forest fires per forest area (n ha^{-1}) that occurred in the Czech Republic during 2006 to 2015 to predictor variables with statistically significant effects. Results of analysis conducted on a summer scale are presented. Smoother functions fitted by Generalized Additive Models (line), 95% confidence interval (blue shaded area), and residuals (points) centered at a zero mean value are indicated. Forest fire responses to the (**a**) percentage of conifers, (**b**) length of the wildland–urban interface, (**c**) number of overnights, and (**d**) air temperature are displayed.

On the summer season time scale (i.e., considering data from summer seasons only, July and August), the predictor variables explained approximately 50% of the variability in the number of forest fires (Table 1). Although the percentage of conifers was a significant predictor variable, the relationship was difficult to explain in that the number of forest fires tended to decrease as the percentage increased from 15 to 40%, but then increased as the percentage increased from 50 to 88% (Figure 6b). The number of forest fires increased as the length of the wildland–urban interface increased (Figure 6a). The number of forest fires increased relative to the number of overnight tourists between 0 and 25 overnight tourists per hectare of the forest per year (the majority of the data), but decreased for higher overnight tourist values (Figure 6c). The number of forest fires was positively associated with temperature, showing a sharper increase when temperatures were above 18 °C (Figure 6d).

4. Discussion

4.1. Patterns and Drivers of Forest Fires

The intra-annual distribution of forest fires showed distinct spring and summer peaks that were present during most of the study period (see Appendix B). However, while these peaks were obvious in terms of forest fire numbers, the median size of the burned area showed only an indistinct spring peak (Figure 2). The intra-annual variability in the burned area size was not large, which likely corresponded with the short interval of time that it takes firefighters to respond to fire. Still, larger fires (mostly up to 0.5 ha) mainly occurred in spring (Figure 2). Although we cannot provide any data-driven explanation for this pattern, it is noteworthy that there were different mechanisms behind the two fire seasons. There were indications that the spring peak was related to the increased intensity of forestry operations after winter seasons, such as slash pile burning. In addition, large amounts of flammable dry grass typically occur after mild winters and during dry early springs, further increasing fire risk. The summer peak likely resulted from the combination of hot and dry weather and increased tourism and recreation activities. Interestingly, such a bi-modal pattern of wildfire occurrence was also identified in Portugal, with a March peak associated with forestry and agriculture activities; however, this peak provided only a small contribution to the annually burned areas [67].

The observed seasonal pattern corresponds with the significant effect of climatic variables on a monthly and a summer season scale, while climatic effects were insignificant on the annual scale. We suspect that the yearly resolution of climate data is too coarse to capture weather patterns associated with increased fire incidence. The authors of [68] found a similar time-scale dependency—the probability of forest fire occurrence increased with daily but not with monthly average temperatures. In our current study, however, monthly climate variation had a significant effect. The number of forest fires was positively associated with air temperature on a monthly and on a summer season scale, although the increase in forest fires was nonlinear on the summer season scale. Specifically, forest fire numbers were unrelated to temperature until the mean monthly temperature reached 18 °C; then, the forest fire numbers increased (Table 2; Figures 5c and 6d). Such monthly temperatures were common for June, July, and August, between 2011 and 2020; however, average monthly temperatures in those three months seldom reached 18 °C before 2000. Such a threshold-type response is disturbing because the critical temperature limit may be exceeded more frequently in the future, including currently colder locations in higher elevations. This implies that the current summer season fire peak may be expected to increase, and that the fire season may be extended in the future. Such threshold-type responses were also identified by other authors. For example, in Poland and Serbia, 60% of the forest fires occurred when the daily temperature was above 24 °C and 25 °C, respectively; air humidity was <40%; and precipitation was lacking [69,70]. The identified negative correlation of forest fires with precipitation agrees with numerous previous research studies (e.g., [71–74]). Precipitation increases fuel moisture content and reduces the probability of ignition [75,76].

Table 2. Summary of characteristic trends with regard to the relationship between number of forest fires and predictor variables characterizing climate, land cover, and human activity factors in the Czech Republic between 2006 and 2015, at the three time scales investigated in this study (monthly, summer season, and annual). Values at which the trend changes are given in parentheses.

Predictor Variable	Characteristic Trend per Time Scale		
	Monthly	Summer Season	Annual
Wildland–urban interface (m ha^{-1})	Increasing, then constant (500)	Increasing	Increasing
Overnight tourists (n ha^{-1})	No trend	Unimodal response (25,000)	Decreasing
Population density (n ha^{-1})	No trend	No trend	Unimodal response (30,000)
Conifer cover (%)	Increasing	Constant, then increasing (60)	Constant, then increasing (60)
Precipitation (mm)	Decreasing	No trend	No trend
Temperature (°C)	Constant, then increasing (18)	Constant, then increasing (18)	No trend

The number of forest fires was positively related to the percentage of conifers on a monthly scale; on the annual and summer season scales, there was a positive correlation between conifer percentage and forest fire incidents only if the forest covered over 60% of the area (Table 2). This response was expected as forest fires have been found to be more closely associated with coniferous forests than with broadleaved forests in Mediterranean, temperate, and boreal regions [77–79]. We assumed that the proportion of pines would positively affect forest fire frequency because pines are the most flammable native species growing in the Czech Republic [60], producing resinous and easily combustible debris [61]. However, this association was not confirmed. The reasons why the presence of pine was not a significant factor affecting fire occurrence could include the fact that forests in the Czech Republic have a relatively low pine proportion (17%), or that the analysis, which was aimed at administrative districts, was performed on too coarse of a scale.

In Europe, 97% of forest fires were directly or indirectly caused by humans [23,80] which was also indicated by our analyses. On a summer season scale, the number of forest fires was unimodally associated with the number of overnight tourists per forest hectare per year (Table 2; Figure 6c). The relationship between the number of forest fires and the density of the local human populations was also unimodal on an annual scale; forest fire numbers initially increased as population density increased, but then decreased as human inhabitants exceeded 30 000 ha^{-1} (Table 2; Figure 4d). The likely explanation for such a response is that not all tourists visit the forests. In the cities (annual-scale analysis) and water-recreation areas (summer season scale analysis), where overnight-tourist numbers are highest, tourists may be visiting historical and cultural monuments, attractions, and recreational areas rather than forests. Both population density and the number of overnight tourists have been related to the number of forest fires in other studies [57,72,74,80–83]. In Latvia, the geographical distribution of forest fires showed two distinct clusters near its two largest cities, which also indicates the predominance of human-caused ignitions [34].

Wildland–urban interface dynamics have been receiving increased recognition globally because of the accelerating expansion of urban areas as well as the increasing wildland–urban interface length [84]. Increased fire hazard is related to increased human activity in wildlands [46,62,85]. The wildland–urban interface was found to be behind several noticeable effects, such as winter fire progression and a moderate increase in fire incidence linked to human-caused fires (e.g., [35]). In our study, the extent of the wildland–urban interface was identified as positively related to the number of forest fires; at the same time, it had a significant effect on all investigated times scales (monthly, summer season, and annual). Forest fire response to interface length was relatively sharp and increased linearly, suggesting this factor's importance. In Central Europe, this factor is expected to affect forest fire ignition risk by facilitating forest accessibility to people in the short term for collection of mushrooms and other products, and in the longer term for sport and recreation activities [86,87].

4.2. Methodological Considerations

Limited data availability and quality, including short and inconsistent time series, is a common problem of forest disturbance mapping and assessment in Europe [1]. Remote-sensing-based mapping helps overcome some of these shortcomings [88]; however, mapping small-scale disturbances, such as forest fires in Central Europe, and identifying disturbance causes remains challenging [89]. Such data constraints are disturbing because recent trends and model projections indicate that future forest fire impacts may be considerable [40,90], and consistent datasets could be essential for identifying regime shifts and fire-prone areas. For example, here, the fire occurrence data that we used were created as a by-product of firefighting interventions, not by a professional forestry agency. Therefore, metadata about a fire's possible cause and local forest stand and site description, including fuel parameters, were lacking. Limited forest fire monitoring, mapping, and data collection is typical that part of Central Europe in which forest fires are not yet a major factor in forest disturbance.

We focused on the drivers of forest fire occurrence (i.e., the ignitions) rather than on the size of burned areas. This may limit the comparability of this study with studies from fire-prone regions that often focus on burned areas (e.g., [3]). However, we maintain that the number of forest fires is a relevant descriptor of the fire regime in Central Europe that is characterized by many small fires, which are extinguished before they expand in the vast majority of cases. We found that only 5% of fires exceeded one hectare, with one fire that affected a 497-hectare area in 2014. Moreover, the inter- and intra-annual patterns of forest fire numbers were more distinct than the patterns of burned areas, thereby providing better interpretation options (Figure 2; Appendix C). Studies [40,46] found a strong climatic signal in forest fire occurrence in Central Europe, which also supports the use of forest fire numbers as an adequate and responsive indicator of the regional fire regime.

The present study examined data from the period 2006–2015, which precedes the recent series of climatically extreme years that significantly altered European forest disturbance patterns. Although more recent data were not accessible during this study, extending the investigated time series could yield valuable insights into the shifts in fire dynamics resulting from progressive climate aridification. Consequently, the current study can serve as a reference for subsequent research endeavors.

4.3. Practical Implications

The insights obtained in this study have several practical implications. First, we highlighted the limitations of current fire monitoring and reporting procedures. Missing information about the causes of fire ignition and local site and forest structure and composition data significantly limit interpretation options. Detecting these changes can be important because the recent wave of drought- and bark-beetle-related forest mortality have considerably transformed forest landscapes [42], changing species composition, fuel distribution, and patterns of human presence on the landscape. These changes can alter forest fire responses identified in this current study; therefore, updating the statistical models presented here with new data on a regular basis will be essential for understanding transient fire conditions in Central Europe. The above-mentioned processes are further affected by an increasingly warmer and drier climate, which is likely to affect the occurrence of fires in the regions. We need to create better and more detailed fire datasets, by engaging forest experts and fire departments, to better understand ongoing changes and improve fire risk assessment models.

Second, the identified factors driving fire occurrence can be used for delimiting fire risk zones at the scale of administrative districts of the Czech Republic. While this scale corresponds with the socio-economic and demographic data structure, which can be straightforwardly integrated in the statistical models, it is obviously too coarse for operational management and resource allocation planning. Still, identifying fire-prone districts based on their location in drier and warmer conditions with a large proportion of coniferous forest, extensive wildland–urban interface, and high population density and tourism can guide targeted risk management activities. These may include targeted investments into firefighting and monitoring infrastructure, improving national and regional policies, and increasing public awareness about fire risk (e.g., [91,92]).

5. Conclusions

Forest fire occurrence in Central Europe is driven by a specific combination of climatic and non-climatic factors, predominantly the proportion of coniferous species and human activity on the landscape. The latter factor includes different aspects of human activity, which can be approximated by variables such as the number of overnight tourists, population density, and wildland–urban interface. The identified forest fire drivers and constructed statistical model can support fire danger delineation of the country and inform the targeted implementation of measures such as firefighting infrastructure development, an increase in public awareness, and regulation of human activities in fire-prone areas during fire seasons. We emphasize the importance of improving the current fire monitoring and data management system, which will allow for a more comprehensive understanding of fire drivers and encourage foresters, firefighters, and local authorities to adopt more efficient forest management and fire-control measures such as the building of water reservoirs and the education of the general public. This is particularly important in the wake of the anticipated increase in fire-conducive weather and alterations of forest structure and human activity patterns, which can shift regional fire regimes.

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Appendix A

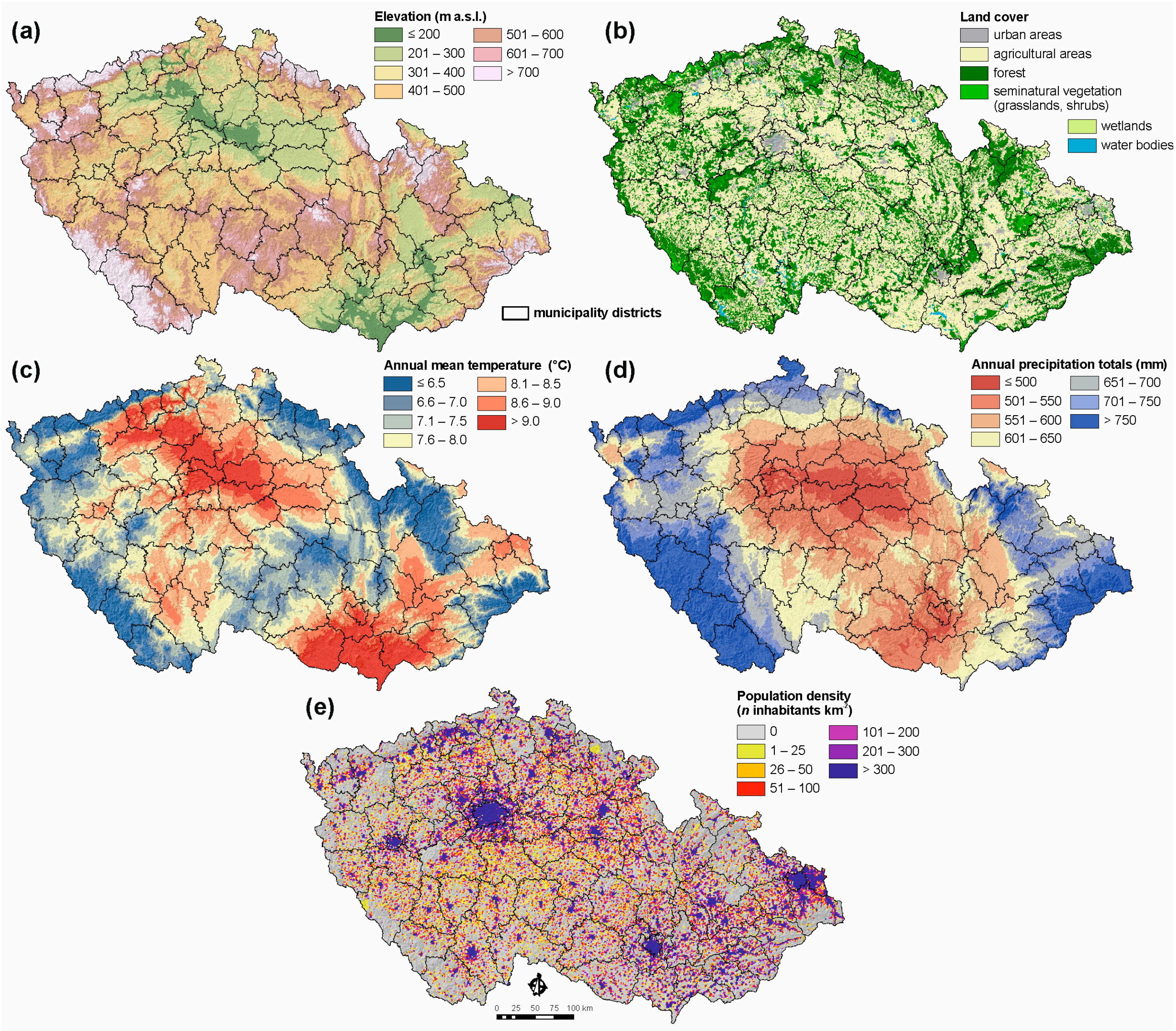

Figure A1. Landscape, social, and climatic conditions of the Czech Republic, (**a**) digital elevation model; (**b**) major landcover categories; (**c**) annual mean temperature in the period 1961 to 1990; (**d**) mean annual precipitation totals in the period 1961 to 1990; and (**e**) population density.

Appendix B

Predictor Variable	Mean	Median	Minimum	Maximum	SD
Forest complex area (ha)	414.7	388.0	115.5	766.6	166.2
Conifer cover (%) *	61.8	75.1	17.3	87.6	23.4
Difference in number of days with snow cover from the long-term mean (days)	6.3	5.1	0.1	22.4	5.0
Difference of mean monthly temperature (April to October) from the long-term mean (°C)	0.0	−0.1	−2.8	3.6	1.2
Difference of total precipitation (April to October) from the long-term mean (mm)	0.0	−4.0	−86.0	243.4	35.6
Ellenberg's climate quotient (Ellenberg 1996) from 1981 to 2000 (mm °C^{-1})	28.5	29.7	16.8	41.9	7.1
Forest-agricultural land interface per hectar of forest (m ha^{-1}) *	3332.2	3244.1	2059.3	6729.8	1023.5
Wildland-urban interface per hectare of forest (m ha^{-1}) *	362.1	183.2	44.5	2463.9	564.6
Mean annual temperature (from 1981 to 2000; °C)	7.9	7.9	6.2	9.5	1.0
Mean monthly temperature (April to October; °C) *	14.1	14.3	5.4	23.0	4.2
Number of days with snow cover (days)	28.3	25.7	0.4	71.1	19.8
Average overnight tourist density per hectare of forest (n ha^{-1} yr^{-1}) *	20.4	11.1	3.7	92.6	23.5
Proportion of forest area (%)	32.2	33.5	6.7	59.3	13.6
Proportion of forests with water-limited soils (%)	4.0	3.1	0.2	12.4	3.4
Proportion of Pinus sylvestris forests (%)	14.2	12.2	1.2	42.1	10.8
Relative difference of mean monthly temperature (April to October) from the long-term mean (°C)	0.0	−0.9	−29.2	39.9	10.3
Relative difference of total precipitation (April to October) from the long-term mean (%)	0.0	−6.4	−94.2	208.5	48.5
Population density per hectare of forest (n ha^{-1}) *	9.8	4.2	7.2	59.8	15.2
Monthly precipitation totals (April to October; mm) *	71.1	64.1	1.7	373.6	42.9

Figure A2. Candidate predictor variables used to determine drivers of forest fire frequency in the Czech Republic, where we investigated the relationship between number of forest fires and variables characterizing climate, land cover, and human activity conditions between 2006 and 2015. Only the subset of variables with significant effects (indicated by an asterisk, *) was used to construct the statistical models. SD = standard deviation.

Appendix C

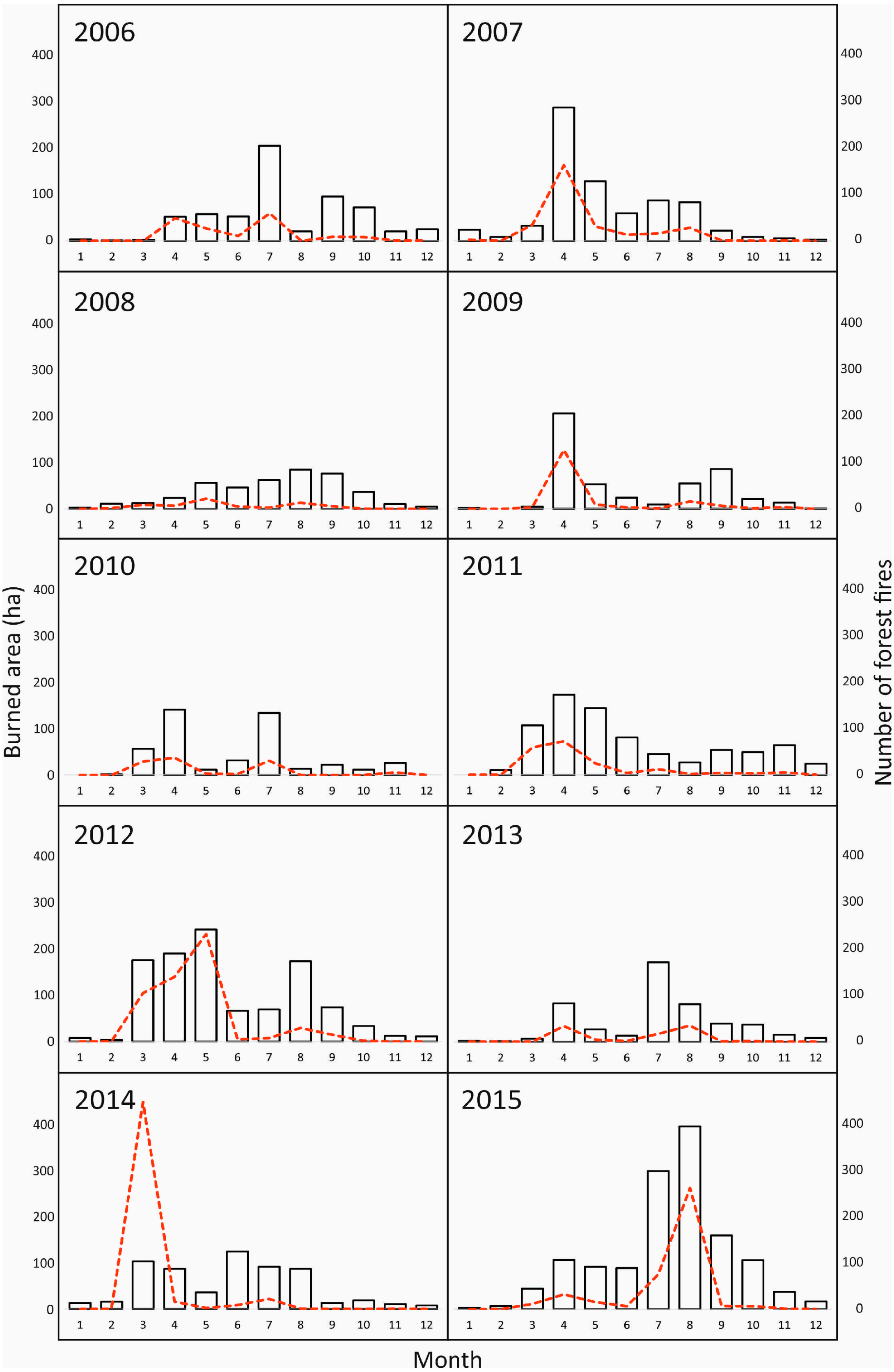

Figure A3. Number of forest fires (bars) and burned area (red line) for each year of our study (2006 to 2015) in the Czech Republic.

References

1. Patacca, M.; Lindner, M.; Lucas-Borja, M.E.; Cordonnier, T.; Fidej, G.; Gardiner, B.; Hauf, Y.; Jasinevičius, G.; Labonne, S.; Linkevičius, E.; et al. Significant increase in natural disturbance impacts on European forests since 1950. *Glob. Chang. Biol.* **2023**, *29*, 1359–1376. [CrossRef]
2. Grünig, M.; Seidl, R.; Senf, C. Increasing aridity causes larger and more severe forest fires across Europe. *Glob. Chang. Biol.* **2023**, *29*, 1648–1659. [CrossRef] [PubMed]
3. Giorgio, L.; Artés, V.T.; Thaïs, L.; Hugo, C.; Jesús, S.-M.-A.; Alfredo, B.; Tracy, D.; Fabio, L.; Daniel, N.; Christofer, A.A.; et al. *Forest fires in Europe, Middle East and North Africa 2017*; Publications Office of the European Union technical report EUR 29318 EN; Publications Office of the European Union: Luxembourg, 2018. [CrossRef]
4. Krüger, R.; Blanch Gorriz, X.; Grothum, O.; Eltner, A. Using multi-scale and multi-model datasets for post-event assessment of wildfires. In Proceedings of the Poster Presentation of the European Geosciences Union General Assembly 2023, Vienna, Austria & Online, 23–28 April 2023. EGU23-13008. [CrossRef]
5. Walker, X.J.; Rogers, B.M.; Veraverbeke, S.; Johnstone, J.F.; Baltzer, J.L.; Barrett, K.; Bourgeau-Chavez, L.; Day, N.J.; de Groot, W.J.; Dieleman, C.M.; et al. Fuel availability not fire weather controls boreal wildfire severity and carbon emissions. *Nat. Clim. Chang.* **2020**, *10*, 1130–1136. [CrossRef]
6. Littell, J.S.; McKenzie, D.; Peterson, D.L.; Westerling, A.L. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecol. Appl.* **2009**, *19*, 1003–1021. [CrossRef] [PubMed]
7. Forzieri, G.; Girardello, M.; Ceccherini, G.; Spinoni, J.; Feyen, L.; Hartmann, H.; Beck, P.S.A.; Camps-Valls, G.; Chirici, G.; Mauri, A.; et al. Emergent vulnerability to climate-driven disturbances in European forests. *Nat. Commun.* **2021**, *12*, 1081. [CrossRef]
8. Ruffault, J.; Moron, V.; Trigo, R.M.; Curt, T. Objective identification of multiple large fire climatologies: An application to a Mediterranean ecosystem. *Environ. Res. Lett.* **2016**, *11*, 75006. [CrossRef]
9. Bedia, J.; Golding, N.; Casanueva, A.; Iturbide, M.; Buontempo, C.; Gutiérrez, J.M. Seasonal predictions of Fire Weather Index: Paving the way for their operational applicability in Mediterranean Europe. *Clim. Serv.* **2018**, *9*, 101–110. [CrossRef]
10. Kasischke, E.S.; Turetsky, M.R. Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. *Geophys. Res. Lett.* **2006**, *33*, L09703. [CrossRef]
11. Turetsky, M.R.; Benscoter, B.; Page, S.; Rein, G.; van der Werf, G.R.; Watts, A. Global vulnerability of peatlands to fire and carbon loss. *Nat. Geosci.* **2015**, *8*, 11–14. [CrossRef]
12. Field, R.D.; van der Werf, G.R.; Fanin, T.; Fetzer, E.J.; Fuller, R.; Jethva, H.; Levy, R.; Livesey, N.J.; Luo, M.; Torres, O.; et al. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 9204–9209. [CrossRef]
13. Westerling Anthony LeRoy. Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Phil. Trans. R. Soc. B.* **2016**, *371*, 20150178. [CrossRef]
14. Abatzoglou, J.T.; Williams, A.P. Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 11770–11775. [CrossRef] [PubMed]
15. Elia, M.; D'Este, M.; Ascoli, D.; Giannico, V.; Spano, G.; Ganga, A.; Colangelo, G.; Lafortezza, R.; Sanesi, G. Estimating the probability of wildfire occurrence in Mediterranean landscapes using Artificial Neural Networks. *Environ. Impact Assess. Rev.* **2020**, *85*, 106474. [CrossRef]
16. Müller, M.M.; Vilà-Vilardell, L.; Vacik, H. Towards an integrated forest fire danger assessment system for the European Alps. *Ecol. Inform.* **2020**, *60*, 101151. [CrossRef]
17. Calheiros, T.; Pereira, M.; Nunes, J. Assessing impacts of future climate change on extreme fire weather and pyro-regions in Iberian Peninsula. *Sci. Total. Environ.* **2021**, *754*, 142233. [CrossRef]
18. Miller, C.; Ager, A.A. A review of recent advances in risk analysis for wildfire management. *Int. J. Wildland Fire* **2013**, *22*, 1–14. [CrossRef]
19. Emmons, H.W. Heat Transfer in Fire. *J. Heat Transf.* **1973**, *95*, 145–151. [CrossRef]
20. Osvald, A. *Požiarnotechnické Vlastností Dreva a Materiálov na Báze Dreva*; Vedecké štúdie 8/97/A; Technickej univerzity vo Zvolene: Zvolen, Mexico, (In Slovakia). 1997.
21. Roy, P.S. Forest fire and degradation assessment using satellite remote sensing and Geographic Information System. In *Satellite Remote Sensing and GIS Applications in Agricultural Meteorology, Proceedings of a Training Workshop, 7–11 July 2003, Dehra Dun, India*; Sivakumar, M.V.K., Roy, P.S., Harmsen, K., Saha, S.K., Eds.; World Meteorological Organisation: Geneva, Switzerland, 2003; pp. 361–400.
22. Zachar, M. *Vplyv Ohrevu na Termickú Degradáciu Vybraných Druhov Dreva. [The Effect of Heating on the Thermal Degradation of Selected Types of Wood.]*; Technická univerzita vo Zvolene: Zvolen, Czech Republic, 2009. (In Slovaka)
23. Thomas, P.A.; McAlpine, R.S.; Hirsch, K.; Hobson, P. *Fire in the Forest*; Cambridge University Press (CUP): Cambridge, UK, 2010; ISBN 9780511780189. [CrossRef]
24. Moritz, M.A.; Parisien, M.-A.; Batllori, E.; Krawchuk, M.A.; Van Dorn, J.; Ganz, D.J.; Hayhoe, K. Climate change and disruptions to global fire activity. *Ecosphere* **2012**, *3*, 1–22. [CrossRef]
25. Martínez, J.; Vega-Garcia, C.; Chuvieco, E. Human-caused wildfire risk rating for prevention planning in Spain. *J. Environ. Manag.* **2009**, *90*, 1241–1252. [CrossRef]

26. Grissino-Mayer, H.D.; Romme, W.H.; Floyd, M.L.; Hanna, D.D. Climatic and human influences on fire regimes of the southern san juan mountains, Colorado, USA. *Ecology* **2004**, *85*, 1708–1724. [CrossRef]
27. Mollicone, D.; Eva, H.D.; Achard, F. Human role in Russian wild fires. *Nature* **2006**, *440*, 436–437. [CrossRef] [PubMed]
28. Müller, M.M.; Vacik, H. Characteristics of lightnings igniting forest fires in Austria. *Agric. For. Meteorol.* **2017**, *240–241*, 26–34. [CrossRef]
29. Wotton, B.M.; Martell, D.L.; Logan, K.A. Climate Change and People-Caused Forest Fire Occurrence in Ontario. *Clim. Chang.* **2003**, *60*, 275–295. [CrossRef]
30. Clark, J.S.; Merkt, J.; Muller, H. Post-Glacial Fire, Vegetation, and Human History on the Northern Alpine Forelands, South-Western Germany. *J. Ecol.* **1989**, *77*, 897. [CrossRef]
31. Ellenberg, H. *Vegetation Mitteleuropa Smit den Alpen in Okologischer, Dynamischer und Historischer Sicht*; Ulmer: Stuttgart, Germany, 1996. (In German)
32. Tinner, W.; Conedera, M.; Ammann, B.; Lotter, A.F. Fire ecology north and south of the Alps since the last ice age. *Holocene* **2005**, *15*, 1214–1226. [CrossRef]
33. Niklasson, M.; Zin, E.; Zielonka, T.; Feijen, M.; Korczyk, A.F.; Churski, M.; Samojlik, T.; Jędrzejewska, B.; Gutowski, J.M.; Brzeziecki, B. A 350-year tree-ring fire record from Białowieża Primeval Forest, Poland: Implications for Central European lowland fire history. *J. Ecol.* **2010**, *98*, 1319–1329. [CrossRef]
34. Donis, J.; Kitenberga, M.; Snepsts, G.; Matisons, R.; Zarins, J.; Jansons, A. The forest fire regime in Latvia during 1922–2014. *Silva Fenn.* **2017**, *51*, 7746. [CrossRef]
35. Rodrigues, M.; Jiménez-Ruano, A.; de la Riva, J. Fire regime dynamics in mainland Spain. Part 1: Drivers of change. *Sci. Total. Environ.* **2020**, *721*, 135841. [CrossRef]
36. Martell, D.L.; Otukol, S.; Stocks, B.J. A logistic model for predicting daily people-caused forest fire occurrence in Ontario. *Can. J. For. Res.* **1987**, *17*, 394–401. [CrossRef]
37. Garcia, C.; Woodard, P.; Titus, S.; Adamowicz, W.; Lee, B. A Logit Model for Predicting the Daily Occurrence of Human Caused Forest-Fires. *Int. J. Wildland Fire* **1995**, *5*, 101–111. [CrossRef]
38. A Parks, S.; Holsinger, L.M.; Panunto, M.H.; Jolly, W.M.; Dobrowski, S.Z.; Dillon, G.K. High-severity fire: Evaluating its key drivers and mapping its probability across western US forests. *Environ. Res. Lett.* **2018**, *13*, 44037. [CrossRef]
39. Vasilakos, C.; Kalabokidis, K.; Hatzopoulos, J.; Kallos, G.; Matsinos, Y. Integrating new methods and tools in fire danger rating. *Int. J. Wildland Fire* **2007**, *16*, 306–316. [CrossRef]
40. Mozny, M.; Trnka, M.; Brázdil, R. Climate change driven changes of vegetation fires in the Czech Republic. *Theor. Appl. Clim.* **2021**, *143*, 691–699. [CrossRef]
41. Trnka, M.; Možný, M.; Jurečka, F.; Balek, J.; Semerádová, D.; Hlavinka, P.; Štěpánek, P.; Farda, A.; Skalák, P.; Cienciala, E.; et al. Observed and estimated consequences of climate change for the fire weather regime in the moist-temperate climate of the Czech Republic. *Agric. For. Meteorol.* **2021**, *310*, 108583. [CrossRef]
42. Hlásny, T.; Zimová, S.; Merganičová, K.; Štěpánek, P.; Modlinger, R.; Turčáni, M. Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. *For. Ecol. Manag.* **2021**, *490*, 119075. [CrossRef]
43. Hicke, J.A.; Johnson, M.C.; Hayes, J.L.; Preisler, H.K. Effects of bark beetle-caused tree mortality on wildfire. *For. Ecol. Manag.* **2012**, *271*, 81–90. [CrossRef]
44. Hart, S.J.; Veblen, T.T.; Mietkiewicz, N.; Kulakowski, D. Negative Feedbacks on Bark Beetle Outbreaks: Widespread and Severe Spruce Beetle Infestation Restricts Subsequent Infestation. *PLoS ONE* **2015**, *10*, e0127975. [CrossRef] [PubMed]
45. Sjöström, J.; Plathner, F.V.; Granström, A. Wildfire ignition from forestry machines in boreal Sweden. *Int. J. Wildland Fire* **2019**, *28*, 666–677. [CrossRef]
46. Trnka, M.; Balek, J.; Možný, M.; Cienciala, E.; Čermák, P.; Semerádová, D.; Jurečka, F.; Hlavinka, P.; Štěpánek, P.; Farda, A.; et al. Observed and expected changes in wildfire-conducive weather and fire events in peri-urban zones and key nature reserves of the Czech Republic. *Clim. Res.* **2020**, *82*, 33–54. [CrossRef]
47. Tolasz, R.; Míková, T.; Valeriánová, A.; Voženílek, V. *Atlas Podnebí Česka [Climate Atlas of Czechia]*; Palacky Univerzity and Czech Hydrometeorological Institute: Olomouc, Czech, 2007. (In Czech)
48. Pokorná, A.; Štrombachová, V.; Mužík, J.; Dolanová, D.; Búřilová, P.; Pospíšil, M.; Kučerová, J.; Gregor, J.; Komenda, M.; Dušek, L. *Národní Portál Systém Hlášení Nežádoucích Událostí*; Ústav Zdravotnických Informací ČR: Praha, Czech, 2016. Available online: https://shnu.uzis.cz/ (accessed on 20 December 2019). (In Czech)
49. Chytrý, M. Vegetation of the Czech Republic: Diversity, ecology, history and dynamics. *Preslia* **2012**, *84*, 427–504.
50. Ministry of Agriculture of the Czech Republic. *Information on Forests and Forestry in the Czech Republic by 2020*; Ministry of Agriculture of the Czech Republic: Prague, Czech, 2021.
51. Ministry of Interior of the Czech Republic. *Database of Forest Fires 2006–2015*; General Directorate of the Fire Rescue Service of the Czech Republic, Ministry of Interior of the Czech Republic: Prague, Czech, 2019.
52. Berčák, R.; Holuša, J.; Lukášová, K.; Hanuška, Z.; Agh, P.; Vaněk, J.; Kula, E.; Chromek, I. Forest fires in the Czech Republic—Characteristics, Prevention and Firefighting: Review. *Zprávy Lesn. Výzkumu.* **2018**, *63*, 184–194. Available online: https://www.vulhm.cz/files/uploads/2019/02/533.pdf (accessed on 1 July 2018). (In Czech).
53. Holuša, J.; Berčák, R.; Lukášová, K.; Hanuška, Z.; Agh, P.; Vaněk, J.; Kula, E.; Chromek, I. Forest fires in the Czech Republic—Definition and classification: Review. *Zprávy Lesn. Výzkumu.* **2018**, *63*, 20–27. (In Czech)

54. State Administration of Land Surveying and Cadastre. Czech Geodetic and Cadastral Office. 2019. Available online: https://www.cuzk.cz/en (accessed on 20 December 2021).
55. Flannigan, M.D.; Logan, K.A.; Amiro, B.D.; Skinner, W.R.; Stocks, B.J. Future Area Burned in Canada. *Clim. Chang.* **2005**, *72*, 1–16. [CrossRef]
56. Aldersley, A.; Murray, S.J.; Cornell, S.E. Global and regional analysis of climate and human drivers of wildfire. *Sci. Total. Environ.* **2011**, *409*, 3472–3481. [CrossRef] [PubMed]
57. Zumbrunnen, T.; Menéndez, P.; Bugmann, H.; Conedera, M.; Gimmi, U.; Bürgi, M. Human impacts on fire occurrence: A case study of hundred years of forest fires in a dry alpine valley in Switzerland. *Reg. Environ. Chang.* **2012**, *12*, 935–949. [CrossRef]
58. Vacchiano, G.; Foderi, C.; Berretti, R.; Marchi, E.; Motta, R. Modeling anthropogenic and natural fire ignitions in an inner-alpine valley. *Nat. Hazards Earth Syst. Sci.* **2018**, *18*, 935–948. [CrossRef]
59. Dupire, S.; Curt, T.; Bigot, S.; Fréjaville, T. Vulnerability of forest ecosystems to fire in the French Alps. *Eur. J. For. Res.* **2019**, *138*, 813–830. [CrossRef]
60. Ubysz, B.; Valette, J.-C. Flammability: Influence of fuel on fire. In *Towards Integrated Fire Management—Outcomes of the European Project Fire Paradox*; Silva, J.S., Rego, F., Fernandes, P., Rigolot, E., Eds.; European Forest Institute: Joensuu, Finland, 2010; pp. 23–34.
61. Lecomte, N.; Simard, M.; Bergeron, Y.; Larouche, A.; Asnong, H.; Richard, P.J. Effects of fire severity and initial tree composition on understorey vegetation dynamics in a boreal landscape inferred from chronosequence and paleoecological data. *J. Veg. Sci.* **2005**, *16*, 665–674. [CrossRef]
62. Ganteaume, A.; Barbero, R.; Jappiot, M.; Maillé, E. Understanding future changes to fires in southern Europe and their impacts on the wildland-urban interface. *J. Saf. Sci. Resil.* **2021**, *2*, 20–29. [CrossRef]
63. European Environment Agency. Indicator Assessment: Forest Fires. 2018. Available online: https://www.eea.europa.eu/data-and-maps/indicators/forest-fire-danger-2/assessment (accessed on 1 April 2019).
64. Wood, S.N. *Generalized Additive Models*; Chapman and Hall/CRC: Boca Raton, FL, USA, 2017. [CrossRef]
65. Wood, S.N. Stable and Efficient Multiple Smoothing Parameter Estimation for Generalized Additive Models. *J. Am. Stat. Assoc.* **2004**, *99*, 673–686. [CrossRef]
66. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2021. Available online: https://www.R-project.org/ (accessed on 23 May 2022).
67. Silva, P.; Carmo, M.; Rio, J.; Novo, I. Changes in the seasonality of fire activity and fire weather in Portugal: Is the wildfire season really longer? *Meteorology* **2023**, *2*, 74–86. [CrossRef]
68. Unal, Y.S.; Tan, E.; Mentes, S.S. Summer heat waves over western Turkey between 1965 and 2006. *Theor. Appl. Clim.* **2013**, *112*, 339–350. [CrossRef]
69. Vasić, M. *Wildfires*; University of Belgrade, Faculty of Forestry: Belgrade, Serbia, 1992.
70. Ubysz, B.; Szczygiel, R.; Kwitkowski, M.; Piwnicki, J. *Intrukcja Ochrony Przeciwpozarowej Lasu*; Panstwowe Gospodarstwo Lesne, Lasy Panstwowe: Warsa, Poland, 2012. (In Polish)
71. Engelmark, O. Early post-fire tree regeneration in a Picea-Vaccinium forest in northern Sweden. *J. Veg. Sci.* **1993**, *4*, 791–794. [CrossRef]
72. Pew, K.; Larsen, C. GIS analysis of spatial and temporal patterns of human-caused wildfires in the temperate rain forest of Vancouver Island, Canada. *For. Ecol. Manag.* **2001**, *140*, 1–18. [CrossRef]
73. Koutsias, N.; Xanthopoulos, G.; Founda, D.; Xystrakis, F.; Nioti, F.; Pleniou, M.; Mallinis, G.; Arianoutsou, M. On the relationships between forest fires and weather conditions in Greece from long-term national observations (1894–2010). *Int. J. Wildland Fire* **2013**, *22*, 493–507. [CrossRef]
74. Guo, F.; Su, Z.; Wang, G.; Sun, L.; Lin, F.; Liu, A. Wildfire ignition in the forests of southeast China: Identifying drivers and spatial distribution to predict wildfire likelihood. *Appl. Geogr.* **2016**, *66*, 12–21. [CrossRef]
75. Flannigan, M.D.; Harrington, J.B. A Study of the Relation of Meteorological Variables to Monthly Provincial Area Burned by Wildfire in Canada (1953–80). *J. Appl. Meteorol.* **1988**, *27*, 441–452. [CrossRef]
76. Flannigan, M.D.; Wotton, B.M.; Marshall, G.A.; de Groot, W.J.; Johnston, J.; Jurko, N.; Cantin, A.S. Fuel moisture sensitivity to temperature and precipitation: Climate change implications. *Clim. Chang.* **2016**, *134*, 59–71. [CrossRef]
77. Díaz-Delgado, R.; Lloret, F.; Pons, X. Spatial patterns of fire occurrence in Catalonia, NE, Spain. *Landsc. Ecol.* **2004**, *19*, 731–745. [CrossRef]
78. Sturtevant, B.R.; Zollner, P.A.; Gustafson, E.J.; Cleland, D.T. Human influence on the abundance and connectivity of high-risk fuels in mixed forests of northern Wisconsin, USA. *Landsc. Ecol.* **2004**, *19*, 235–254. [CrossRef]
79. Parisien, M.-A.; Parks, S.A.; Krawchuk, M.A.; Flannigan, M.D.; Bowman, L.M.; Moritz, M.A. Scale-dependent controls on the area burned in the boreal forest of Canada, 1980–2005. *Ecol. Appl.* **2011**, *21*, 789–805. [CrossRef] [PubMed]
80. Ganteaume, A.; Camia, A.; Jappiot, M.; San-Miguel-Ayanz, J.; Long-Fournel, M.; Lampin, C. A Review of the Main Driving Factors of Forest Fire Ignition Over Europe. *Environ. Manag.* **2013**, *51*, 651–662. [CrossRef]
81. Cardille, J.; Ventura, S.J. Environmental and social factors influencing wildfires in the upper Midwest, United States. *Ecol. Appl.* **2001**, *11*, 111–127. [CrossRef]
82. Martínez-Fernández, J.; Chuvieco, E.; Koutsias, N. Modelling long-term fire occurrence factors in Spain by accounting for local variations with geographically weighted regression. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 311–327. [CrossRef]

83. Adámek, M.; Jankovská, Z.; Hadincová, V.; Kula, E.; Wild, J. Drivers of forest fire occurrence in the cultural landscape of Central Europe. *Landsc. Ecol.* **2018**, *33*, 2031–2045. [CrossRef]
84. Jenerette, G.D.; E Anderson, K.; Cadenasso, M.L.; Fenn, M.; Franklin, J.; Goulden, M.L.; Larios, L.; Pincetl, S.; Regan, H.M.; Rey, S.J.; et al. An expanded framework for wildland–urban interfaces and their management. *Front. Ecol. Environ.* **2022**, *20*, 516–523. [CrossRef]
85. Spyratos, V.; Bourgeron, P.S.; Ghil, M. Development at the wildland–urban interface and the mitigation of forest-fire risk. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 14272–14276. [CrossRef] [PubMed]
86. Šodková, M.; Purwestri, R.C.; Riedl, M.; Jarský, V.; Hájek, M. Drivers and Frequency of Forest Visits: Results of a National Survey in the Czech Republic. *Forests* **2020**, *11*, 414. [CrossRef]
87. Jarský, V.; Palátová, P.; Riedl, M.; Zahradník, D.; Rinn, R.; Hochmalová, M. Forest Attendance in the Times of COVID-19—A Case Study on the Example of the Czech Republic. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2529. [CrossRef] [PubMed]
88. Gao, L.; Wang, X.; Johnson, B.A.; Tian, Q.; Wang, Y.; Verrelst, J.; Mu, X.; Gu, X. Remote sensing algorithms for estimation of fractional vegetation cover using pure vegetation index values: A review. *ISPRS J. Photogramm. Remote Sens.* **2020**, *159*, 364–377. [CrossRef]
89. Stahl, A.T.; Andrus, R.; Hicke, J.A.; Hudak, A.T.; Bright, B.C.; Meddens, A.J. Automated attribution of forest disturbance types from remote sensing data: A synthesis. *Remote Sens. Environ.* **2023**, *285*, 113416. [CrossRef]
90. Carnicer, J.; Alegria, A.; Giannakopoulos, C.; Di Giuseppe, F.; Karali, A.; Koutsias, N.; Lionello, P.; Parrington, M.; Vitolo, C. Global warming is shifting the relationships between fire weather and realized fire-induced CO_2 emissions in Europe. *Sci. Rep.* **2022**, *12*, 10365. [CrossRef] [PubMed]
91. Balch, J.K.; Schoennagel, T.; Williams, A.P.; Abatzoglou, J.T.; Cattau, M.E.; Mietkiewicz, N.P.; Denis, L.A.S. Switching on the Big Burn of 2017. *Fire* **2018**, *1*, 17. [CrossRef]
92. Dunn, C.J.; O'connor, C.D.; Abrams, J.; Thompson, M.P.; E Calkin, D.; Johnston, J.D.; Stratton, R.; Gilbertson-Day, J. Wildfire risk science facilitates adaptation of fire-prone social-ecological systems to the new fire reality. *Environ. Res. Lett.* **2020**, *15*, 025001. [CrossRef]