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RESEARCH ARTICLE

Drivers of forest fire occurrence in the cultural landscape of Central Europe

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Abstract
Context Wildfires in temperate Central Europe have traditionally been perceived as a mere consequence of human activity without any relevance to natural forest development, despite their documented frequent occurrence. As a result, knowledge about local fire ecology and patterns of wildfire occurrence in the landscape is lacking.
Objectives We aimed to reveal the factors influencing the spatial distribution of forest fires in the Czech Republic as a model area for the broader region. Specifically, we aimed to (1) find out which factors influence the occurrence and frequency of the forest fires at the country scale and in a selected fire-prone region; (2) examine the relationship of lightning strikes and their polarity with wildfire incidence; (3) identify the conditions determining areas with naturally driven fire-prone conditions.
Methods We took data on 15,985 wildfire records and explored their spatial distribution using GIS layers of human, topographic, climatic and vegetation composition factors. We analysed the data using GLM and hierarchical partitioning methods.
Results Wildfire occurrence was controlled mostly by environmental factors whereas wildfire frequency was strongly driven by human factors. In the selected fire-prone region, the effect of environmental factors was even more pronounced and wildfire frequency was also driven, albeit marginally, by lightning strikes of positive polarity.
Conclusion The pattern of wildfire occurrence in the Czech Republic was similar also to those from regions

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where wildfire is considered a natural part of local ecosystems. We identified the areas with natural fire-prone conditions which probably led to the development of local fire-adapted ecosystems.

Keywords Wildfire · Spatial pattern · Temperate · *Pinus sylvestris* · Lightning strikes · Polarity

Introduction

Fire is an important disturbance factor shaping forest vegetation worldwide (Engelmark 1993; Skre et al. 1998; Pausas and Vallejo 1999; Podur et al. 2003). On the Northern Hemisphere, fire is generally supposed to be an integral part of natural dynamics of boreal forests and Mediterranean ecosystems. In temperate regions of Central Europe, by contrast, the role of fire in the functioning of local forest ecosystems has been traditionally marginalized, and wildfires have been perceived just as harmful consequence of human activity without any relevance to natural processes (Clark and Merkt 1989; Ellenberg 1996; Tinner et al. 2005; Niklasson et al. 2010).

The reasons for such attitude to wildfire in Central European forests can be relatively dense human population and long-lasting land-use associated with strong influence of natural vegetation and processes, including the long tradition of fire suppression, compared to e.g. Northern America or boreal Eurasia (Angelstam and Kuuluvainen 2004). Another reason can lie in typical fire behaviour, related to fire adaptations of dominant tree species in temperate and boreal Eurasia, which is represented by low intensity surface fires (Rogers et al. 2015). These fires are relatively easy to suppress and there is no need to implement special prevention management such as prescribed burning to reduce fuels. That is why this topic had long been neglected by ecological studies from this region, including the analysis of factors influencing the wildfire incidence in the landscape. However, wildfires have recently been recognized as an important factor also in temperate regions of Europe, namely in Alps and Carpathians (Delarze et al. 1992; Tinner et al. 1999; Stahli et al. 2006; Müller et al. 2013; Valese et al. 2014; Feurdean et al. 2017) and in *Pinus sylvestris* forests of Lithuania, Poland and the Czech Republic (Marozas et al. 2007; Niklasson et al. 2010; Adámek et al. 2015; Zin et al. 2015). Further investigations on the connection of fire with local ecosystems are thus needed.

Lightning strikes are a major natural cause of wildfires (Pyne et al. 1996). The proportion of lighting-ignited fires varies substantially worldwide. In the period of 2006–2010, lightning strikes ignited 7.3% of forest fires in Northern Europe, 0.5% in Central Europe and 4.7% in Southern Europe, whereas in Canada and the USA, the proportion of naturally caused fires is about 48% (Cardille and Ventura 2001; Ganteaume et al. 2013). This proportion, however, depends on the local population density, as lightning-caused fires prevail in remote areas with low populations (e.g. Flannigan et al. 2000). Different perspective can be provided by comparing the spatial frequency of lightning-ignited forest fires, which in some parts of the USA and in European Alpine regions reaches up to 0.9 fires/(year 100 km^2). In Mediterranean Europe, the average density has been estimated to be 0.12 fires/(year 100 km^2). In the Czech Republic, the area of our study, the average wildfire density (0.065 fires/(year 100 km^2), is slightly lower than in W Siberia (0.075) but slightly higher than in Northern European boreal countries (0.039) (Granström 1993; Larjavaara et al. 2005; Kula and Jankovská 2013; Müller et al. 2013), even though in the Czech Republic, there is a higher proportion of mixed and broadleaved forests, which are considered less fire-prone than coniferous forests (Clark and Royall 1996; Moreira et al. 2001).

It is generally accepted that most lightning ignitions in forests are caused by lightning with long continuing current of returning strokes. However, because of poor detection of this quality by current lightning-detection systems, other related lightning characteristics like stroke polarity, stroke multiplicity or current strength are used instead (Pineda et al. 2014). Highly discussed is the role of stroke polarity. Lightning strikes of positive polarity are traditionally considered to ignite fires more likely than negative ones, due to higher current amplitudes, greater probability of a long continuing current and less accompanying precipitation (Flannigan and Wotton 1991; Larjavaara et al. 2005). However, the real importance of positive lightnings on forest fire occurrence still remains unclear, while recent studies provided contradicting results on this topic (Larjavaara et al. 2005; Wotton and Martell 2005; Pineda et al. 2014; Müller and Vacik 2017).

Although forest fires are a natural phenomenon, their main cause in populated landscapes is human activity. In Europe, 97% of forest fires of known cause within the period of 2006–2010 were directly or indirectly caused by humans (Ganteaume et al. 2013). Moreover, palaeoecological and fire-history studies suggest that during the Holocene period, the frequency of fire events was markedly positively influenced by human presence in the landscape (Niklasson and Granström 2000; Vannière et al. 2008; Molinari et al. 2013; Bobek et al. 2017). Equally, the overwhelming majority of recent forest fires in the Czech Republic is caused by humans.

Besides ignition triggers, the distribution of wildfires in the landscape is also influenced by environmental factors of both anthropogenic and natural origin (Cardille and Ventura 2001; Yang et al. 2007; Avila-Flores et al. 2010). Thus, human presence in the landscape usually acts as an ignition trigger, while environmental factors influence wildfire probability. Such factors can be biotic, such as the vegetation cover influencing the fuel type, load and inflammability, or abiotic, such as the climate, topography or soil type influencing fuel moisture and spreading of the fire (Engelmark 1993; Cardille and Ventura 2001; Díaz-Delgado et al. 2004). Anthropogenic factors influencing fire occurrence can be socio-economic, such as population density or the rate of unemployment, as well as socio-environmental, such as land use (Moreira et al. 2001; Ganteaume et al. 2013). However, the effect of all these factors on fire incidence varies among habitat types and depends on the temporal and spatial scale, as, for example, climatic variables usually operate on a broader than regional scale (Yang et al. 2007; Avila-Flores et al. 2010; Miranda et al. 2012).

Since the Central European landscape is influenced by long-term human presence, human-ignited fires could be an important factor shaping forest vegetation throughout the Holocene period (Tinner et al. 2005). Stable natural conditions increasing the fire-proneness of a locality can promote the development of specific fire-adapted vegetation even in temperate landscapes (Adámek et al. 2015). Knowledge of how the environment affects patterns of wildfire occurrence is therefore important for understanding the processes influencing the development of the Central European landscape. Moreover, this knowledge can be useful for the purposes of nature conservation and for fire prevention planning, especially at present, when the fire risk in Europe is rising due to climate change (Lindner et al. 2010).

In this study, we aimed to fill in the knowledge gap in global fire ecology by revealing the rules of the wildfire occurrence in the cultural landscape in humid temperate climate, characterized by a long-term and relatively dense human presence. As we are aware, it is the first quantitative investigation of the influence of human, biotic and abiotic factors on the spatial distribution of recent forest wildfires in the Central European region. Specifically, we aimed to find out: (a) which factors influence the occurrence and frequency of the forest fires on the country scale and in a selected fire-prone region; (b) what is the role of lightning strikes and their polarity in wildfire occurrence; and (c) which conditions determine naturally fire-prone areas in the landscape.

Methods

Study area

We aimed to reveal the drivers of the occurrence of forest fires operating at different geographical scales. We therefore selected two model areas. The large (country) scale was represented by the Czech Republic (78,866 km^2) situated in Central Europe, in the middle of the temperate zone of the Northern Hemisphere (Fig. 1). Its climate is mild with four seasons, transitional between oceanic and continental, and characterized by prevailing western winds, intensive cyclonal activity and relative high precipitation. The average temperature varies between ca. – 3 °C (January) and 17 °C (July), and average annual precipitation across more than 60% of the country's area is 600–800 mm (Tolasz 2007). The climate is, however, considerably influenced by the relatively rapidly changing elevation and relief. The elevation ranges from 115 to 1603 m a.s.l. with a median of 430 m a.s.l.. The prevailing relief type are hills and highlands. The average population density is 133 persons/km^2.

The naturally dominant vegetation formation in the Czech Republic are mixed beech-fir forests transitioning towards broadleaved oak-dominated forest in the lowlands and towards coniferous spruce-dominated forests at higher altitudes (Chytrý 2012). However, as

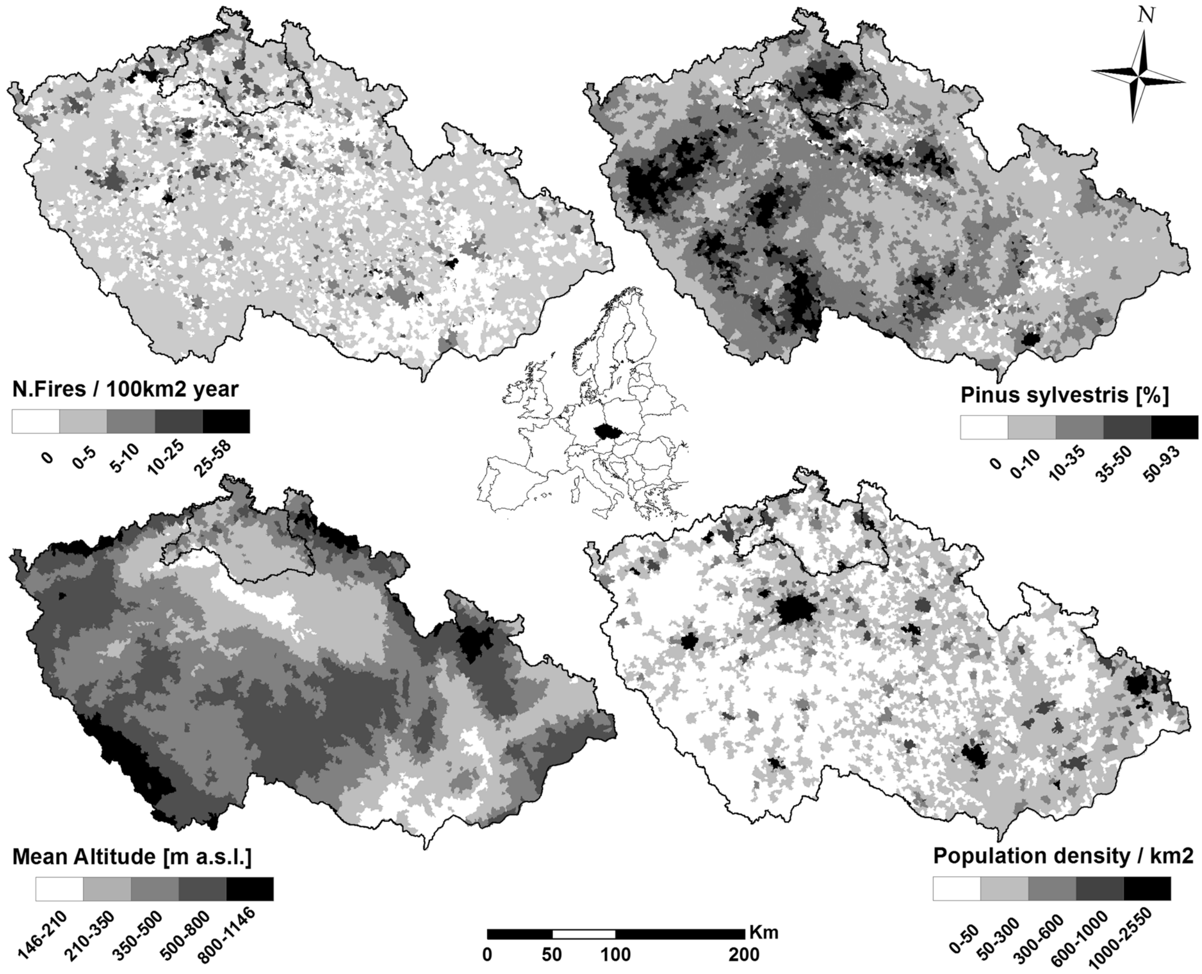

Fig. 1 Localization of the study area in the European context (country scale) and within the Czech Republic (selected region). Maps show the number of wildfires/100 km^2 of forested area per year and values of important drivers of wildfire occurrence in municipality cadastres: *Pinus sylvestris* abundance, Mean altitude; Population density

a result of intensive forestry management, practised since the 19th century, the present forest composition differs markedly from the natural state. Forests at present cover 33.9% of the country and are mainly composed of *Picea abies* (52%), *Pinus sylvestris* (17%), *Fagus sylvatica* (7%), *Quercus* spp. (7%), *Larix decidua* (4%), *Betula pendula* (3%), *Abies alba* (1%). Other broad-leaved species (e.g. *Carpinus betulus*, *Acer* spp., *Fraxinus* spp., *Populus* spp., *Salix* spp., *Tilia* spp.) occupy ca. 8% of the forested area (www.uhul.cz).

About 90% of the area of the Czech forests is represented by commercial forests with intensive forestry management, managed mostly by clear-cutting system. More than 60% of the forested area is state-owned (www.mzp.cz). The main threats for the commercial forestry in the Czech Republic, in the sense of the volume of salvage logging, are abiotic factors, mainly the windstorms (> 50%), followed by droughts (5–13%), snow (2–12%) and frost (1–12%). Biotic factors, mostly the insect outbreaks contribute with 10–27%. Wildfire plays relatively minor role with 1–7% of the volume of salvage logging (Rychtecká and Urbancová 2008) without greater socio-economic and ecologic impact. It is related with relatively efficient system of fire detection and suppression where all wildfires are suppressed. The use of fire as a management tool in forests is restricted only to the burning of harvest residues on clearcut areas while prescribed fires to reduce forest fuels are not allowed (Albers 2012).

In the period of 1992–2004, the average number of forest fires in the country per year was 1230, with a mean burned area of 0.49 ha/fire, median area of 0.025 ha/fire and the largest burned area of 400 ha/fire. The causes of fire were: unexplained (29.9%), human-caused—mostly fire raising, smoking and forestry management (68.7%), and lightning strike (1.4%). The absolutely prevailing type of the fires was ground fire (Kula and Jankovská 2013). Present-day climate-change scenarios for Central Europe predict increasing frequency of droughts and wildfires (Lindner et al. 2010; Trnka et al. 2015).

The regional scale was represented by an area of 4925 km^2, located in the NW part of the Czech Republic (Fig. 1). It was chosen due to its characteristic and various natural conditions and markedly frequent occurrence of wildfires (Kula and Jankovská 2013). We focused on this specific region to test the drivers of wildfire occurrence on a narrower geographical scale. Such conditions enabled us to test the role of lightnings as a potential natural ignition trigger on finer scale, with regard to stroke polarity, using precise data on the frequency of cloud-to-ground lightning strikes. The region is characterized by a relatively high forest cover with preserved natural and semi-natural forests since the main part of the area is situated in natural protected areas, including, for example, Bohemian Switzerland National Park. The topography and geology of the region is very diverse, encompassing tertiary volcanic hills, quartzite mountain ranges, sandstone rocky areas, river valleys and tablelands. The elevation ranges between 115 m a.s.l. (Elbe river valley) and 1012 m a.s.l. (Ještěd mountain). A large part of the region is characterized by sandstone bedrock with a typical rugged relief ("rock towns") with *Pinus sylvestris* as the dominant tree species, forming there so-called "relic pinewoods". Forests on volcanic bedrock are mainly composed of broadleaved tree species such as *Fagus sylvatica* and *Quercus* spp. Other parts of the regions are covered mainly by forests dominated by *Picea abies*. The semi-natural coniferous forests of this region have recently been recognized as an extrazonal lowland taiga that has probably been shaped by recurrent wildfires over millennia (Chytrý 2012; Novák et al. 2012; Adámek et al. 2015).

Data on forest fire occurrence

In our analyses, we used a database of 15,985 forest fires that occurred in the Czech Republic in the period of 1992–2004. The dataset originated from the administrative central evidence of fires of the General Directorate of Fire Rescue Service of the Czech Republic (GŘ HSZ ČR). The data on forest fires in the central evidence originate from forest owners whose duty is to send the report of wildfires to the central evidence every year. The database contains the records of all events considered as wildfires by forest owners, with burned area ranging from < 1 m^2 to 400 ha, with the mean size of 0.49 ha and median size 0.025 ha. The database was subsequently manually verified to exclude non-forest fires (Kula and Jankovská 2013). All fire records were localized into 3474 cadastres (corresponding to LAU2 units of the Nomenclature of Territorial Units for Statistics of European Union) from the total of 6251 existing in the Czech Republic. Prior to our analyses, we excluded cadastres without forest cover, military areas due to missing or inaccurate data and the two largest cities, Prague and Brno. The final dataset thus included 6097 cadastres on the country scale and their subset of 330 on the regional scale. The area of the cadastres analysed ranged from 0.25 to 214.9 km^2 (mean 12.4 km^2, median 8.1 km^2, SD 13.6). Fire counts per cadastre over the period of 1992–2004, further referred as fire frequency ranged from 0 to 191 (mean 2.5, median 1, SD 7).

Fire occurrence predictors

We computed the values of particular factors used to explain the occurrence of wildfires in each cadastre polygon using ArcGIS 10.1. software (www.esri.com). For a complete list of factors used in our analyses, see Table 1. The data source for human factors such as the population density and the number of accommodation facilities (a proxy for the rate of tourism) in cadastres was the Czech Statistical Office (www.csu.cz). Distance from the nearest city was computed as the distance from the nearest settlement with more than 50,000 inhabitants. The mean precipitation and temperature figures for each municipality for the period 1992–2004 were computed from grid data (cell size 500 m) on mean annual temperature and sum of annual precipitation provided by the Czech Hydrometeorological Office (CHMI; www.chmi.cz).

Table 1 Factors used as fire predictors and their descriptive statistics

Factors	Country scale				Regional scale			
	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD
Anthropic								
Population (per km^2)	0.9	2362	91.4	138	5.2	1486	94.6	153.8
N. of accomodation (per km^2)	0	28.1	0.08	0.4	0	2.3	0.1	0.2
Distance from city (km)	0	75	22.2	13.6	0	49.7	15.1	11.2
Climatic								
Precipitation (mm)	434.8	1355	660.7	125	434.8	1090	718	125.3
Temperature (°C)[a]	4.1	10	8.3	0.9	6.5	9.6	8.2	0.6
N. of all lightnings (per km^2)	17.2	51.2	27.6	5.3	NA	NA	NA	NA
N. of CG− lightnings (per km^2)	NA	NA	NA	NA	0	32.9	15.6	4.3
N. of CG+ lightnings (per km^2)	NA	NA	NA	NA	0	13.1	4.8	1.9
Topographic and soil								
Altitude (m a.s.l.)	146.2	1145	412.4	144	146.2	606.7	348.1	84.1
Ruggednes index	0.3	22.4	4.7	2.9	1.1	22.4	6.9	3.3
Available water capacity	0.069	0.116	0.094	0.006	0.073	0.114	0.094	0.007
Forest composition (%)								
Abies alba	0	33.1	0.5	1.2	0	0.8	0.1	0.1
Betula spp.[b]	0	85	3.4	4.5	0	36.7	6	4.2
Carpinus betulus	0	47.2	1.9	3.8	0	22.8	2.2	3.3
Fagus sylvatica	0	65.4	3.5	6	0	57.5	5	6.1
Larix decidua	0	40	3.6	3.8	0	15.1	3.1	2.5
Picea abies	0	100	32.4	25.6	0	70.4	23.9	17.8
Pinus sylvestris	0	92.1	18	18.3	0	76	19.6	19.1
Populus spp.[c]	0	87	2.2	7.1	0	80	1	4.9
Populus tremula	0	26	0.5	1.2	0	5.7	0.6	0.7
Quercus petraea	0	74.8	2.7	7.2	0	54.9	3.5	8.1
Quercus robur	0	100	9	12.1	0	76	12.6	12
Robinia pseudacacia	0	100	3.4	10.6	0	42.3	2.7	6.8
Tilia spp.[d]	0	83.3	2.1	4.2	0	20	1.8	2.9
Forested area (ha)	0.25	167	9.1	11.4	0.25	167	10.9	14.5

[a]Factors excluded from GLM analyses due to collinearity

[b]*Betula pendula, B. pubescens*

[c]*Populus nigra, P. alba, P. x canadensis*

[d]*Tilia cordata, T. platyphyllos, T. x vulgaris*

The data on lightning strikes frequency came from the Central European Lightning Detection Network (CELDN) provided by the CHMI. The number of cloud-to-ground (CG) lightning strikes, a potential ignition trigger, was calculated from annual sums for the period of 2002–2009. The only available data for the whole country were the sums of all CG lightnings in 77 districts of the Czech Republic. For the region of the NW Czech Republic, we used sums of lightnings in cadastres from the same period computed from gridded data (1 × 1 km), where lightnings were divided according to their polarity into negative (CG−) and positive (CG+) lightnings. We used these categories as separated factors because CG+ lightnings are claimed to be a stronger source of the wildfire ignition than the more frequent CG− lightnings (Latham and Williams 2001), although this is still disputed (e.g. Flannigan and Wotton 1991; Nauslar 2014). Topographic factors such as mean altitude and the ruggedness index (Riley et al. 1999) of each cadastre were computed from the LiDAR Digital Elevation Model (DEM) of the Czech Republic provided by the

Czech Office for Surveying, Mapping and Cadaster in the form of the DMR 4G service, resampled to a grid cell size of 20 m. The available water capacity of the soil was computed from grid data of 500 m cell size downloaded from European Soil Data Centre (ESDAC) (http://esdac.jrc.ec.europa.eu), where it was derived as the difference between the − 33 kPa and the − 1500 kPa water content (expressed as volume fraction) (Ballabio et al. 2016). The percentage abundance of particular tree species in the forested area of each cadastre was computed from grid data of 500 m cell size, provided by the Czech Forest Management Office (www.uhul.cz).

Data analyses

We performed our analyses on two geographical scales to compare the drivers of fire occurrence for the whole country and for a region selected for its specific natural conditions. For the regional scale, we used more precise lightning data divided into two factors (CG− and CG+), summed for each cadastre. For both spatial scales, we performed analyses with two dataset types: (a) fire presence/absence data to reveal the general pattern of fire occurrence and (b) fire counts > 0 data to reveal factors influencing the fire frequency. The idea of this way of analysis is that one process is causing the absence of fire, and at those sites where fire is present, there is a second process influencing the number of fires (Zuur et al. 2009). To check the robustness of the analysis, we performed additional analysis of the fire frequency including zero values. On the country scale, we finally included 6097 cadastres using presence/absence data and 3461 cadastres using the fire counts data. In the regional-scale analyses, we included 330 and 218 cadastres for presence/absence and frequency data, respectively.

When the correlation of two factors exceeded the arbitrary threshold of Spearman's $r_S = 0.7$, we only retained the better interpretable factor for further analyses. We thus excluded altitude from the country scale analyses, which was critically correlated with temperature and *Picea abies* abundance, and temperature from both country scale and regional analyses, which was critically correlated with precipitation. The presence/absence data were analysed using generalized linear models (GLM) with binomial distribution of errors; for counts data, we used GLM with a quasi-Poisson distribution to account for overdispersion. In the analyses, we incorporated all factors, including the size of forested area [ha] as a covariable to be filtered out. For all four analyses, we subsequently produced a minimal adequate model containing all significant factors and we computed pseudo-R^2 of particular models to provide the proportion of explained variance of the model, using the most common approach: (null deviance—residual deviance)/null deviance (Zuur et al. 2009). We subsequently plotted residuals of the model into the map of cadasters to check our results for spatial autocorrelation.

To compare the relative importance of significant factors (percentage of explained variance), we used the hierarchical partitioning method using the R package hier.part (Mac Nally and Walsh 2004). For this comparison, we used a maximum of nine significant factors with the highest z/t values from each analysis due to the inaccuracy of the hier.part method with > 9 factors included (Olea et al. 2010). The significance of these factors was tested using the randomization test method (rand.test) of the hier.part package.

Within the selected NW region, we examined the relationship of the frequency of CG− and CG+ lightnings with altitude and precipitation, using linear regression. We additionally visualized the total number of fires in cadastres classified by the dominant tree species (dominating and with abundance ≥ 30%), related to the area of forest dominated by the given tree species (number of fires/100 km^2 of forest). Similarly, we visualized the frequency of fires across altitudinal zones using average altitude values for each cadastre: planar (146–210 m a.s.l.), colline (210–500 m a.s.l.), submontane (500–800 m a.s.l.), montane (800–1145 m a.s.l.). On the regional scale, we similarly visualized the effect of geology and geomorphology on fire frequency. We distinguished four landscape categories: areas with prevailing granodiorite bedrock ("Granite"); landscapes with volcanic basalt hills ("Basalt"); sandstone rock towns with a characteristic rugged relief formed by cliffs, rock walls, pillars, canyons and narrow gorges ("Rock towns"); relatively flat areas with sandstone bedrock ("Sandstone"); and areas with prevailing loess or loess-like loam sediments ("Loess"). Geological areas were distinguished according to the geological map of the Czech Republic 1:50,000 (www.geology.cz), and sandstone "rock towns" were identified using the digital map of landscape typology of the Czech Republic (Löw and Novák 2008).

Results

Country scale

The most fire-prone were forests dominated by *Betula* spp. (110 fires/100 km^2 of forest of such composition), *Pinus sylvestris* (38 fires/100 km^2) and *Quercus petraea* (33 fires/100 km^2), and the least fire-prone were forests dominated by *Tilia* spp. (2 fires/100 km^2), *Populus* spp. (11 fires/100 km^2) and non-native *Robinia pseudoacacia* (14 fires/100 km^2). In the most widespread forest type, dominated by *Picea abies,* fires occurred with an intermediate frequency similarly as in *Quercus robur* or *Fagus sylvatica*-dominated forests—23 fires/100 km^2 (Fig. 2a). As for the different altitudinal zones, the highest fire frequency was in forests of the colline and planar zones and decreased markedly towards higher altitudes (Fig. 2c).

The occurrence of forest fires in the Czech Republic in the period of 1992–2004 in the sense of the presence or absence of fire events depended more on environmental than on human factors. The incidence of wildfires increased with increasing abundance of *Picea abies* (explained variance 14.4%), *Pinus sylvestris* (10.4%), *Betula* spp. (0.3%) and *Fagus sylvatica*; and with increasing Ruggedness index (9.2%). Conversely, the incidence of wildfires decreased with the abundance of *Populus* spp. and with increasing precipitation (3.9%), which was strongly correlated with altitude and temperature ($r_S = 0.63$ and $r_S = -0.73$, respectively); the latter factors were excluded from the analysis (see Data analyses). Moreover, fire occurrence was influenced also by the soil texture, namely it decreased with increasing Available Water Capacity (7.8%). Somewhat weaker predictors of fire occurrence were human factors. Fire occurrence increased with population density (4.7%) and the density of accommodation facilities. Conversely, it decreased with the distance from the nearest large city (> 50.000 inhabitants) (1%).

The frequency of fires in cadastres, by contrast, was driven mostly by population density (34.7%), and the other human factors were significant as well. Fire frequency was significantly influenced also by environmental factors. It was positively influenced by the abundance of *Betula* spp. (4.6%), *Pinus sylvestris* (1.6%), *Fagus sylvatica* and *Larix decidua*, by the frequency of cloud-to-ground lightning strikes (4.2%), the Ruggedness index (3.8%) and negatively by the soil available water capacity (2.6%), precipitation (1.9%) and by the abundance of *Tilia* spp. (1.4%) and other mostly deciduous tree species (Table 2).

Fire-prone NW region

The narrower range of the environmental conditions of the selected region in comparison with the country scale harboured a lower diversity of forest types. The most fire-prone forests were those dominated by *Betula* spp. (238 fires/100 km^2) followed by *Pinus sylvestris* (68 fires/100 km^2) and *Picea abies* (56 fires/100 km^2). The least fire-prone were forests dominated by *Populus tremula* and *Quercus petraea* (no fires), *Fagus sylvatica* (8 fires/100 km^2) and non-native *Robinia pseudacacia* (10 fires/100 km^2). *Q. robur* forests exhibited intermediate proneness to fires (32 fires/100 km^2) (Fig. 2b). The highest fire frequency occurred in areas with sandstone bedrock, especially in sandstone "rock towns", where the frequency of wildfires was almost double that of less rugged sandstone areas. Less fire-prone forests were in areas with granodiorite bedrock, in landscapes with volcanic basalt hills and on loess sediments (Fig. 2d).

In the selected NW region, we found that pattern of wildfire occurrence depends also on lightning strikes occurrence. The frequency of wildfires was significantly driven by the frequency of positive (CG+) lightnings, while negative (CG−) lightnings did not exhibit any significant effect. However, the significance of the CG+ lightning was not proved by the hierarchical partitioning method, neither by additional glm model including zero values (Online Resource 1), thus its effect might not be principal. CG+ lightnings, which were about three times less frequent than CG− (Table 1), occurred in the region more frequently at lower altitudes (p value = < 0.001, $R^2 = 0.113$) and in places with low precipitation (p value = < 0.001, $R^2 = 0.33$). CG− lightnings, by contrast, were slightly more frequent at higher altitudes (p value = 0.013, $R^2 = 0.014$), but without a significant relationship with precipitation (Fig. 3).

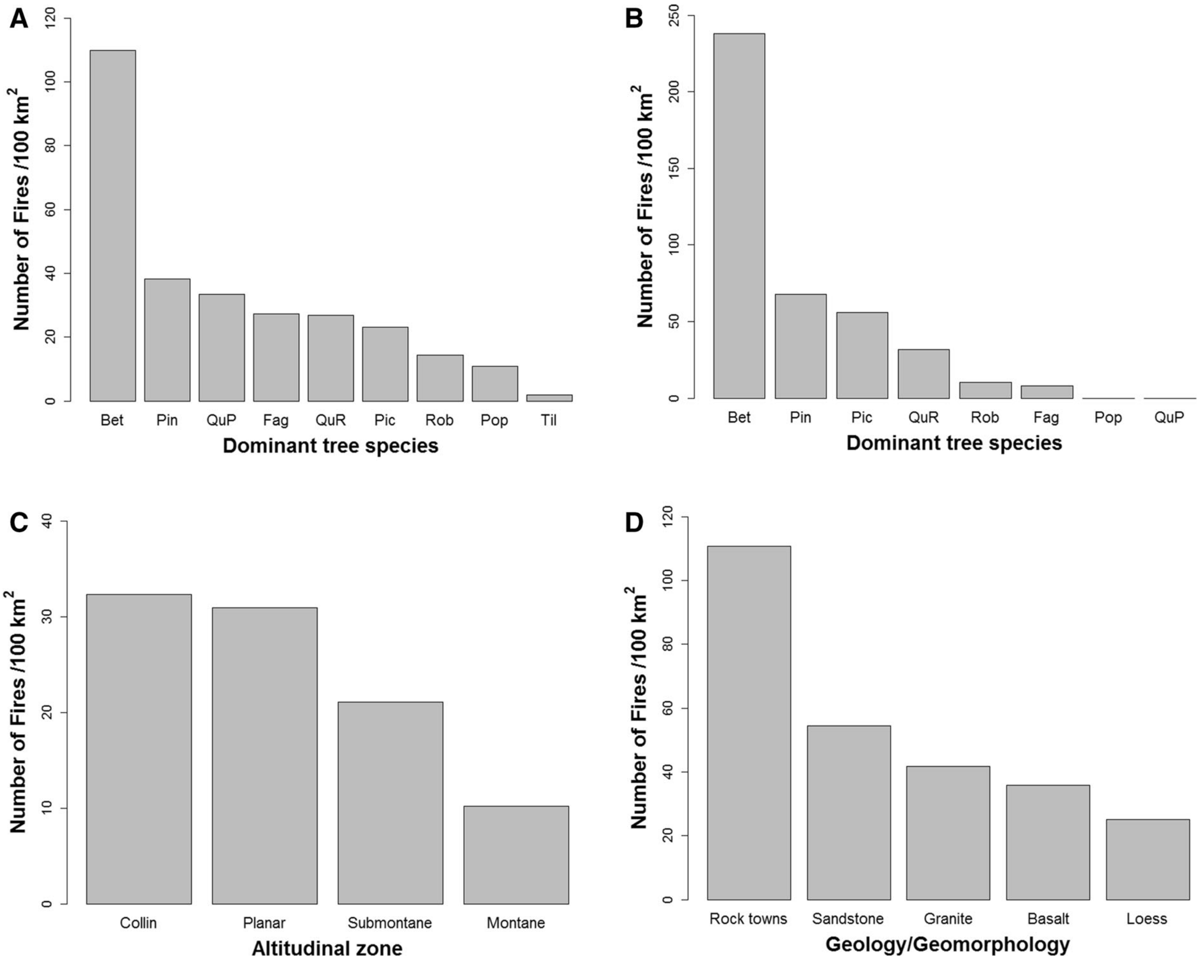

Fig. 2 Wildfire counts per 100 km^2 of forested area of given characteristics. Wildfire frequency by tree dominant on the country scale (**a**) and the regional scale (**b**); Wildfire frequency on the country scale by altitudinal zone (**c**) and according to geology/geomorphology on the regional scale (**d**). The prevalent sandstone bedrock is divided into two categories: sandstone "rock towns" and other sandstone areas

Overall, the results of the analyses showed a similar pattern to the broader country scale, but the effect of environmental factors on the occurrence of wildfires in the selected region was more pronounced. Fire occurrence was driven only by forest composition, with positive effect of the abundance of coniferous species such as *Pinus sylvestris* (26.1%) and *Picea abies* (12.3%) and negative effect of deciduous *Populus tremula* (3.1%). Human factors were not significant.

Similarly to the country scale, the frequency of wildfires was driven the most by human factors like population density (10.1%) and the density of accommodation facilities (9.6%) than by environmental factors. The strongest environmental factor increasing wildfire frequency was *P. sylvestris* abundance (7.4%). The other significant factor was the Ruggedness index and the abundance of *Betula* spp. and *Quercus robur* (Table 2).

The additional analysis of fire frequency with included zero values provided comparable results to the original analysis and thus largely confirmed its results (Online Resource 1).

Discussion

Our results show that the spatial pattern of wildfire occurrence in the cultural temperate Central European landscape (represented by our model country, the

Table 2 Factors significantly influencing the spatial distribution of wildfires, at least at one scale level and explaining either fire occurence (pres/abs) or fire frequency (Counts per cadaster over 1992–2004)

Factors	Country scale				Regional scale			
	Pres/abs		Frequency		Pres/Abs		Frequency	
	z-val.	I (%)	t-val.	I (%)	z-val.	I (%)	t-val.	I (%)
Human								
Population (per km^2)	8.87	4.70*	27.01	34.69*	NS		6.17	10.11*
Accomodation (per km^2)	2.65		5.22		NS		3.54	9.56
Distance from city	− 5.19	0.96*	− 4.4		NS		2.86	0.98
Climatic								
Altitude	NA		NA		NS		NS	
Precipitation	− 7.47	3.85*	− 8.16	1.86*	NA		NA	
Lightnings (per km^2)	NS		4.76	4.20*	NA		NA	
CG+ lightnings (per km^2)	NA		NA		NS		2.37	0.4
Topographic and soil								
Ruggednes index	5.91	9.18*	7.47	3.76*	NS		4.33	4.26
Available water capacity	− 6.88	7.80*	− 5.54	2.62*	NS		NS	
Forest composition (%)								
Abies alba	NS		− 2.33		NS		2.1	
Betula spp.	3.96	0.33*	8.59	4.63*	NS		3.11	2.33
Carpinus betulus	NS		− 4.42		NS		− 2.6	
Fagus sylvatica	3.2		3.85		NS		NS	
Larix decidua	NS		4.23		NS		2.69	
Picea abies	14.87	14.44*	NS		3.77	12.25*	2.04	
Pinus sylvestris	13.87	10.42*	6.84	1.60*	5.33	26.07*	3.51	7.40*
Populus spp.	− 2.08		− 3.79		NS		NS	
Populus tremula	NS		− 5.63		− 2.4	3.11*	NS	
Quercus robur	NS		NS		NS		3.24	1.18
Tilia spp.	NS		− 6.02	1.43*	NS		NS	
Forested area (ha)	20.9	48.32*	40.52	45.21*	6.2	58.57*	10.82	63.78*
Pseudo-R^2	0.24		0.55		0.36		0.59	

Given are z/t values from GLM analyses of presence/absence and fire frequency data, and the proportion of explained variance [%] of max. 9 selected factors from hierarchical partitioning analyses (I column) and pseudo-R^2 of the models. Plus and minus signs of z and t values indicate a positive or negative effect on wildfire occurrence

NS Not significant, *NA* not available

* Indicate the factors significant in the randomization test

Czech Republic) is driven by a combination of human and environmental biotic and abiotic factors. We found that environmental factors mainly influence the location of wildfires whereas human factors mostly determine their frequency. Similar results comparing the occurrence and frequency of forest fires have been reported by Martínez-Fernández et al. (2013) from Spain. This suggests that the frequency of wildfires in environmentally conditioned fire-prone areas depends mainly on the availability of ignition triggers, which in the conditions of Central Europe are mostly of human origin (Ganteaume et al. 2013; Kula and Jankovská 2013). However, wildfire frequency is also driven naturally, even though to a lesser extent, by the frequency of cloud-to-ground lightning strikes.

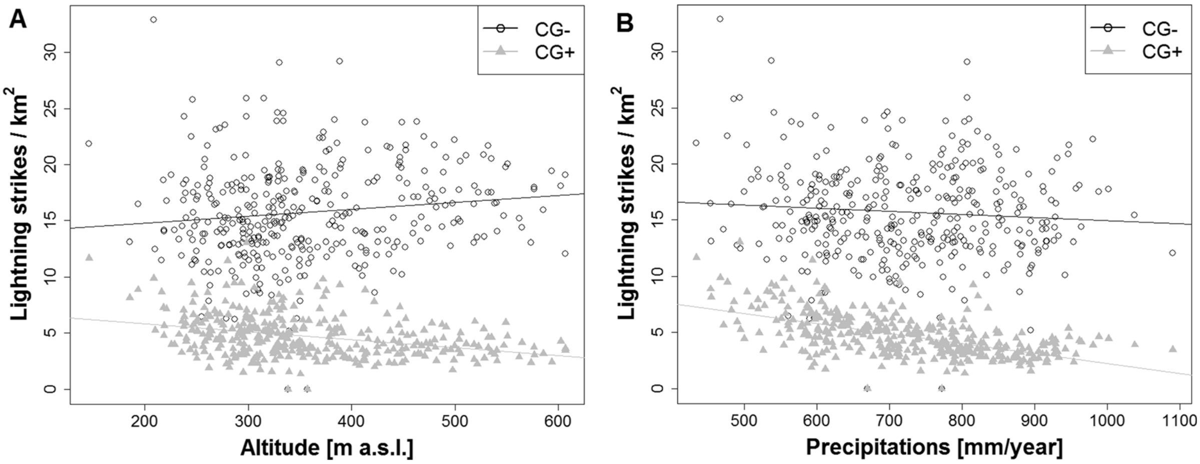

Fig. 3 Frequency of cloud-to-ground lightning strikes of negative (CG−) and positive (CG+) polarity in the NW region, related to altitude (**a**) and precipitation (**b**). **a** CG− : $R^2 = 0.014$; p value = 0.013; CG+ : $R^2 = 0.113$, p value = < 0.001; **b** CG− : $R^2 = 0.004$, p value = 0.131; CG+ : $R^2 = 0.33$, p value = < 0.001

Biotic drivers of wildfire incidence

Our findings regarding the susceptibility of coniferous forests to fire, especially those dominated by *Pinus sylvestris*, is in agreement with other ecological studies claiming *P. sylvestris* as a fire-adapted and simultaneously fire-attracting species due its easily flammable, resiny litter and sparse canopy that enables the ground layer to dry out (Agee 1998; Angelstam 1998; Gromtsev 2002; Lecomte et al. 2005). *Betula* spp. also markedly indicated the higher probability of forest fires. This might be due to several reasons. *Betula* is a pioneer tree species that typically colonizes burnt areas (Huotari et al. 2008; Reyes and Casal 2012), so an explanation might be the abundance of birch is actually a consequence of previous fire occurrence. However, wildfires are usually not as extensive to explain the prevalence of birch in the region, and, moreover, almost all burnt areas have been reforested by tree species that are economically more valuable. *Betula* spp. often accompanies *Pinus sylvestris* in nutrient-poor conditions and possesses highly flammable bark that remains on the forest ground after decaying of old trunks and branches. In the case of a fire, this could increase the likelihood of its spreading. Wildfires, to some extent, also occurred in forests dominated by deciduous species like *Fagus sylvatica* or *Quercus* spp. This result supports the theory that also temperate oak and beech forests are associated with the occurrence of wildfires (Abrams 1992; Brose et al. 2013; Ascoli et al. 2015). The least fire-prone were forests dominated by *Populus* spp. and *Tilia* spp. (Fig. 2a, b), which grow in relatively moist conditions of flood plains and shady scree slopes, respectively (Chytrý 2012).

Abiotic drivers of wildfire incidence

The occurrence of wildfires depended on abiotic environmental factors such as the relief, climate and altitude. Although we did not use altitude as a predictor in the country scale analysis, since it highly correlated with precipitation and temperature, its effect was clearly evident in our comparison of fire frequency, which was markedly lower at higher altitudes (Fig. 2c). This result is in accordance with numerous other studies which have found a negative effect of altitude and precipitation on wildfire incidence (e.g. Engelmark 1993; Pew and Larsen 2001; Futao et al. 2016). However, in drier climatic conditions, the effect of these factors can be the opposite, as fuel availability increases with increasing precipitation values (Martínez-Fernández et al. 2013).

In our study, the occurrence and frequency of wildfires increased with increasing ruggedness of the relief, which is consistent with the results of similar studies (Kalabokidis et al. 2002; Ganteaume et al. 2013). In rugged landscapes there are more fire-prone sites than on flat land, such as south-oriented slopes and convex rock tops with shallow soils drying out more easily (Angelstam 1998; Mouillot et al. 2003).

Our previous study (Adámek et al. 2015) has found that the most fire-prone sites in rugged sandstone landscape of “rock towns” are steep SW-facing slopes and elevated rock plateaus. Additionally, such protruding, convex sites attract lightning strikes, the main natural ignition trigger (Engelmark 1993; Vogt 2011).

The frequency of cloud-to-ground lightning strikes turned out to have a significant positive effect on wildfire frequency also in more populated landscapes, although they provably cause only about 1.4% of forest fires in the Czech Republic (Kula and Jankovská 2013). Using more precise data on the frequency of lightning strikes, we found wildfire frequency to be driven, albeit marginally, by positive (CG+) lightnings. CG+ lightnings, in contrast to negative (CG−) lightnings, occurred more frequently in the areas with lower altitudes and precipitation (Fig. 3). CG+ lightnings are claimed to be a stronger ignition trigger than CG− lightnings, even though they are less frequent. This has been explained by their larger magnitude, temperature, higher probability of a long continuing current (Latham and Williams 2001; Müller and Vacik 2017) and by the fact that they more often accompany convective or so-called “good weather” thunderstorms, which last a short time and bring little rainfall. This is in accordance with our results where CG+ lightnings are associated with lower precipitations. CG− lightnings, by contrast, occur more frequently with frontal thunderstorms accompanied by higher rainfall (Larjavaara et al. 2005). This result indicates a possible interconnection between the occurrence of a fire-adapted lowland pine taiga in the region and the frequency of CG+ lightning strikes as a natural ignition trigger.

Wildfire incidence also depended on the physical characteristics of soil, namely the available water capacity of (AWC) which influenced wildfire occurrence negatively. AWC largely depends on the soil texture with the lowest values on sandy and gravel soils (Saxton and Rawls 2006; Ballabio et al. 2016). This result thus probably reflects the fire-prone conditions of drainable soils. A positive effect of coarse soils on the incidence of wildfires was also found by Cardille and Ventura (2001).

The frequency of wildfires in the NW region strikingly differed depending on geological conditions. It was higher on sandstone bedrock, where the pine-dominated lowland taiga occurs (Chytrý 2012; Novák et al. 2012), and lower on more fertile basalt and loess bedrock with a higher cover of broadleaved forests. However, the most fire-prone areas of the region were sandstone rock towns (Fig. 2d), which is related with the high abundance of *Pinus sylvestris*, touristic attractiveness and ruggedness of the landscape.

The pattern of this pine region resembles, for example, the Pitch Pine (*Pinus rigida*) barrens of New Jersey and adjacent regions (North Eastern USA) which occur on acidic and drainable soils within humid temperate climate and are highly fire-dependent (Boerner 1981; Landis et al. 2005). The occurrence of fire-prone pinewood regions in temperate climate, related with drainable and nutrient-poor acidic soils, thus applies globally.

Human drivers of wildfire incidence

In our study, population density together with distance from the nearest large city facilities and density of accommodation, as a proxy for tourism intensity, turned out to be important drivers of wildfire occurrence similarly as in other studies explaining a large proportion of wildfire ignitions by the human factors (Cardille and Ventura 2001; Pew and Larsen 2001; Zumbrunnen et al. 2012; Ganteaume et al. 2013; Martínez-Fernández et al. 2013; Futao et al. 2016). However, in our results these factors influenced mainly the fire frequency whereas their effect on fire occurrence was less pronounced. These results thus contradict the idea that human factors can more or less obscure the effects of environmental factors such as the climate or topography (Flatley et al. 2011; Zumbrunnen et al. 2012). In our study, by contrast, environmental factors did have an apparent effect on fire occurrence despite relatively high population density of the Czech Republic.

Conclusions

The pattern of wildfire distribution in the Czech Republic follows similar rules as in other regions of the world, even those where wildfire is considered part of the natural dynamics of local ecosystems. In the densely populated cultural landscape of Central Europe, the distribution of wildfires, not surprisingly, depends strongly on human factors. However, people act mainly as a ubiquitous ignition trigger whereas natural environmental factors determine the susceptibility of habitats to being ignited. The main natural conditions that increase the likelihood of wildfires are: a rugged relief at lower altitudes, drainable soils with a prevalence of coniferous forests, especially of *Pinus sylvestris*, and mixed with *Betula* spp. If sufficient ignition triggers are available, be it of human or natural origin, such conditions can in the long term lead to the development of fire-adapted ecosystems, even in relatively humid climate. Natural conditions, including occurrence of positive cloud-to-ground lightning strikes as a potential natural ignition trigger determine the susceptibility of habitats in the sandstone landscapes of NW Bohemia to fire. This region is a good example of a naturally conditioned fire-prone area within temperate Central Europe where fire-adapted vegetation is shaped also by lightning-ignited wildfires.

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