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Vegetation fires along the Czech rail network

Vojtěch Nezval^{*} , Richard Andrášik and Michal Bíl

Abstract

Background: In the past, fires around railways were often associated with steam locomotives. Although steam locomotives have disappeared from everyday rail traffic, fires still occur. A vegetation fire near Bzenec (Czech Republic) on 21 June 2018 affected, for example, 124,110 m² of forest and grassland. The investigation revealed that the fire was caused by a spark from a passing train. In this study, we analyzed vegetation fires that occurred near Czech railway lines between 2011 and 2019 to investigate their temporal pattern and relation to weather conditions or to identify the most hazardous locations.

Results: Fires were concentrated mainly between March and August in the afternoon. They are also more likely to occur during periods of high air temperature, low rainfall, low relative air humidity, and low wind speed. Using the KDE+ method, we identified 186 hotspots, which contained 510 vegetation fires and represented only 0.3% of the length of the entire Czech rail network. Spatial analysis revealed that there are more than 4 times higher odds that a vegetation fire occurs near an electrified railway line than near a non-electrified line or that additional 10 freight trains per 24 h increases the odds by 5%.

Conclusions: As the results show, vegetation fires near railway lines are still relatively common phenomenon, mainly due to favorable weather conditions. Grassy areas with dry or dead vegetation are particularly at risk. These areas can be ignited, for example, by sparks from the brakes of railway vehicles. Due to global warming, vegetation fires can be expected to occur more frequently in the future. The identified hotspots can thus be used to reduce the risk of fires, for example by managing the surrounding vegetation.

Keywords: Wildfire, Lineside fire, Trackside fire, Vegetation, Weather, Hotspot, Railway

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Resumen

Antecedentes: En el pasado, los incendios alrededor de las vías férreas eran frecuentemente asociados con locomotoras a vapor. Aunque estas locomotoras han desaparecido del tráfico ferroviario, los incendios continúan ocurriendo. Un incendio de vegetación ocurrido cerca de Bzenec (República Checa) el 21 de junio de 2018, afectó, por ejemplo, 124.110 m² (unas 12 ha) de bosques y pastizales. La investigación reveló que el incendio fue causado por una chispa de un tren que pasaba. En este estudio analizamos los fuegos de vegetación que ocurrieron cerca de las líneas del ferrocarril de la república Checa entre 2011 y 2019 para investigar su patrón temporal, la relación con las condiciones del tiempo, e identificar las ubicaciones más peligrosas.

Resultados: Los incendios estuvieron concentrados principalmente entre marzo y agosto, y en horas de la tarde. Estos fuegos ocurrieron más frecuentemente durante períodos con altas temperaturas, bajas precipitaciones, baja humedad relativa del aire y baja velocidad del viento. Usando el método KDE+, identificamos 186 puntos calientes, que contuvieron 510 fuegos de vegetación y representaron solo el 0,3% de la longitud del total del sistema checo de ferrocarriles. El análisis espacial reveló que hay cuatro veces más probabilidades de que un fuego de vegetación ocurra cerca de un ferrocarril electrificado que en otra línea no electrificada, o que un adicional de diez trenes de carga en 24 h incremente esa probabilidad en un 5%.

Conclusiones: Como muestran los resultados, los fuegos de vegetación aledaños a las vías del tren son todavía un fenómeno común, debido fundamentalmente a condiciones meteorológicas favorables. Las áreas de pastizales con vegetación seca o muerta son particularmente riesgosas. Estas áreas pueden ser prendidas fuego, por ejemplo, por chispas de los frenos de los vagones ferroviarios. Debido al cambio climático global, se espera que estos fuegos de vegetación ocurran más frecuentemente en el futuro. La identificación de los puntos calientes puede ser entonces usada para reducir el riesgo de incendios, por ejemplo manejando la vegetación adyacente.

Background

Since the introduction of Stephenson's Rocket in 1829, rail transport has become one of the most important modes of transport in the world (Rodrigue et al. 2017). In the early days of rail operations, steam locomotives posed an increased risk of fire caused by sparks or embers from the fire box (e.g., Leavitt 1928; MacMillan and Gutches 1910). As a result, the vegetation along railways was carefully maintained to eliminate fire hazard (Gellatley et al. 1995). This effort has been reduced, however, with the massive expansion of diesel and electric locomotives, which have become a dominant mode of transportation in many countries since the 1970s (Grunstra and Martell 2014). Some places were subsequently overgrown with vegetation, which created conditions for the easier spread of vegetation fires or tree falls on rail infrastructures (e.g., Bíl et al. 2017; Network Rail 2020). Fires in relation to railways have not attracted much research interest in recent years, as the main source of risk (steam locomotives) has disappeared from day-to-day rail operations. Vegetation fires along railway lines still, however, occur today (Fig. 1), especially during periods of warm and dry weather. A vegetation fire near Bzenec (Czech Republic) on 21 June 2018 affected, for example, 124,110 m² of forest and grassland and caused rail traffic to be shut down for 8 h. The investigation subsequently revealed that the fire was caused by a spark from a passing train (HZS JMK 2018).

Over the following years, an increase in average air temperature due to global warming can be expected in some regions, including Central Europe (IPCC 2019). Consequently, drought, heat waves, or vegetation fires may occur more frequently in this area (Možný et al. 2020; Trnka et al. 2015a, 2016). In the railway sector, these phenomena can cause buckling of railway tracks, sagging of overhead power lines, failure of rail equipment, or fires (Baker et al. 2010; Dobney et al. 2009, 2010; Ferranti et al. 2016; Nguyen et al. 2012). Fires can be ignited in many ways, including both natural (lightning strikes) and human (sparks from rail vehicles, discarded cigarettes, arson fires) activity. Smoke reduces visibility, a fire can damage infrastructure, disrupt traffic, or endanger human health (e.g., Finlay et al. 2012; Moeltner et al. 2013).

The aim of this study is to investigate vegetation fires that occurred near railway lines in the Czech Republic. Previous studies dealing with vegetation fires in this area (e.g., Adámek et al. 2015, 2018; Jurečka et al. 2019; Kula and Jankovská 2013) did not focus directly on rail transport. More specifically, we were interested in answering the following research questions: (1) How frequent are vegetation fires at present along the Czech rail network? (2) Where and when do they occur most often? (3) How do weather conditions affect the occurrence of fires? (4) Are there other non-natural factors that contribute to fires?

Methods

Study area

The Czech Republic is a landlocked country in Central Europe with a hilly landscape (Fig. 2) and a humid continental climate (Peel et al. 2007), which is characterized by large temperature differences between winter and summer. Based on 1991–2020 meteorological observations, the average air temperature was 8.3 °C (CHMI 2022a) and annual precipitation reached on average 684 mm (CHMI 2022b). The coldest month was January (−1.4 °C), followed by February (−0.4 °C) and December (−0.4 °C). In contrast, the warmest months were July and August (>17 °C). In the summer half of the year (April–September), heat waves (Kyselý 2010; Urban et al. 2020) or drought (Trnka et al. 2016; Zahradníček et al. 2014) occurs in the Czech Republic. The heat wave in South Moravia in 1994 was particularly intense, lasting continuously for more than 30 days with air temperatures around 30 °C (Kyselý 2003). The highest air temperature (40.4 °C) was measured on 20 August 2012 near the capital city of Prague (CHMI 2022c).

Rail transport, together with road transport, forms the backbone of the Czech national transport system. Despite the fact that many unused, local, or damaged railway lines were offered for sale to private entities or rebuilt into cycle paths in recent years, the Czech rail network still ranks among the densest in the world (UIC 2019). The total length of operated railway lines is 9562 km, out of which 3231 km (33.8%) is electrified (Eurostat 2021). The main railway lines, called corridors, are completely electrified and are part of the TEN-T (European Commission 2018). Trains are allowed to run here at speeds of up to 160 km per hour.

Fire data

Data on vegetation fires along railway lines were provided by the fire brigade unit of the Czech Railway Infrastructure Administration (CRIA). A total of 2723 fires between 2011 and 2019 were identified in the CRIA database. Most records contained a brief description of the fire incident, where it occurred, the date and time the fire was detected and extinguished, the number of fire brigade units intervened at the incident site, the area of the fire, or the cause of the fire. Using the hectometer information listed in the database (i.e., points along railway lines 100 m from each other), it was possible to locate 1862 vegetation fires (68.4%) with an average accuracy of 9 m. Records that could not be precisely located ($n = 861$) were not used in spatial analyses.

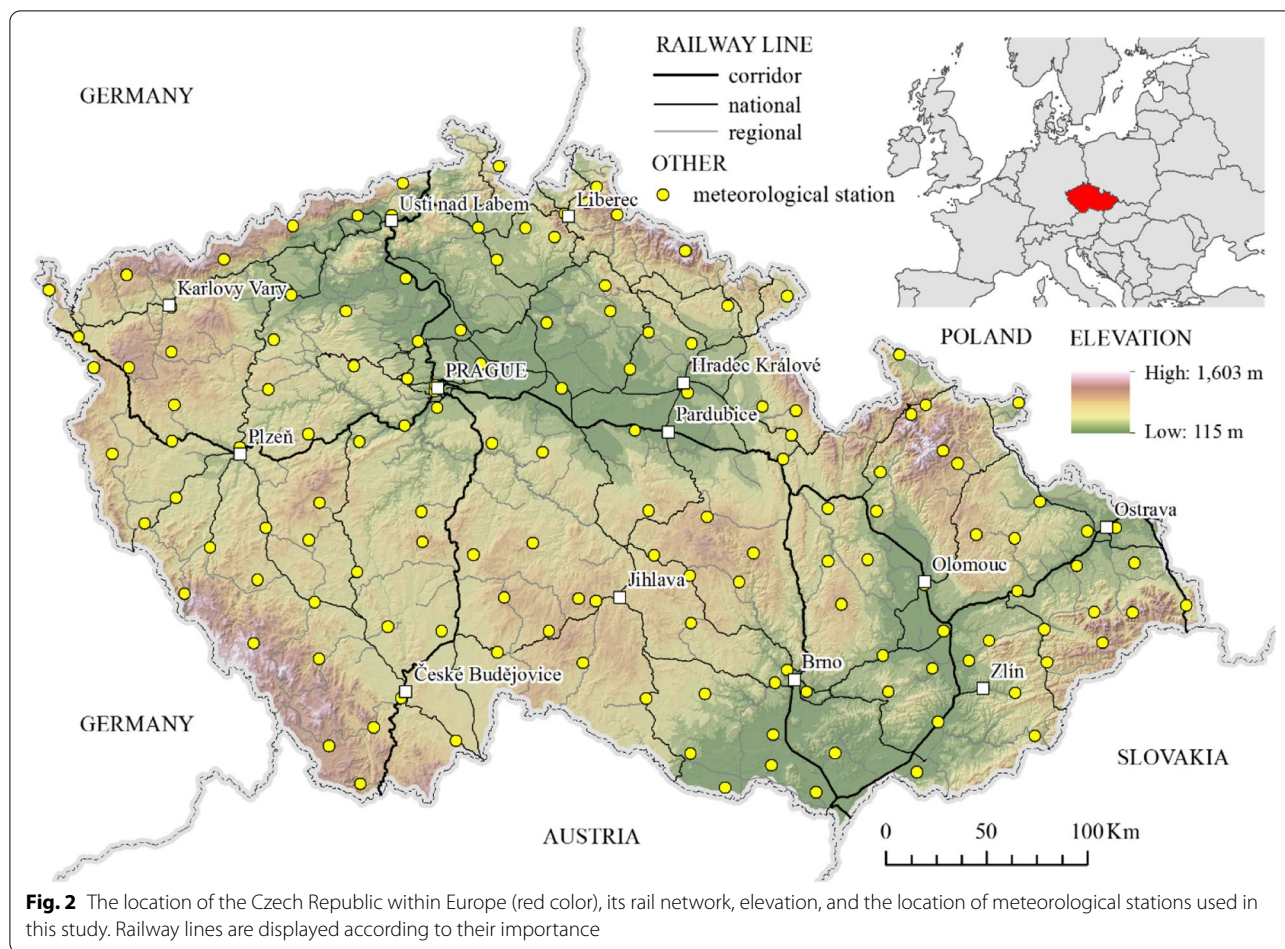
In addition to fire data, we also used data on rail network, rail traffic intensity, and delimitation of railway stations from the CRIA; rail geometry data from the ROCA toolbox (Bíl et al. 2018; <https://roca.cdvinfo.cz>); data on urbanized areas from the Data200 database (ČÚZK 2021); forest and road data from the OpenStreetMap project (www.openstreetmap.org); elevation data from the SRTM digital elevation model (USGS 2018); population density from the ArcČR 500 database (ARCDATA PRAHA, ZÚ, ČSÚ 2016); and meteorological data from the Czech Hydrometeorological Institute (CHMI 2020a; <http://portal.chmi.cz>).

Time pattern of vegetation fires

We first studied the occurrence of vegetation fires with respect to the year and daytime. We considered a grid on which the x-axis represented the months of the year



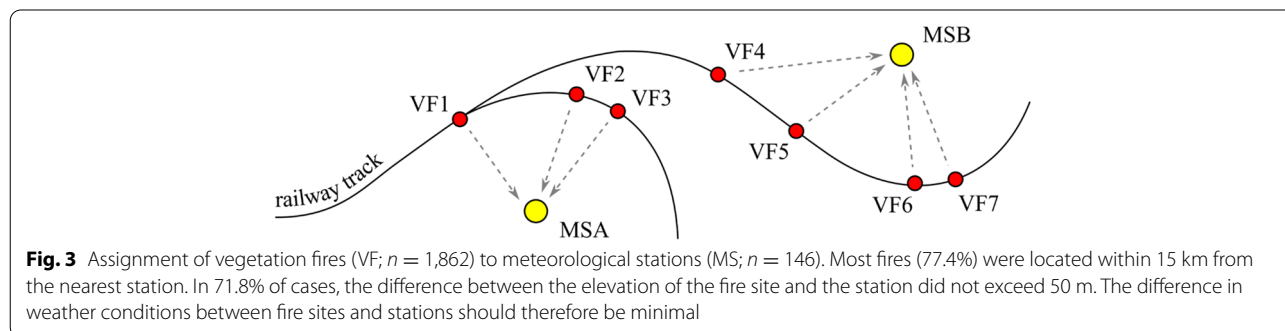
Fig. 1 Vegetation fire near Bzenec on 21 June 2018 (left) and vegetation fire near Ostrov on 7 April 2013 (right) on images of the fire brigade unit (HZS JMK 2018; HZS KVK 2013). Both fires were caused by a spark from a passing train



and the y-axis the time of day. The grid thus contained 12×24 cells, representing each combination of month and hour. Subsequently, we determined the number of records in each cell of the grid and applied the exact binomial test (Hollander et al. 2014) to evaluate the null hypothesis of vegetation fires being distributed according to the uniform probability distribution. Grid cells in which the number of fires was greater than the calculated threshold represent the concentration of the phenomenon over time.

Occurrence of vegetation fires in relation to weather conditions

Warm and dry weather provide a favorable environment for fires. We therefore focused on the frequency of vegetation fires in relation to meteorological variables such as air temperature, precipitation, relative air humidity, and wind speed. Individual fires were assigned to the nearest meteorological station from which the specific values were taken (see Fig. 3). As exposure, randomly selected data from the meteorological stations spanning the entire



study area (see Fig. 2) were used. To avoid short-term weather extremes and capture weather conditions more reliably (heat wave, drought periods), we used a 10-day average (i.e., the average value of a given meteorological variable on the day on which the fire occurred and the averages from the previous 9 days).

We applied empirical cumulative distribution functions, along with the Kolmogorov-Smirnov (KS) test (e.g., Dodge 2008), to compare previously selected meteorological variables at a given time and place of vegetation fires with exposure. Subsequently, we built a logistic regression model (Dobson 1990) to evaluate the influence of these variables on the occurrence of fires. The dependent variable was binary: vegetation fire occurred/did not occur in the vicinity of 9 days, as the 10-day averages were used. Finally, the results obtained from this analysis were interpreted using the odds ratio (OR; Simon 2001).

Identification of vegetation fire hotspots

We used the KDE+ software (Bíl et al. 2016; www.kdepl.us.cz) to identify places on the Czech rail network where vegetation fires frequently occurred. This tool is based on the KDE+ method (Bíl et al. 2013) and allows users to identify statistically significant concentration of points along lines, i.e., the most hazardous locations (hotspots) along transportation networks. Hotspots can be further ranked by several parameters, such as the number of incidents (individual fires) in the hotspot, length, cluster strength and density, or collective risk (for more information see Bíl et al. 2013; Favilli et al. 2018). *Cluster strength* (CS) indicates the relative importance of clusters on a scale between 0 and 1. It is the degree of violation of the null hypothesis (H_0 : Vegetation fires follow a uniform distribution along the rail tracks.). The higher the value, the more important the cluster is. *Density* (DEN) represents the average number of incidents per kilometer per year. In this study, we used *collective risk* (CR), which

combines cluster strength and density of incidents in the cluster as an indicator of the importance of a hotspot. To identify the most hazardous places, we selected only hotspots that contain more than three fire incidents and ranked them according to the CR.

Factors contributing to vegetation fires

To better describe fire locations, we selected several explanatory variables (see Table 1) and tested their influence on the occurrence of a fire. The variables were selected both on the basis of available data and on the basis of previous research (e.g., Cardille et al. 2001; Martínez et al. 2009). Seven of these variables were continuous and three categorical. Subsequently, we randomly selected the same number of control places as the number of localized vegetation fires ($n = 1,862$). The control locations were selected not to be closer than 200 m from the fire locations. Since the dependent variable is binary (fire occurrence yes/no), the logistic regression, a particular generalized linear model (Dobson 1990), was applied to find a relationship between the dependent variable and the explanatory variables.

Before building the logistic regression model, we inspected the data structure of continuous variables using the Pearson and Spearman correlation matrices (Myers et al. 2003), while checking for a linear and monotone relationship, respectively. The data structure of categorical variables was examined through the Cramer V association matrix (Cramér 1946). We also calculated variance inflation factors (VIFs) to check for multicollinearity in the data (Fox and Monette 1992) (Appendix). The logistic regression model was built using a stepwise procedure with respect to the Akaike information criterion (AIC; Akaike 1973). The estimated parameters of the model were interpreted in terms of odds ratio (OR; Simon 2001), which we calculated for each explanatory variable in the final model along with its 95% confidence interval (95% CI). All calculations were performed in R software (R Core Team 2019).

Table 1 Explanatory variables used in the logistic regression model

Variable	Metric	Data source
Rail traffic intensity—total	Trains per day	CRIA
Rail traffic intensity—freight	Trains per day	CRIA
Railway line electrification	Yes, no	CRIA
Railway line geometry	Curve, tangent	ROCA
Railway station district	Inside, outside	CRIA
Distance to the forest	m	OSM
Distance to the nearest road	m	OSM
Distance to the build-up area	m	Data200
Population density	No. of inhabitants per km ²	ArcCR 500
Elevation	m	SRTM DEM

Results

Size, causes, and time pattern of vegetation fires

Based on the input data, 85.2% of vegetation fires occurred on grassy areas. Orthophoto images revealed that these sites also include shrubs or individual trees. The fire area did not exceed 500 m² in 69.9% of cases. The cause of the fire was not known for 86.7% of the records, while the rest of the incidents were related to sparks from trains, discarded cigarettes, or an electrical fault. The frequency of vegetation fires varied from year to year. Most fires were recorded in 2018 ($n = 442$), which was the warmest year in the monitored period with an average air temperature of 9.6 °C (1.3 °C above

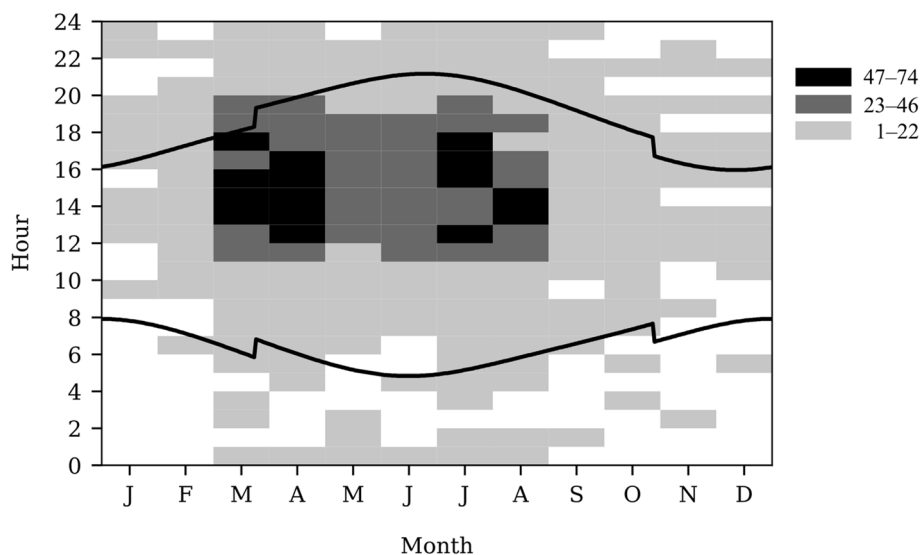


Fig. 4 Time distribution pattern of vegetation fires along railway lines in the Czech Republic between 2011 and 2019 ($n = 2723$). The dark gray and black cells represent the time when fires concentrated. The white cells contained no fires. The black lines represent the times of sunrise and sunset

the 1991–2020 period). In contrast, the lowest number of fires was recorded in 2016 ($n = 157$). The time distribution of vegetation fires by month and time of day showed that they were concentrated mainly (74.8% of the incidents) between March and August from 11 am to 8 pm (see Fig. 4).

Weather conditions at the time of vegetation fires

We found, by comparing the 10-day averages of selected meteorological variables at the time of vegetation fires with exposure (KS test), that the air temperature was significantly higher when a vegetation fire occurred, while precipitation and relative air humidity were significantly lower when a vegetation fire occurred (see Fig. 5 depicting empirical cumulative distribution functions). In terms of wind speed, the exposure contained more extreme values (both higher and lower) than in the case of vegetation fires.

Before building the regression model, we evaluated the relationship between the selected meteorological variables (i.e., air temperature, precipitation, relative air humidity, and wind speed) using the Spearman and Pearson correlation coefficient. Since the highest correlations are -0.34 (Spearman) and -0.46 (Pearson) between the air temperature and relative air humidity, all variables can be used as explanatory variables in the model. The parameters of the resulting model can be interpreted in terms of the odds ratio (see Table 2). We found, for example, that $1\text{ }^{\circ}\text{C}$ increase in a 10-day average air temperature increases the odds of a vegetation fire by 26%. In contrast, a one-unit increase in 10 days for the other three

examined variables reduces the odds of a fire between 9 and 36%.

The most hazardous fire locations on the Czech rail network

We identified 186 hotspots containing a total of 510 vegetation fires (27.4%), which represent only 0.3% of the length of the entire Czech rail network (see Fig. 6). The number of fires in individual hotspots ranged from 2 to 8. More than half of the hotspots (62.4%) contained, however, only two incidents. They are concentrated on railway lines with higher freight traffic intensity (e.g., near Most, Nymburk, Česká Třebová railway stations) and in areas with a higher annual average air temperature based on the 1981–2010 meteorological observations. To obtain the most important ones, we selected only those hotspots with more than three vegetation fires and ranked them according to the collective risk value (Table 3).

Spatial analysis of vegetation fires

We first examined the relationship between the selected explanatory variables that are listed in Table 1. A very high positive correlation was observed between total and freight traffic intensity according to both Pearson (0.78) and Spearman (0.86) correlation coefficient. The VIFs for these two variables are also relatively high (3.13 and 3.11), which means that the interpretation of the resulting coefficients should be done with caution. The best logistic regression model according to AIC (4283.7) and build by the step procedure, constitutes all the selected explanatory variables excluding total rail

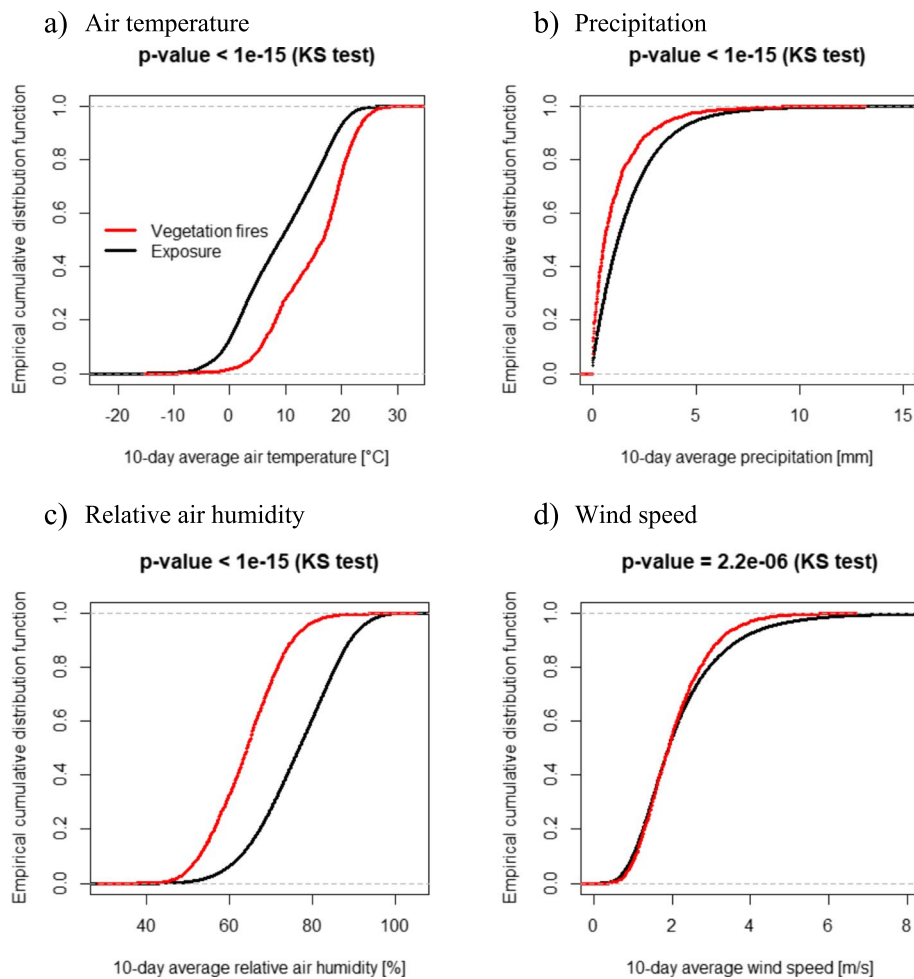


Fig. 5 Comparison of 10-day averages of air temperature (a), precipitation (b), relative air humidity (c), and wind speed (d) at the time of vegetation fires with exposure (KS test). The exposure (black curve) is represented by randomly selected data from meteorological stations

Table 2 Results of the logistic regression model for selected meteorological variables (10-day averages) interpreted in terms of odds ratio (OR)

Variable	Unit	OR	95% CI
Air temperature	°C	1.26	1.24–1.28
Relative air humidity	%	0.91	0.91–0.92
Wind speed	m/s	0.86	0.81–0.91
Precipitation	mm	0.64	0.60–0.67

traffic intensity, railway line geometry, and distance to the forest variables. The results of the final model are interpreted using the odds ratio (see Table 4). For categorical variables, each category is compared to a reference category. For continuous variables, odds ratio stands for a one-unit increase.

We found, for example, that in the vicinity of an electrified railway line there is more than 4 times higher odds that a vegetation fire occurs than near a non-electrified line. The odds are also higher for those parts of the rail network which are located within the perimeter of a railway station or are intensively used by freight traffic. With every 100 inhabitants per km², the odds of a vegetation fire increase by 4% and with every 100 m further from residential areas the odds decrease by 3%. The elevation variable is closely related to the climate, where every 100 m increase reduces the odds of a vegetation fire by 15%.

Discussion

Frequency of vegetation fires in the Czech Republic

We found that a total of 2723 vegetation fires occurred along the rail network in the Czech Republic between 2011 and 2019. It represents 303 fires per year on average. Although they did not reach the

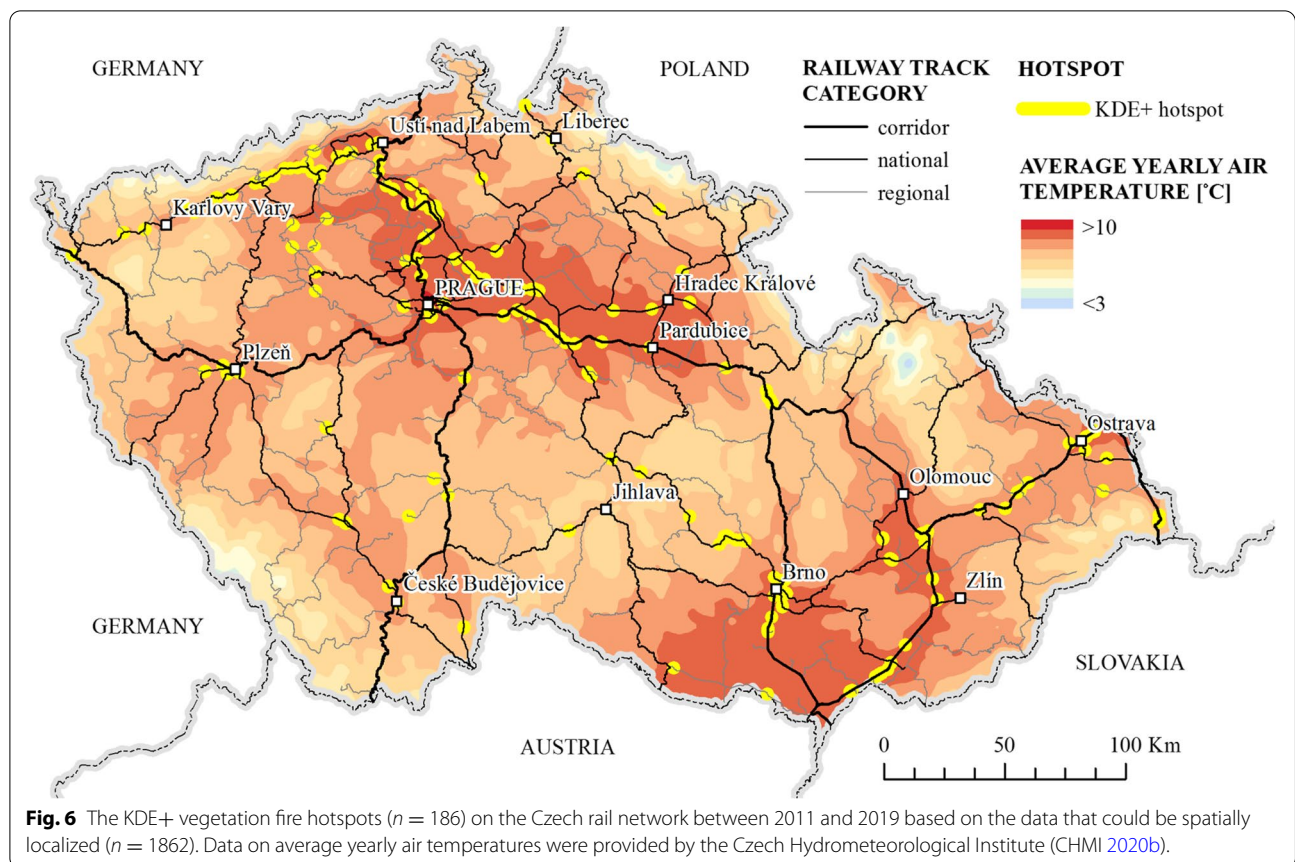


Table 3 10 most important vegetation fire hotspots with more than three incidents on the Czech rail network between 2011 and 2019 ranked by collective risk (CR)

Rank	Section ^a	Hotspot parameters				
		<i>n</i>	LEN [m]	CS ^b	DEN ^c	CR ^d
1	Nymburk hl.n. – Nymburk město	5	190	0.722	2.924	5.000
2	Otradovice – Stará Boleslav	6	222	0.643	3.003	4.699
3	Kolín – Hlízov	5	231	0.766	2.405	3.588
4	Louny předměstí – Louny město	6	239	0.553	2.789	3.485
5	Liběchov – Štětí	6	252	0.588	2.646	3.333
6	Obrnice – České zlatníky odbočka	4	182	0.682	2.442	3.296
7	Tišice – Neratovice	4	173	0.599	2.569	3.215
8	Veletice – Trnovany	4	196	0.750	2.268	3.124
9	České Zlatníky odbočka – Most	6	267	0.556	2.497	2.807
10	Nymburk hl.n. – Kamenné Zboží	4	162	0.459	2.743	2.797

^a The section contains a link with the spatial location on the map (middle point)

^b Cluster strength represents the individual importance of the hotspot on a scale 0–1

^c Density of vegetation fires in the hotspot (average number of fires per kilometer per year)

^d Measure of the collective importance of a hotspot (a positive number)

Table 4 The results of the logistic regression using odds ratio

Explanatory variable	Reference/unit	OR	95% CI
Track electrification = yes	Track electrification = no	4.15	3.45–4.98
Station district = inside	Station district = outside	1.35	1.10–1.67
Freight traffic intensity	10 * Number of trains / 24 h	1.05	1.02–1.09
Population density	100 * inhabitants / km ²	1.04	1.02–1.05
Distance to the built-up area	100 * m	0.97	0.95–0.99
Distance to the nearest road	100 * m	0.90	0.86–0.94
Elevation	100 * m	0.85	0.80–0.91

size of wildfires in California (www.fire.ca.gov/incidents) or Australia (NSW and DPIE 2020), they still caused property damage, affected rail operations, and endangered human health. The number of fires in the period under review varied from year to year. Možný et al. (2020) then found in the period 1971–2015 a statistically significant rising trend in the number of vegetation fires in the Czech Republic. Fires along railways were then concentrated between March and August in the afternoon. This is in line with the findings of Kula and Jankovská (2013), who focused on forest fires in the Czech Republic in the period 1992–2004. Fires in the spring months (March, April) can be partly attributed to the deliberate burning of vegetation (for more information, see Bryant 2008). This practice, although prohibited by legislation in the Czech Republic (Act No. 133/1985 Coll.; HZS 2020), is often seen.

Vegetation fires in relation to weather conditions

The expected increase in average air temperature in the Czech Republic due to global warming (IPCC 2019; Zahradníček et al. 2020) may result in more frequent and prolonged periods of drought (Trnka et al. 2015a, b, 2016), thus also forming suitable conditions for vegetation fires (Možný et al. 2020; Trnka et al. 2020). We found that an increase in the average air temperature by 1 °C in a 10-day period increases the odds of a vegetation fire by 26% and, in contrast, each mm increase of precipitation in a 10-day period decreases the odds by 36%. Weather conditions, together with the expected increase in rail traffic intensity (ERA 2020), may lead to more frequent fires in the future. Currently, there has been a greater effort to predict the risk of fires (e.g., Jurečka et al. 2019; <https://www.firerisk.cz>).

Vegetation fire hotspots on the Czech rail network

Hotspots were concentrated mainly in areas with a higher annual average air temperature (e.g., in the Polabská nížina) and accounted for only 0.3% of the length of the entire Czech rail network. They contained a total of 510 incidents, which represents 27.4% of all spatially localized data. We identified 18 hotspots with 5 or more fires. In these places, where vegetation fires occurred on a regular basis and which are together only 5.5 km long, careful vegetation management should be applied. Such measures not only reduce the risk of fire (Ma et al. 2020; Texas A&M 2014), but also help reduce tree falls on the rail infrastructure, which is also an issue in the Czech Republic (Bíl et al. 2017), or can help reduce the risk of train collisions with animals (Jaren et al. 1991; Seidel et al. 2018).

Spatial analysis of vegetation fires in the Czech Republic

Based on the results of logistic regression, it is more likely that a fire will occur in the vicinity of an electrified railway line compared to a non-electrified line. Fires can occur when vegetation comes in contact with power lines (e.g., Ma et al. 2020; Texas A&M 2014), as occurred, for example, on the Czech rail network on 18 June 2012 between Rybník and Lipno nad Vltavou railway stations. The spruce fell on the traction line and subsequently caused a forest fire. Due to the reduction of vegetation maintenance along railway lines in recent decades (see also Gellatley et al. 1995), the vegetation is much more likely to meet the electrified parts of the railways. In addition to vegetation contact, fires can also be ignited by a fallen power line, contact with animals, or as a result of various faults (Texas A&M 2014; Russell et al. 2012). Although the general incidence of electrically induced vegetation fires during the year is low (Plucinski 2014; Mitchell 2013), they appear to be much more common on days of increased fire risk (Collins et al. 2016; Miller et al. 2017; Mitchell 2013). The transition to electric operations then helped to reduce the risk of fires from steam locomotives, but the risk does not seem to disappear completely.

The occurrence of a fire near a railway infrastructure also depends on the freight traffic intensity. Freight trains are usually long with a large number of wagons carrying heavy loads. Several cases of vegetation fire have already been reported due to sparks from these freight trains (e.g., CT24 2018; Snowdon 2019). The results for the perimeter of the railway station, population density, and distance from built-up areas seem to be related to the human factor (e.g., negligence, intentionally set fires), as a high proportion of fires are usually caused by humans (e.g., Balch et al. 2017;

Ganteaume et al. 2013; Vilar et al. 2016). This is in line with Adámek et al. (2018), who found that the incidence of forest fires in the Czech Republic between 1992 and 2004 increased with population density and the density of accommodation facilities.

The distance to the forest was not relevant in the occurrence of vegetation fires, as most fires along the Czech rail network, according to the input data, occurred on grassy areas. The forest is closer than 50 m for 30% of the entire rail network length in the Czech Republic (Bíl et al. 2017). This was probably reflected in the number of forest fires caused directly by rail transport, when Kula and Jankovská (2013) identified only 166 (1% of all cases) such incidents between 1992 and 2004. The odds of a vegetation fire then decrease with increasing elevation. In general, the air temperature decreases with increasing altitude and thus the weather conditions for vegetation fires are less favorable in these areas. The fact that vegetation fires are more likely to occur near roads can be related to the already mentioned human factor.

Conclusion

This study focused on vegetation fires that occurred near railway lines in the Czech Republic between 2011 and 2019. As many as 74.8% of the incidents were concentrated between March and August from 11 am to 8 pm. Fires were more likely to occur during periods of high air temperature, low precipitation, low relative air humidity, and low wind speed. Based on the description of the individual incidents, most fires (85.2%) occurred on grassy areas and the fire area did not exceed 500 m² in 69.9% of the cases. The exact cause of the fire was not known for 86.7% of the records. Using the KDE+ method, 186 hotspots were identified on the Czech rail network. They contained 510 vegetation fires and represented only 0.3% of the length of the rail network. Hotspots were concentrated on railway lines with higher freight traffic intensity (e.g., near Most, Nymburk, Česká Třebová railway stations) which were situated in areas with a higher annual average air temperature. Spatial analysis revealed that there are more than 4 times higher odds that a vegetation fire occurs near an electrified railway line than near a non-electrified line or that additional 10 freight trains per day increases the odds by 5%. These findings can be used to reduce the risk of vegetation fires to an acceptable level, for example by managing vegetation in the identified high-risk areas. The results also indicated possible human factors causing fires as they concentrated near railway stations and close to roads.

Appendix

Tables 5 and 6

Table 5 The results of the variance inflation factors for selected parameters

Variable	VIF
Rail traffic intensity—freight	3.13
Rail traffic intensity—total	3.11
Railway line electrification	1.66
Distance to the built-up area	1.38
Elevation	1.41
Distance to the nearest road	1.34
Population density	1.24
Distance to the forest	1.11
Railway station district	1.09
Railway line geometry	1.06

Table 6 The best logistic regression model, according to AIC

Variable	Estimate	95% CI
Intercept	−0.2344	−0.5178 to 0.0490
Railway line electrification	1.4235	1.2421–1.6064
Railway station district	0.3037	0.0937–0.5153
Rail traffic intensity—freight	0.0498	0.0166–0.0834
Population density	0.0365	0.0209–0.0526
Distance to the build-up area	−0.0323	−0.0532 to −0.0116
Distance to the nearest road	−0.1014	−0.1457 to −0.0580
Elevation	−0.1578	−0.2256 to −0.0907

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Authors' contributions

VN collected, processed, and analyzed the data and wrote the manuscript. RA performed statistical analysis and contributed to sections of the manuscript. MB supervised the research and contributed to the writing of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

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The authors declare that they have no competing interests.

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