Ann. For. Res. 65(1): 17-30, 2022
https://doi.org/10.15287/afr.2022.2183

ANNALS OF FOREST RESEARCH
www.afrjournal.org

Future forest fires as functions of climate change and attack time for central Bohemian region, Czech Republic

Peter Lohmander[1], Zohreh Mohammadi[1]✉, Jan Kašpar[1], Meryem Tahri[1], Roman Berčák[1], Jaroslav Holuša[1], Robert Marušák[1]

Lohmander P., Mohammadi Z., Kašpar J., Tahri M., Berčák R., Holuša J., Marušák R., 2022. Future forest fires as functions of climate change and attack time for central Bohemian region, Czech Republic. Ann. For. Res. 65(1): 17-30.

Abstract This paper presents a new analysis of how global warming may affect the size of forest fires through its effects on air temperature, relative humidity, and wind speed. The effects of attack time on the size of the final burned area were also determined simultaneously in the statistical analysis. Two nonlinear functions determining the size of fires in the Prague-East District of the Czech Republic were estimated, based on a set of explanatory variables including air temperature, relative humidity, wind speed, and attack time. The functions were determined by multiple regression analysis combined with logarithmic transformations. The effects of climate change scenarios on future forest fires were calculated using the estimated fire-size function. The results show that if global warming leads to increased air temperature, reduced humidity, and stronger winds, we can expect larger fires. According to climate change scenarios, an upturn in the size of fires is predicted over this century. While we can control the fire by reducing the attack time, the results also show that if firefighters can reach a fire more quickly, the size of the fire will be reduced. If forest management methods, infrastructure, and fire brigade capacity are not adapted to the new climate, larger areas can be expected to be destroyed by fire.

Keywords: air temperature, relative humidity, wind speed, attack time, global warming, forest burned area.

Addresses: [1]Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Praha-Suchdol, Czech Republic.

✉ **Corresponding Author:** Zohreh Mohammadi (Mohammadiz@fld.czu.cz).

Manuscript: received April 07, 2021; revised January 28, 2022; accepted March 04, 2022.

Introduction

Fires are an inseparable component of ecosystem dynamics in European landscapes. On average, about 60000 fires occurred annually in Europe from 2000 to 2009. The burned area was about half a million hectares of wildland and forest yearly. The rising trend has occurred in forest fire activity in Europe since 2000 (San-Miguel-Ayanz et al. 2012). The number and burned areas of fires in the Czech Republic have increased approximately 70% in the period 1991-2015 in comparison with 1971-1990 (Mozny et al. 2021).

Forest fires are the result of complex interactions between climatic and non-climatic factors. Fires are a worldwide phenomenon that have apparent impacts on ecosystems with their biogeochemical cycles and biogeophysical properties (Bowman et al. 2009). An increase in the number of fires is expected in the future due to climate change, which has been identified as the most significant feature for future fire regimes (Mouillot et al. 2002, Moriondo et al. 2006, Amatulli et al. 2013). Climate change is likely to entail a considerable increase in the number of heatwaves, droughts, and dry spells across most of the Mediterranean area, which will probably extend the period when fires occur and the area at risk and lead to larger fires, possibly intensifying desertification (Wu et al. 2015). In other words, climate changes can lead to less precipitation, and lower humidity can make the vegetation and soil dryer and increase the frequency of fires in regions with fire-prone vegetation (Eskandari et al. 2020). Several studies have established a connection between burned areas and climate change (Flannigan et al. 2013, Abatzoglou & Williams 2016, Halofsky et al. 2020). According to a report by the Czech Hydrometeorological Institute in 2009, a notable increase in the frequency and length of drought periods by the end of the century is identified in future climate projections for the European area. They applied the Regional Climate Model (RCM) for producing weather series representing the changing climate in the Czech Republic. The greenhouse gas emission scenarios used to consist of Representative Concentration Pathways (RCP) 4.5 (milder scenario) and RCP8.5 (pessimistic scenario). Based on these scenarios, a rise in air temperature and minor changes in relative humidity are predicted by the end of the century, which can affect the size of the burned area.

In addition to climatic factors, the non-climatic ones may also play a considerable part in the spread of fires. Some of these anthropogenic factors significantly affect fires, in particular. Human demographic patterns and activities, especially fire management and land use, are notable examples (Chuvieco et al. 2008, Marlon et al. 2008). Fires can be started directly by humans and can be prevented; road networks can be designed and constructed, for instance, to improve access for firefighters and facilitate firefighting operations (Zhang et al. 2020). If fires are not discovered and extinguished quickly, the result may be major economic losses and severe consequences for the local environment (Hayati et al. 2013). Since forest fires are usually unexpected, it is essential to facilitate a rapid reaction to extinguish them at an early stage (Santín et al. 2016, Bui et al. 2017). Lohmander (2020) demonstrated that all relevant information, such as fire condition, infrastructure, and available local firefighting resources, is important for optimal firefighting management and international cooperation globally.

A well-developed forest road network can provide easier access to fire areas for forest fire fighting vehicles, and with a denser forest road network, it takes less time to reach these areas (Zhang et al. 2020). Lohmander (2021a) investigated the sensitivity of fire areas to different conditions in 29 countries. This international study showed that the burned area increases with average temperature and a proxy for attack time. The burned area decreases with a proxy for firefighting capacity.

Several recent studies have identified various climatic and non-climatic factors that affect fires. For instance, in China, Zhang et al. (2019) studied how forest fires are affected by average precipitation, average wind speed, maximum temperature, specific humidity, precipitation rate, average temperature, forest coverage ratio, a normalized difference vegetation index, distance to roads and distance to rivers. In Mozambique, Nhongo et al. (2019) estimated how fires are affected by elevation, aspect, slope, average monthly temperature, relative humidity, monthly precipitation, distance to roads, distance to settlements, and a normalized difference vegetation index. Monjarás-Vega et al. (2020) in Mexico estimated the effects that climate variables such as precipitation, and non-climate variables such as distance to urban areas, distance to roads, and distance to agriculture areas, have on fires.

The Czech Republic is an example of a landscape with fragmented terrain and dense forest roads. As a result, forest fires can often be extinguished in their early stages, so catastrophic damage seldom occurs (Holuša et al. 2018). Forest fires are expected to increase in the future due to climate change (Schelhaas et al. 2010); for this reason, it is important to increase our understanding of forest fires and the potential consequences of climate-related changes.

For the present research, two nonlinear functions determining the size of fires in the Prague-East district of the Czech Republic were estimated, based on a set of explanatory variables including air temperature, relative humidity, wind speed and attack time in two versions with and without wind speed. Because wind speed data can be challenging to collect, especially when used in many regional or international comparisons, as it covers all regions. In addition, if wind speed information is expensive or takes more time, it may be more rational to use the function without wind speed, even if the complete function is marginally better concerning the expected error.

The functions were determined by multiple regression analysis combined with logarithmic transformations. The influence of time on the size of the fire was considered nonlinear and strictly convex. Since a typical fire starts as a very small fire and, as time goes, it grows in all directions. Under very stable conditions, without wind, it grows like a bigger and bigger circle. In such cases, the size of a fire is approximately proportional to the time in the square. The fire grows like a growing ellipse if the wind is weak and stable. Again, the area is proportional to the square of time. Such functions are strictly convex. In several cases, the fire starts as ground fire, as a circle or ellipse, and later spreads to the tree crowns. Then, the speed of growth can rapidly increase. For all of these reasons, it is assumed that the size of a fire can be approximated as a strictly convex function of time. An exponential function is strictly convex and approximates all of these phenomena.

Earlier models have not considered the simultaneous effect of climate variables and attack time on the size of forest fires. This study deals with the effects of climatic and non-climatic changes on the size of burned area in the Prague-East district and estimates the effects of climate change scenarios on the size of forest fires. The main motivation is to mitigate in order to reduce socio-economic losses.

We hypothesized the simultaneous influence of four fundamental factors on the areas burned by forest fires:

(H1) Increased air temperature leads to an increase in the size of fires;

(H2) Reduced air humidity leading to dryer fuel; forest fires spreading more rapidly;

(H3) Increased wind speed leading to fires spreading and growing more rapidly;

(H4) Increased attack time, giving fires more time to grow larger.

In addition, based on the climate change scenarios:

(H5) The average fire size increases in the Czech Republic by the end of the 21st century.

The data and results presented in this study are intended as a basis for further optimization of forest management.

Materials and Methods

Study area

The study focuses on the Prague-East forests located in a district within the central Bohemian region of the Czech Republic (50°5′16″ N, 14°25′14″ E). The forest and agricultural land area are 16985.3 ha and 47709.68 ha, respectively. The average altitude is 431 m. (Figure 1) (Czech Statistical Office 2019). The average annual air temperature is 10°C (17°C in summer), the average annual precipitation is 500 mm (200 mm in summer), the average annual relative humidity is 77%, the average annual wind speed is 22 km h^{-1} (Czech Republic Hydrometeorological Institute 2021).

Data collection

Dependent variable

Forest fire data were collected for the Prague-East district for the period 2006–2015 from the database of the Fire Rescue Service of the Czech Republic (Holuša et al. 2018). These records contained detailed information for each forest fire, including geographic location and fire size. There were 115 fires, of which 27 were not included in the study owing to duplication or missing or incorrectly recorded geographical coordinates (Figure 2a). The average, maximum, and minimum burned area was recorded 0.138 ha, 6 ha, and 0.0001 ha, respectively.

Independent variables

In this paper, independent variables are divided into two different classes: climatic and non-climatic. Climatic data for each fire, including temperature at noon (°C), average relative humidity (%), and average wind speed (km h-1), were acquired from the meteorological station closest to the fire location (Czech Republic Hydrometeorological Institute 2021). Non-climatic data were the calculated attack time (h), i.e., it takes firefighters to reach the fire from the nearest fire station.

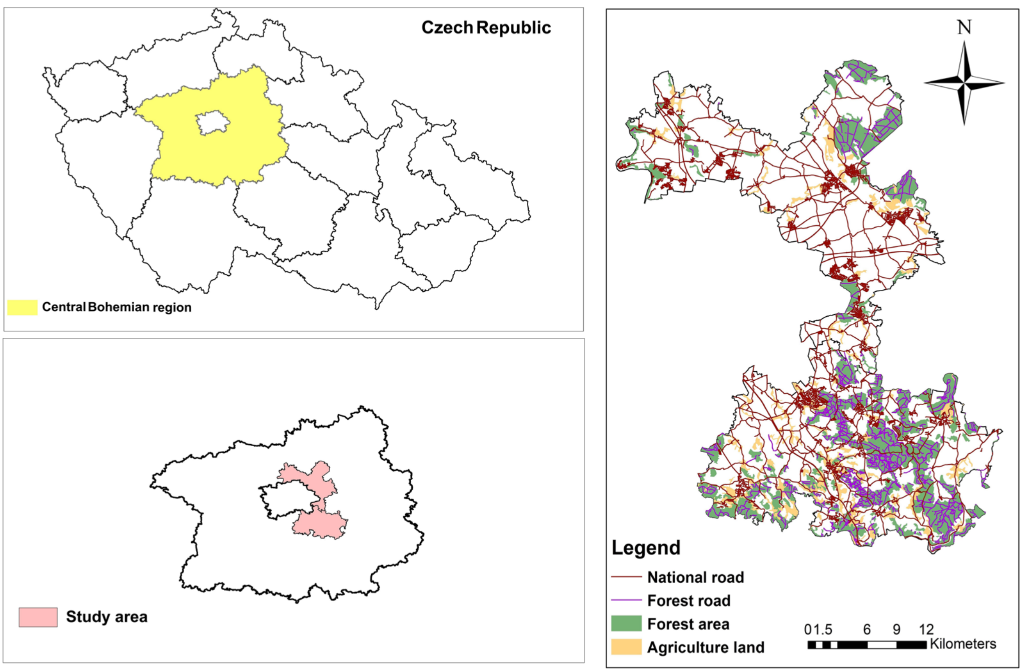

Figure 1 The study area in the Prague-East district within the central Bohemian region of the Czech Republic.

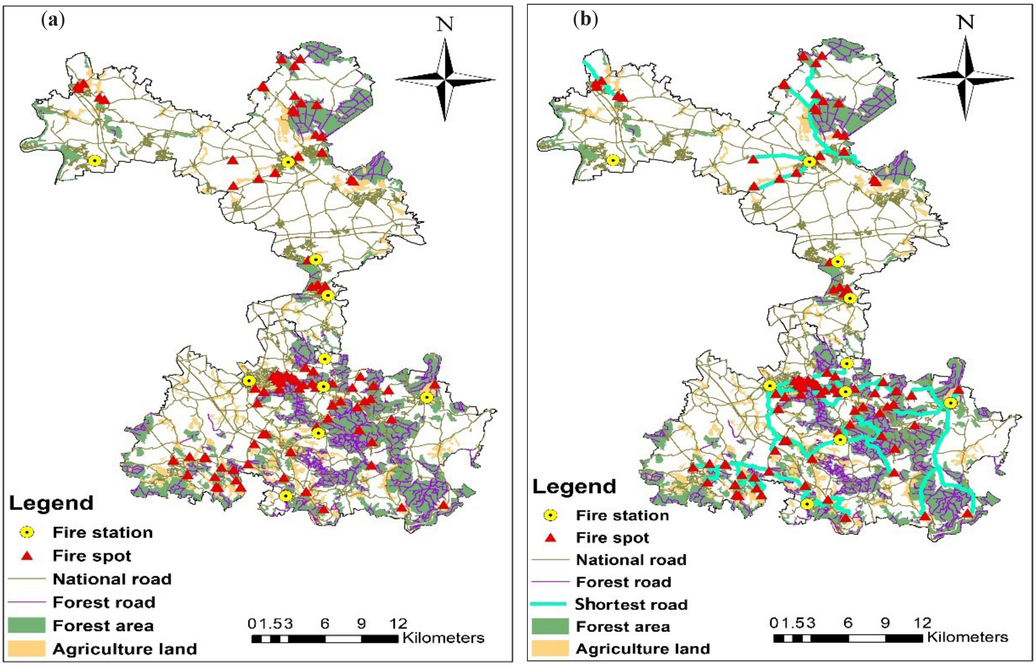

Figure 2 Forest fire spots in the period 2006–2015 in the Prague-East district of the Czech Republic and number of fire stations in the study area (**a**), the most appropriate road between fire stations nearest to forest fire spots in terms of maximum travel speed and length road (**b**).

Attack time calculation by the length of road and maximum travel speed

The attack time was calculated from the length of different roads and the maximum speed of firefighting vehicles on different types of the road; see Equation (1). This is the time required for firefighters to travel from the nearest fire station to a specific location in the forest where a fire has started. The maximum speed that equipped firefighting vehicles are allowed to travel on different types of roads in the Czech Republic depends on the road properties. L_1 grade forest roads suitable for firefighting vehicles and equipment are known as forest transport roads. The special characteristics of these roads include their width, technical facilities, and a maximum gradient of 10-12% (Majlingová 2012). Based on the methodological guide for drafting firefighting documentation in the Czech Republic, the theoretical maximum speed limits are 20-40 km h^{-1} on L_1 roads and 60-100 km h^{-1} on national roads. In this study, the speeds of 40 km h^{-1} and 100 km h^{-1} were applied as the maximum speed for forest and national roads, respectively.

$$T = (L_F / M_F) + (L_P / M_P) \qquad (1)$$

where T is attack time (h), L_F and L_P are forest road length and national road length respectively (km), M_F and M_P are maximum speed limits on forest roads and national roads, respectively (km h^{-1}).

The national and forest road network was mapped using a geographic information system. The road network map was downloaded from the 'OpenStreetMap' dataset and the Czech Institute of Forest Management geoportal (ÚHÚL 2021). Data from 'OpenStreetMap' were extracted using the OpenStreetMap toolbox in ArcGIS, and the web map server (WMS) layer was converted (OpenStreetMap Statistics 2021). Both sets of data were derived to obtain the shapefile line. The ArcGIS network analyst tool was used to find the closest routes from fire station areas across forest fire occurrence zones (Figure 2b). The ArcGIS Network Analyst extension uses the popular Dijkstra's algorithm for finding the shortest routes (Eklund et al. 1996). The optimal route from the fire station to the fire incident was based on travel distance and travel time, and the best route between the incident and the chosen stations was calculated. Modeling of the spatially-distributed rapid road demands incorporated fire stations and fire occurrence location shapefile points; the forest road map then generated the most appropriate road alternatives in terms of maximum travel speed.

Burned area size

The modeling commenced by considering the theory of the size of the burned area studied by Lohmander (2021b) - Eq. (2).

$$S = S(A, W, H_R, T, \varphi) \qquad (2)$$

S (ha) denotes the size of the burned area after a fire. The burned area is considered a function of A air temperature (°C), W wind speed (km h^{-1}), HR relative humidity (%), T attack time (h), and φ representing other non-considered factors.

For this study, we focused on the first four factors, which were discovered to be appropriate for explaining the size of fires (Reid et al. 2010, Pinto et al. 2020, Mohammadi et al. 2021a); the other factors were assumed to be more or less constant.

Estimation of burned area functions

In the first version of the analysis, wind speed W was not considered as an explanatory variable. The burned area was estimated as a function of three explanatory variables: air temperature, relative humidity, attack time.

Hence Eq. (3) was used in the first analysis:

$$S = S(A, H_R, T) \qquad (3)$$

It was, therefore, possible to estimate the function of the burned area. Eq. (4) and Eq. (5) assumed the following functional form:

$$LN(S) = K_T LN(T) + K_A A + K_H H_R \qquad (4)$$

$$S = T^{K_T}\ e^{K_A A + K_H H_R} \qquad (5)$$

LN(S) is the term, where S (ha) or the size of the burned area is the dependent variable. $K_T LN(T)$, $K_A A$, $K_H H_R$ are the terms including the independent variables of A air temperature (°C), H_R relative humidity (%), T attack time (h), and the parameters of K_T, K_A, K_H that would be estimated by multiple regression analysis.

In the second version, W was added to the list of explanatory variables. Hence Eq. (6) was used in the second analysis:

$$S = S(A, H_R, T, W) \qquad (6)$$

The burned area was also estimated as a function of four explanatory variables: attack time, air temperature, relative humidity, and wind speed - Eq. (7) and Eq. (8).

$$S = T^{K_T}\ e^{K_A A + K_H H_R + K_W W} \qquad (7)$$

$$LN(S) = K_T LN(T) + K_A A + K_H H_R + K_W W \qquad (8)$$

where S is the size of the burned area (ha), T is attack time (h), A is air temperature (°C), HR is relative humidity (%), W is wind speed (km h^{-1}), and K_T, K_A, K_H, K_W are parameter values that would be estimated using multiple regression analysis.

If the initial hypotheses (H1, H2, H3, and H4) are correct, the signs of the parameters should be:

$$K_T > 0 \wedge K_A > 0 \wedge K_W > 0 \wedge K_H < 0$$

Estimation of the effects of climate change scenarios on the size of forest fires using the fire model

Climate change scenarios were used to evaluate the size of burned areas in the future, although this does not imply the probability of these scenarios occurring. The scenarios were evaluated for four future periods: 2021–2040, 2041-2060, 2061-2080, and 2081–2100 and compared to the current period. For instance, at the end of the 21st century (2081–2100), the annual average air temperature will have increased by 2°C (RCP4.5 scenario) and 4.1°C (RCP8.5 scenario). The annual average relative humidity will have risen by 0.5% (RCP4.5 scenario) and, the annual average relative humidity will not increase in the RCP8.5 scenario (see Table 1; Czech Hydrometeorological Institute 2009).

The effects of these possible scenarios (Table 1) on future forest fires can be calculated using the estimated fire size function (Eq. 4).

Table 1 Predicted annual rise in air temperature (°C) and annual relative humidity (%) in the Czech Republic by the end of the 21st century based on RCP4.5 and RCP8.5 scenarios.

Emission scenario	Period	Annual air temperature rise (°C)	Annual relative humidity rise (%)
RCP.4.5	2021–2040	0.9	0.4
	2041–2060	1.3	0.4
	2061–2080	1.8	0.5
	2081–2100	2.0	0.5
RCP.8.5	2021–2040	1.0	0.6
	2041–2060	1.8	0.5
	2061–2080	2.8	0.5
	2081–2100	4.1	0

Attack time sensitivity analysis

An analysis was carried out to investigate how fire size varies with changes in attack time. First, the effects of the possible scenarios (Table 1) on future forest fires are calculated using Eq. (4) in conditions where the air temperature and relative humidity change and the attack time is constant. At this stage, changes in attack time were examined simultaneously with the increased climate change. For this process, the attack time was reduced by 0%, 20%, and 40% for each climate change scenario. The empirically estimated function was used for this purpose (Eq. 4).

Results

Results from the estimation of burned area functions

First, according to Eq. (3) in subsection 2.5. the multiple regression results were estimated with the function of the burned area determined by three explanatory variables. The regression analysis of Eq. (4) gave a highly significant function (Table 2). For multiple R = 0.9349, the F-value of the regression was 197, and the p-value of the regression was 7.31×10^{-38}. The regression analysis results have shown that the fire size is negatively correlated with relative humidity and positively correlated with attack time and air temperature (Table 2).

Table 2 Estimated parameters of the regression analysis based on Eq. (4).

Variable	Coefficients	Standard error	t-value	P-value
Ln(T)	1.12	0.2514	4.70	0.000024
A	0.0589	0.0218	2.70	0.0085
H_R	-0.05	0.0126	-3.94	0.00017

The burned area was estimated as a function of attack time, air temperature, and relative humidity on the day of the fire, Eq. (9).

$$S = T^{1.12}\, e^{0.0589A-0.0500H_R} \tag{9}$$

The estimated equation in logarithm form is found in Eq. (10).

$$LN(S) = 1.12LN(T) + 0.0589A - 0.05H_R \tag{10}$$

Second, following Eq. (6) in subsection 2.5. an alternative model was estimated where the wind speed was included in the set of explanatory variables (Eq. 8). As expected, the model revealed that if wind speed increases, the size of the fire also increases. However, the p-value of the wind speed parameter exceeded 5% (Table 3).

Table 3 Estimated parameters of the regression analysis based on Eq. (8).

Variable	Coefficients	Standard error	t-value	P-value
Ln(T)	1.16	0.2499	4.621	0.000013
A	0.0505	0.0222	2.267	0.02
H_R	-0.0574	0.0402	-4.281	0.000049
W	0.0640	0.0134	1.591	0.10

This alternative model is found in equations (11) and (12). If wind speed is included in the function, the multiple R = 0.9369. All parameters change marginally.

The estimated burned area as a function of attack time, air temperature, relative humidity on the day of the fire, and wind speed is found in Eq. (11).

$$S = T^{1.16}\, e^{0.0505A-0.0574H_R+0.0640W} \tag{11}$$

The function in logarithm form is found in Eq. (12).

$$LN(S) = 1.16LN(T) + 0.0505A - 0.0574H_R + 0.0640W \tag{12}$$

After determining the regression parameters, the residuals were analyzed for all variable dimensions. Since the points in the residual plots were randomly dispersed around the horizontal axis, the models were found to describe the relationships correctly (Figures 3 & 5). The predicted and observed values of the size of the burned area are compared in Figures 4 & 6. The models between LN(S) indices and independent variables performed well, so the predicted LN(S) closely resembles the observed LN(S) (Figures 4 & 6).

Results from the estimation of the effects of climate change scenarios on the size of forest fires

The average percentage increase to the current value that was estimated using possible climate change scenarios, including the predicted annual rise in air temperature (°C) and annual relative humidity (%) (Table 1) and the estimated burned area function (Eq.10). According to the climate change scenarios, the size of the fire increases with the air temperature rise and relative humidity reduction. Based on the RCP.4.5 scenarios, the annual air temperature and relative humidity will increase by 0.9 °C and 0.4%, respectively, by the next 20 years. While according to the RCP. 8.5 scenarios, the annual air temperature, and annual relative humidity will increase by 1 °C and 0.6%, respectively, by the next 20 years. As a result, the predicted average fire size will increase by 3.36 % (RCP.4.5) and 2.93% (RCP.8.5) by the next 20 years. The results have shown that an upturn in forest fire size due to climate change is predicted over the 21st century; according to climate scenarios, fire size, for instance, will increase by 9.72% (RCP.4.5) and 27.31% (RCP.8.5) by the end of the 21st century (Figure 7).

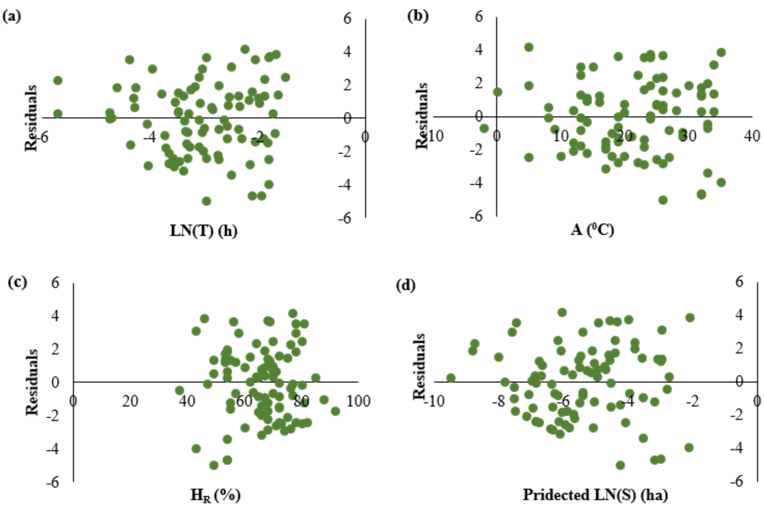

Figure 3 Model of residuals of burned area size (Eq. [10]) with respect to T attack time (h) **(a)**, air temperature (°C) **(b)**, H_R denoting relative humidity (%) **(c)** and predicted LN(S) (ha) values **(d)**.

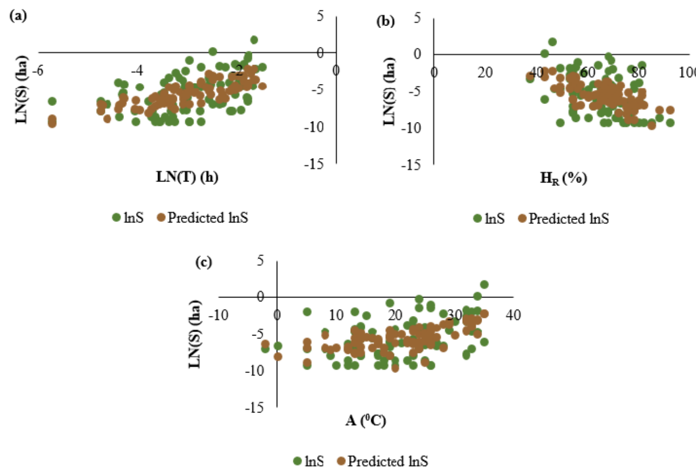

Figure 4 Observed and predicted size of burned area based on Eq. (10).

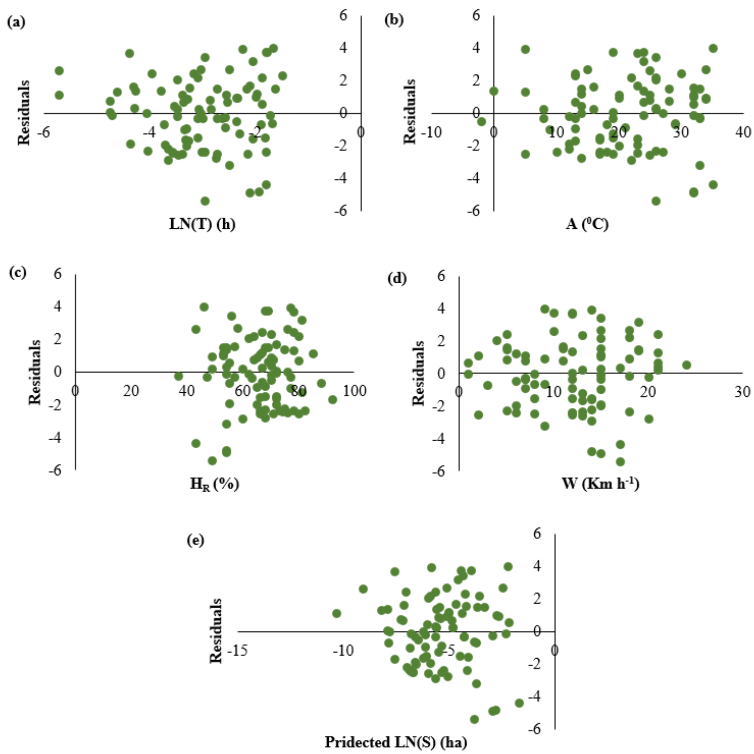

Figure 5 Model of residuals of burned area size (Eq. [12]) with respect to T attack time (h) (**a**), air temperature (°C) (**b**), H_R denoting relative humidity (%) (**c**) and wind speed W (km h-1) (**d**), predicted LN(S) (ha) values (**e**).

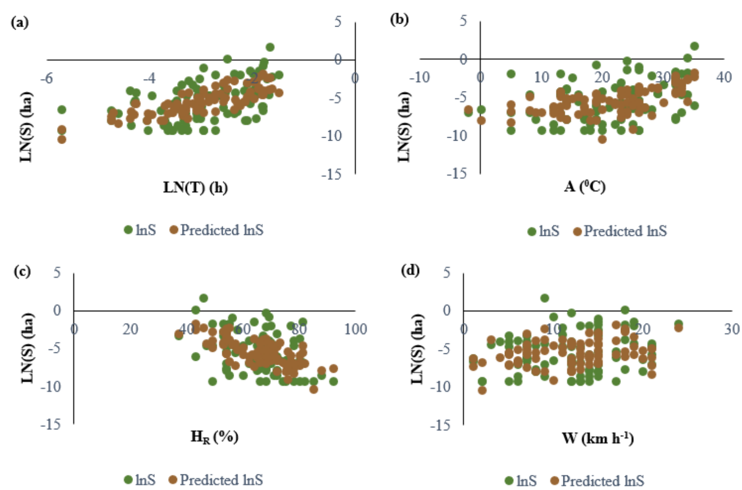

Figure 6 Observed and predicted size of burned area based on Eq. (12).

Results of attack time sensitivity analysis

Improvements in the road network may reduce future fire problems since attack times greatly influence fire size. The effects of attack time were estimated based on the climate scenarios, the empirical model of forest fire size (Eq.10), and alternative levels of attack time reduction. Assuming that the road network and attack times remain constant, the prediction is that fire size will increase considerably due to climate change. While the fire size can be decreased by reducing the attack time, the results also show that if firefighters can reach a fire more quickly, the size of the fire will be reduced. In summary, if attack times are reduced, the size of fires can be reduced in the future, even taking into account climate change. The results have shown that a 20% reduction in attack time will reduce the fire size by 12.07% (RCP 4.5) and 2.01% (RCP 8.5) by the end of the 21st century. While with a 40% reduction in attack time, the fire size

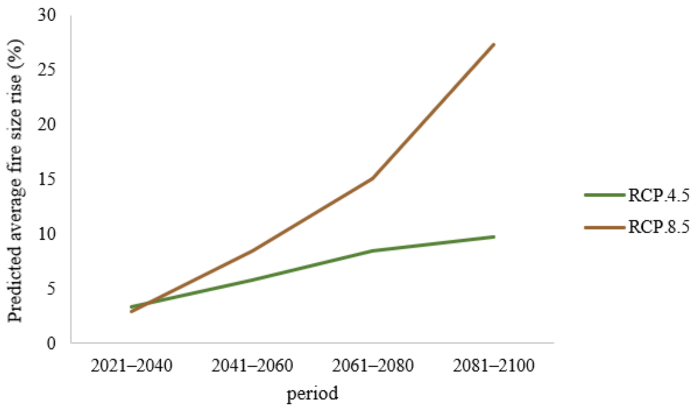

Figure 7 Predicted average fire size increase (%) in the Czech Republic by the end of the 21st century based on RCP4.5 and RCP8.5 scenarios and the empirical model of forest fire size Eq. (10).

will be reduced by 34.05% (RCP 4.5) and 23.48% (RCP 8.5) compared to the current condition. These results are reported with more details in Table 4.

Table 4 Effect of attack time on fire size under alternative climate change scenarios. The climate scenarios are RCP4.5 and RCP8.5, and the empirical model of forest fire size is Eq. (10).

Emission scenario	Period	Annual air temperature rise (°C)	Annual relative humidity rise (%)	Predicted average fire size changes (%)		
				Attack time reduction (0%)	Attack time reduction (20%)	Attack time reduction (40%)
RCP.4.5	2021–2040	0.9	0.4	+3.36	-17.17	-37.88
	2041–2060	1.3	0.4	+5.82	-15.20	-36.40
	2061–2080	1.8	0.5	+8.44	-13.10	-34.82
	2081–2100	2.0	0.5	+9.72	-12.07	-34.05
RCP.8.5	2021–2040	1.0	0.6	+2.93	-17.51	-38.13
	2041–2060	1.8	0.5	+8.44	-13.10	-34.82
	2061–2080	2.8	0.5	+15.02	-7.83	-30.87
	2081–2100	4.1	0	+27.31	-2.01	-23.48

Discussion

The purpose of this study is to identify the simultaneous effects of air temperature, attack time, relative humidity, and wind speed on the size of forest fires in the Prague-East district of the Czech Republic and to estimate the effects of climate change scenarios on the size of forest fires, leading to the development and estimation of the burned area size function. function is less reliable. However, the four variable functions probably explain the development of fires better than the version with three variables.

The results showed that two of the climatic (air temperature and relative humidity) and non-climatic (attack time) explanatory variables investigated significantly influenced the spread of forest fires. Based on the output of the first model, increased attack time and air temperature will increase the size of fires. If humidity increases, however, fires will be smaller. The explanatory variables all have p-values under 1%; the estimated fire size function based on these three explanatory variables can therefore be considered extremely reliable.

A second, more detailed version of the fire size function was also developed, with wind speed included as an explanatory variable. As expected, the estimated effect was that fire size is another function of increased wind speed. The p-value of wind speed, however, was only 12%. For this reason, the second function is less reliable. However, the four variable functions probably explain the development of fires better than the version with three variables.

As the results of this study show, climatic variables play a key role in fire dynamics in the Prague-East district Forest. Numerous studies support our result that air temperature affects fires (Koutsias et al. 2012, Živanović et al. 2015). As temperature increases, fire size increases, consistent with our hypothesis (H1). For instance, In China, Tian et al. (2019) likened climate change, weather, and burn probability during the fire season. Their results show that the daily average maximum temperature during the fire season increases. Živanović et al. (2020) analyzed the effects of air temperature and precipitation on the risk of forest fires in Serbia. Their results revealed that air temperature and precipitation significantly impact fire occurrence.

There are three elements that explain the positive relationship between temperature and fire. First, there is more evapotranspiration with higher temperatures since there is a steep increase in the atmosphere's ability to hold moisture with higher temperatures (Roulet et al. 1992). Second, increases in air temperatures lead to more thunderstorms and lightning, causing an increase in ignitions (Price & Rind 1994). Third, warmer temperatures can lead to longer fire seasons (Westerling et al. 2006).

The relative humidity is another variable that plays a significant role in growing a forest fire size. A reduction in relative humidity leads to increasing fire sizes. See hypothesis (H2). This has also been noted by other authors (Jolly et al. 2015, Konca-Kędzierska & Pianko-Kluczyńska 2018, Wu et al. 2018) and can be explained by changes in fuel moisture. There is a constant interchange of moisture between dead forest fuels and the air. Low humidity takes moisture from fuels, and the fuels absorb moisture from the air in high humidity conditions. Decreases in relative humidity make refined fuels dryer, so fires grow rapidly (Kane et al. 2018).

In addition to relative humidity, wind speed is another important factor that affects fuel moisture conditions. These, subsequently, influence fire regimes (e.g., burn severity) (Wastl et al. 2013, Viedma et al. 2015). The estimated wind speed parameter did not give a p-value of below 5%, which may be due to the fact that there have not been many strong winds and fires in the region under investigation. In any case, since the model supports the hypothesis (H3) that fire size increases with increased wind speed, this model should also be described in the article.

Our results concur with results obtained by other authors. For instance, Wu et al. (2018) investigated the relationship between weather parameters and spatial burn severity patterns in Chinese boreal forests. The results showed that fire size increases in the dryer and less humid conditions with higher wind speeds. Cruz et al. (2020) analyzed many fires spread rates recorded in conifer forests, eucalypt forests, and temperate shrublands to investigate the eligibility of a simple rule of thumb, providing an initial approximation of the rate of fire spread from wind speed alone. This study confirms the effect of wind speed on the spread of forest fire.

A unique aspect of the proposed approach in the present study is the estimate of attack time as a non-climatic variable in the forest fire model. An increase in attack time leads to larger forest fires since the fires have more time to spread before the firefighters reach the fire, as predicted by our hypothesis (H4). This is also consistent with Hansen (2003), who stressed that fire suppression improves and attack times are reduced with higher road density due to greater accessibility to the fire. In other words, increasing road density leads to reduced fire size (Mohammadi et al. 2021b). In this study, theoretical speed was used. The actual speed may be less than the estimate. Accordingly, the actual attack time could be less depending on the vehicle's type, and age and the fire's size could be shorter.

Based on the RCP4.5 and RCP8.5 climate change scenarios and the empirical model, the size of forest fires is predicted to rise in the Czech Republic by the end of the 21st century (H5). Accordingly, the results of this study indicate that climate change plays a key role in the increasing severity of forest fires. Various studies claim that climate change will directly affect the increase of fires in the future, which supports our results. For instance, Déqué et al. (1998) predicted a significant increase in fire potential for Europe, enlarged the fire-prone areas, and lengthened the fire season, based on climate projections for 2070–2100. Flannigan et al. (2005) used historical relationships between weather/fire danger and burned areas in tandem with two GCMs to estimate future fire size in Canada. The results indicate a 74–118% rise in burned areas by the end of this century. Westerling et al. (2011) modeled fire size using hydroclimate and land surface characteristics in a range of future climate change and development scenarios in California. Their results demonstrate that a rise in fire burned zones is likely for most scenarios by the end of the 21st century. Karali et al. (2014) used a regional climate model based on the Canadian Fire Weather Index system in Greece. They also investigated the effects of climate change on fire risk for 2021–2050 and 2071–2100 under the emissions scenario. Their results showed that critical fire risk is expected by the end of the century.

We studied the attack-time change on forest fire size under climate change in the future. The results showed that if attack time decreases by

40%, the size of the fire is significantly reduced. Although these climate scenarios are possible, if attack times are reduced by improving the road network, or other factors such as investment in and innovation of aerial and field fire brigade equipment, tactics, time, etc., then future fire size can be reduced in spite of the effects of climate change.

Conclusions

The methodology presented proved appropriate for studying how the size of forest fires is affected by climatic and non-climatic variables. It was demonstrated that the size of the burned area depends on various factors, some of which are under human control. In addition, the effects of climate change scenarios were calculated on future forest fires.

Increases in temperature and wind speed and a reduction in humidity can be regarded as consequences of global warming. All of these changes result in larger forest fires. In this sense, this study focused on the effects of global warming on forest fires. Based on the climate change scenarios, more fires are expected by the end of the century.

In addition, humans can significantly affect fires in many ways. This study shows the importance of attack time and its direct effect on the size of the burned area. If forest management methods, infrastructure, and fire brigades' capacity are not adapted to the new climate, larger areas will probably be destroyed by fire.

Forest managers can significantly reduce the severity of forest fires by increasing road density and reducing attack times.

Currently, forest fires in the Czech Republic are small compared to those in many other countries. However, using the estimate function will be a key element for optimizing future forestry and fire management studies in the Czech Republic. Using local data, the fire size model developed in this paper can also be estimated for other countries and regions where the fire problems are even more severe. The model can therefore be used all over the world. A new study focusing on the analytical and numerical optimization of forestry, infrastructure, and fire management, based on general fire size functions of the type estimated in this paper, is found in Lohmander (2021b). This methodology can determine optimal combinations of decisions concerning firefighting capacity, road density, and forest management.

We anticipate that this study, pioneering work and the first of its kind to be carried out in the Czech Republic, will encourage research on this topic. Despite the positive results already obtained, the prediction model could be improved by including more accurate and updated information, with the possible addition of other explanatory variables.

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

Funding

This work was supported by grant "EVA4.0", No. CZ.02.1.01/0.0/ 0.0/16_019/0000803 financed by the Operational Program Research, Development and Education (OP RDE), the Ministry of Education of the Czech Republic.

References

Abatzoglou J. T., Williams A. P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences 113(42): 11770-11775. https://doi.org/10.1073/pnas.1607171113

Amatulli G., Camia A., San-Miguel-Ayanz J., 2013. Estimating future burned areas under changing climate in the EU-Mediterranean countries. Science of the Total Environment 450: 209-222. https://doi.org/10.1016/j.scitotenv.2013.02.014

Bowman D.M., Balch J.K., Artaxo P., Bond W.J., Carlson J.M., Cochrane M.A., D'Antonio C.M., DeFries R.S., Doyle J.C., Harrison S.P., Johnston F.H., 2009. Fire in the earth system. Science 324(5926): 481-484. https://doi.org/10.1126/science.1163886

Bui D.T., Bui Q.T., Nguyen Q.P., Pradhan B., Nampak H., Trinh P.T., 2017. A hybrid artificial intelligence approach using GIS-based neural-fuzzy inference system and particle swarm optimization for forest fire susceptibility modeling at a tropical area. Agricultural Meteorology Programme 233: 32-44. https://doi.org/10.1016/j.agrformet.2016.11.002

Chuvieco E., Giglio L., Justice C., 2008. Global characterization of fire activity: toward defining fire regimes from Earth observation data. Global Change Biology 14(7): 1488-1502. https://doi.org/ 10.1111/j.1365-2486.2008.01585.x

Cruz M.G., Alexander M.E., Fernandes P.M., Kilinc M., Sil Â., 2020. Evaluating the 10% wind speed rule of thumb for estimating a fire's forward rate of spread against an extensive independent set of observations. Environmental Modelling & Software 133: 104818. https://doi.org/10.1016/j.envsoft.2020.104818

Czech Statistical Office, 2019. Characteristics of the district Prague-East. Website. [Online 7 February 2019]. URL: https://www.czso.cz/csu/czso/home

Czech Hydrometeorological Institute, 2009. Update Comprehensive study of impacts, vulnerabilities, and sources of risks related to climate change in the Czech Republic from 2015, https://www.mzp.cz/C1257458002F0DC7/cz/studie_dopadu_zmena_klimatu/$FILE/OEOK-Aktualizovana_studie_2019-20200128.pdf

Czech Republic Hydrometeorological Institute, 2021. Historical data - meteorology and climatology in Czech Republic. http://portal.chmi.cz/historicka-data/pocasi/denni-data/Denni-data-dle-z.-123-1998-Sb

Déqué M., Marquet P., Jones R.G., 1998. Simulation of climate change over Europe using a global variable resolution general circulation model. Climate Dynamics 14(3): 173-189. https://doi.org/10.1007/s003820050216

Eklund P.W., Kirkby S., Pollitt S., 1996. A dynamic multi-source Dijkstra's algorithm for vehicle routing. In 1996 Australian New Zealand Conference on Intelligent Information Systems, ANZIIS 96, 18-20 Nov. 1996. IEEE, Adelaide, SA, Australia, pp. 329-333. https://doi.org/10.1109/ANZIIS.1996.573976

Eskandari S., Pourghasemi H.R., Tiefenbacher J.P., 2020. Relations of land cover, topography, and climate to fire occurrence in natural regions of Iran: Applying new data mining techniques for modeling and mapping fire danger. Forest Ecology and Management 473: 118338. https://doi.org/10.1016/j.foreco.2020.118338

Flannigan M.D., Logan K.A., Amiro B.D., Skinner W.R., Stocks B.J., 2005. Future area burned in Canada. Climatic Change 72(1-2): 1-16. https://doi.org/10.1007/s10584-005-5935-y

Flannigan M., Cantin A.S., De Groot W.J., Wotton M., Newbery A., Gowman L.M., 2013. Global wildland fire season severity in the 21st century. Forest Ecology and Management 294: 54-61. https://doi.org/10.1016/j.foreco.2012.10.022

Hayati E., Abdi E., Majnounian B., 2013. Application of Sensitivity analysis in forest road networks planning and assessment. Journal of Agriculture, Science and Technology 15(4): 781–792.

Hansen R., 2003. Skogsbrandsläckning. Räddningsverket, Karlstad, Sweden, 146 p. (In Swedish).

Halofsky J.E., Peterson D.L., Harvey B.J., 2020. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. Fire Ecology 16(1): 4. https://doi.org/10.1186/s42408-019-0062-8

Holuša J., Bercak R., Lukasova K., Hanuska Z., Agh P., Vanek J., ... Chromek I., 2018. Forest fires in the Czech Republic-definition and classification. Reports on Forestry Research, in Czech 63(2): 102-111.

Jolly W.M., Cochrane M.A., Freeborn P.H., Holden Z.A., Brown T.J., Williamson G.J., Bowman D.M., 2015. Climate-induced variations in global fire danger from 1979 to 2013. Nature Communications 6(1): 1-11. https://doi.org/10.1038/ncomms8537

Karali A., Hatzaki M., Giannakopoulos C., Roussos A., Xanthopoulos G., Tenentes V., 2014. Sensitivity and evaluation of current fire risk and future projections due to climate change: the case study of Greece. Natural Hazards and Earth System Sciences 14(1): 143. http://doi.org/10.5194/nhess-14-143-2014

Kane J.M., Prat-Guitart N., 2018. Fuel moisture. In: Manzello S. (eds) Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. Springer, Chame, Switzerland. https://doi.org/10.1007/978-3-319-51727-8_115-1

Konca-Kędzierska K., Pianko-Kluczyńska K., 2018. The influence of relative humidity on fires in forests of Central Poland. Forest Research Papers 79(3): 269-279. https://doi.org/10.2478/frp-2018-0027

Koutsias N., Xanthopoulos G., Founda D., Xystrakis F., Nioti F., Pleniou M., Mallinis G. and Arianoutsou, M., 2013. On the relationships between forest fires and weather conditions in Greece from long-term national observations (1894–2010). International Journal of Wildland Fire 22(4): 493-507. https://doi.org/10.1071/WF12003

Lohmander P., 2020. Adaptive mobile firefighting resources: stochastic dynamic optimization of international cooperation, International Journal of Robotics and Automation 6(4): 150-155. https://doi.org/10.15406/iratj.2020.06.00213

Lohmander P., 2021a. Forest fire expansion under global warming conditions: multivariate estimation, function properties and predictions for 29 countries. Central Asian Journal of Environmental Science and Technology Innovation 1(5). https://doi.org/ 10.22034/CAJESTI.2020.05.03

Lohmander P., 2021b. Optimization of forestry, infrastructure and fire management. Caspian Journal of Environmental Sciences. 19: 287-316. https://doi.org/10.22124/CJES.2021.4746

Majlingová A., 2012. Opening-up of forests for fire extinguishing purposes. Croatian Journal of Forest Engineering 33(1):159-168.

Marlon J.R., Bartlein P.J., Carcaillet C., Gavin D.G., Harrison S.P., Higuera P.E., Joos F., Power M.J., Prentice I.C., 2008. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience 2(4): 307-307. https://doi.org/10.1038/ngeo313

Mohammadi Z., Lohmander P., Kašpar J., Berčák R., Holuša J., Marušák R., 2021a. The effect of climate factors on the size of forest wildfires (Case study: Prague-East district, Czech Republic). Journal of Forestry Research. https://doi.org/10.1007/s11676-021-01413-w

Mohammadi Z., Lohmander P., Kašpar J., Marušák R., 2021b. The effect of road networks on the forest wildfires 'size. In EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-12000. https://doi.org/10.5194/egusphere-egu21-12000

Moriondo M., Good P., Durao R., Bindi M., Giannakopoulos C., Corte-Real J., 2006. Potential impact of climate change on fire risk in the Mediterranean area. Climate Research 31(1): 85-95. https://doi.org/10.3354/cr031085

Mouillot F., Rambal S., Joffre R., 2002. Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. Global Change Biology 8(5): 423-437. https://doi.org/10.1046/j.1365-2486.2002.00494.x

Monjarás-Vega N.A., Briones-Herrera C.I., Vega-Nieva D.J., Calleros-Flores E., Corral-Rivas J.J., López-Serrano P.M., Pompa-García M., Rodríguez-Trejo D.A., Carrillo-Parra A., González-Cabán A., Alvarado-Celestino E., 2020. Predicting forest fire kernel density at multiple scales with geographically weighted regression in Mexico. Science of the Total Environment 718: 137313. https://doi.org/10.1016/j.scitotenv.2020.137313

Mozny M., Trnka M., Brázdil R., 2021. Climate change driven changes of vegetation fires in the Czech Republic. Theoretical and Applied Climatology 143(1), 691-699. https://doi.org/10.1007/s00704-020-03443-6

Nhongo E.J.S., Fontana D.C., Guasselli L.A., Bremm C., 2019. Probabilistic modelling of fire occurrence based on logistic regression, Niassa Reserve, Mozambique. Geomatics, Natural Hazards and Risk 10(1): 1772-1792. https://doi.org/10.1080/19475705.2019.1615559.

OpenStreetMap Statistics, 2021. OpenStreetMap Foundation. Retrieved 11 May 2020. Web: https://www.openstreetmap.org/#map=6/49.817/15.478

Pinto G.A.S.J., Rousseu F., Niklasson M., Drobyshev I., 2020. Effects of human-related and biotic landscape features on the occurrence and size of modern forest fires in Sweden. Agricultural and Forest Meteorology 291: 108084. https://doi.org/10.1016/j.agrformet.2020.108084.

Price C., Rind D., 1994. The impact of a 2× CO2 climate on lightning-caused fires. Journal of Climate 7(10): 1484-1494. https://doi.org/10.1175/1520-0442(1994)007<1484:TIOACC>2.0.CO;2

Reid A. M., Fuhlendorf S. D., Weir J. R., 2010. Weather variables affecting Oklahoma wildfires. Rangeland Ecology & Management 63(5): 599-603. https://doi.org/10.2111/REM-D-09-00132.1

Roulet N., Moore T.I.M., Bubier J., Lafleur P., 1992. Northern fens: methane flux and climatic change. Tellus 44(2): 100-105. https://doi.org/10.1034/j.1600-0889.1992.t01-1-00002.x.

San-Miguel-Ayanz J., Schulte E., Schmuck G., Camia A., Strobl P., Liberta G., ... & Amatulli G., 2012. Comprehensive monitoring of wildfires in Europe: the European Forest Fire Information System (EFFIS). In Approaches to managing disaster - Assessing hazards, emergencies and disaster impacts. IntechOpen. https://doi.org/10.5772/28441

Santín C., Doerr S.H., Merino A., Bryant R., Loader N.J., 2016. Forest floor chemical transformations in a boreal forest fire and their correlations with temperature and heating duration. Geoderma 264: 71-80. https://doi.org/10.1016/j.geoderma.2015.09.021

Schelhaas M.J., Hengeveld G., Moriondo M., Reinds G.J., Kundzewicz Z.W., Ter Maat H., Bindi, M., 2010. Assessing risk and adaptation options to fires and windstorms in European forestry. Mitigation and Adaptation Strategies for Global Change 15(7): 681-701. https://doi.org/10.1007/s11027-010-9243-0

Tian X., Cui W., Shu L., Zong X., 2019. Effects of climate change on burn probability of forests in Daxing'anling. Forests 10(8): 611. https://doi.org/10.3390/f10080611

Úhúl., 2021. Forest roads 'map in Czech Republic, http://www.uhul.cz/

Viedma O., Quesada J., Torres I., De Santis A., Moreno J.M., 2015. Fire severity in a large fire in a Pinus pinaster forest is highly predictable from burning conditions, stand structure, and topography. Ecosystems 18(2): 237-250. https://doi.org/10.1007/s10021-014-9824-y

Wastl C., Schunk C., Lüpke M., Cocca G., Conedera M., Valese E., Menzel A., 2013. Large-scale weather types, forest fire danger, and fire occurrence in the Alps. Agricultural and Forest Meteorology 168: 15-25. https://doi.org/10.1016/j.agrformet.2012.08.011

Westerling A.L., Hidalgo H.G., Cayan DR., Swetnam TW., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313(5789): 940-943. https://doi.org/10.1126/science.1128834

Westerling A.L., Bryant B.P., Preisler H.K., Holmes T.P., Hidalgo H.G., Das T., Shrestha S.R., 2011. Climate change and growth scenarios for California fire. Climatic Change 109(1): 445-463. https://doi.org/10.1007/s10584-011-0329-9

Wu M., Knorr W., Thonicke K., Schurgers G., Camia A., Arneth A., 2015. Sensitivity of burned area in Europe to climate change, atmospheric CO2 levels, and demography: A comparison of two fire-vegetation models. Journal of Geophysical Research: Biogeosciences 120(11): 2256-2272. https://doi.org/10.1002/2015JG003036

Wu Z., He H.S., Fang L., Liang Y., Parsons R.A., 2018. Wind speed and relative humidity influence spatial patterns of burn severity in boreal forests of northeastern China. Annals of Forest Science 75(3): 66. https://doi.org/10.1007/s13595-018-0749-z

Zhang G., Wang M., Liu K., 2019. Forest fire susceptibility modeling using a convolutional neural network for Yunnan province of China. International Journal of Disaster Risk Science 10(3): 386-403. https://doi.org/10.1007/s13753-019-00233-1

Zhang F., Dong Y., Xu S., Yang X., Lin H., 2020. An approach for improving firefighting ability of forest road network. Scandinavian Journal of Forest Research 35(8): 547-561. https://doi.org/10.1080/02827581.2020.1829029

Živanović S., Gocić M., Ivanović R., Martić-Bursać N., 2015. The effect of air temperature on forest fire risk in the municipality of Negotin. Bulletin of the Serbian Geographical Society 95(4): 67-76. https://doi.org/10.2298/GSGD1504067Z

Živanović S., Ivanović R., Nikolić M., Đokić M., Tošić I., 2020. Influence of air temperature and precipitation on the risk of forest fires in Serbia. Meteorology and Atmospheric Physics 132: 869–883. https://doi.org/10.1007/s00703-020-00725-6