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RESEARCH PAPER

Forest fire expansion under global warming conditions: Multivariate estimation, function properties, and predictions for 29 countries

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Highlights

- The areas of forest fires are explained as functions of average temperature and other factors.
- The relative forest fire area increases with the average temperature and the size of the total forest area. It decreases with the size of the population, a proxy for the national firefighting capacity.
- Climate dependent fire area predictions are made for 29 countries.

Graphical Abstract

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Abstract

The topic of this study is forest fires. This study investigates the average relative burned area, as a function of different conditions, in 29 countries. Detailed international statistics of forest fires, published by FAO and European Commission, are used as empirical data. A multivariate fire area function with empirically very convincing statistical properties is defined, tested, and estimated. A set of hypotheses was created based on three fundamental factors. The hypotheses could not be rejected on statistical grounds, and the estimated parameters obtained the expected signs with very low P-values. The residual analysis supports the selected functional form. Future fire areas are predicted for 29 countries, conditional on three alternative levels of global warming conditions. The estimated fire area function can explain the forest fire areas in different countries via three fundamental factors: 1) the average area of forest fires divided by the total forest area is an increasing function of the average temperature. Hence, global warming is expected to make future forest fire problems even more severe, 2) the average area of forest fires divided by the total forest area is an increasing function of the total forest area, and 3) the average area of forest fires divided by the total forest area is a decreasing function of the population's size.

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1. Introduction

This study investigates if it is possible to explain the areas of forest fires in different countries as functions of factors such as average temperatures and other conditions that differ between nations. These other factors should be available via official statistics and, also, be useful as proxies for capacities of firefighting resources and travel distances between base locations of centralized firefighting resources and typical forest fires. Since forest fires are of key interest in this study, we start with a briefing on recent discoveries and results concerning the development of forest fires. Then, we look at available statistical information. A theoretical model is defined, and hypotheses are created. Later, the hypotheses are tested with statistical analysis. Finally, the developed model is studied, and general results and conclusions are derived.

Some other researchers studied the forests in the western United States of America (Abatzoglou and Williams, 2016). They wrote that human-caused climate change caused over half of the fuel aridity increases since the 1970s and doubled the cumulative forest fire area since 1984. They predicted that anthropogenic climate change would continue to increase the forest fires. Some researchers gave a strong warning for the effects on future forest fires (Coogan et al., 2019). They write that climate-change effects on fire weather may drive the most significant impact on future fire regimes. Fire, weather (i.e., short-term changes in the atmosphere), and climate (i.e., long-term weather patterns in a specific region) are strongly linked, like temperature, wind, precipitation, and atmospheric moisture, among others, are crucial factors driving wildfire activity. Other researchers investigated the period 1972–2018. They indicated that, during this period, California experienced a fivefold increase in the annual burned area, mainly due to more than an eightfold increase in summer forest-fire extent (Williams et al., 2019). They stress that the larger summer forest-fire area very likely occurred due to increased atmospheric aridity caused by warming. Global warming is an understandable effect of the increasing level of CO_2 in the atmosphere (Lohmander, 2020a). He showed how this level could be modeled as a forced differential equation where the forcing is obtained from global emissions. The dynamics of the CO_2 level, and as a consequence, the future climate, can be controlled via emission reductions. However, even with very strong emission reductions, the CO_2 level is predicted to increase during several decades.

Since 2010, the forest fires in a large number of countries have been investigated and documented. Detailed statistical tables have been created and reported (San-Miguel-Ayanz et al., 2019). The tables cover 29 countries during 8 to 9 years and some other countries during shorter periods. In Table 1 central data of particular relevance to this study, are found. The forest areas were obtained from FAO (FAO, 2020). Global warming and average temperatures are important. Populations densities also turn out to be relevant to this study (Cram, 1994; European Commission, 2020; Worldometers, 2020).Some of the particularly interesting findings in Table 1 are the following: The fire areas differ extremely much between different countries. In Russian Federation, the average fire area exceeds 2.2 million hectares and in Estonia, a former Soviet Republic, the corresponding area is just 55 hectares. Of course, the total forest areas are very different in the two countries. For this reason, the relative fire area column has been created and will be the main object of study in this paper. Note that also the relative fire areas differ very much between countries.

Table 1 show that the average relative fire area is in Russian Federation is 0.272%. In Estonia, the corresponding number is 0.002%. Hence, the relative fire area is more than 100 times larger in Russian Federation than in Estonia. However, some countries, particularly in the south, with a warmer climate, have much more dramatic figures: In Portugal, the relative fire area is 4.365 %. Hence, we find that the variations are very large and that climate, including temperature, seems to be a highly important explanation.

For this reason, average temperatures are also included in Table 1. Furthermore, since fires may be well controlled if there are sufficient firefighting resources available, the national populations are also found in Table 1. The population figures are easily available in public statistics and can be used as a proxy for the national firefighting resources. The use of this data source will be demonstrated in the later parts of this paper.

It is a reasonable assumption that higher temperatures can create severe problems, including more dramatic forest fires (Ganteaume et al., 2013). This paper has the ambition to focus on these things. The first main question is if it is likely that global warming, with increasing average temperatures, will lead to more severe forest fires. The second question is how much we should expect forest fires to increase if the average temperature increases by 1, 2, or 3 degrees Celsius (MacDicken, 2015).

Table 1. Empirical background. Sources: The forest areas are the areas reported in FAO, 2020. The fire areas are the average yearly values during the latest 8 or 9 years that are available in the official statistics (San-Miguel-Ayanz et al., 2019). The average relative fire areas are the average fire areas divided by the forest areas. Average temperatures are obtained from Lebanese Economy Forum (2015) (Lebanese Economy Forum, 2015). The populations are retrieved from European Commission (2020) and Worldometers (2020) (European Commission, 2020; Worldometers, 2020).

Country	Forest Area (kha)	Average Fire Area (kha)	Average Relative Fire Area (%)	Average Temperature (Celsius)	Population (M)
Algeria	1949	32.105	1.647	22.5	43.9
Austria	3899	0.072	0.002	6.4	8.9
Bulgaria	3893	5.227	0.134	10.6	7.0
Croatia	1939	12.248	0.632	10.9	4.1
Cyprus	173	1.673	0.967	18.5	0.9
Czech Republic	2677	0.328	0.012	7.6	10.7
Estonia	2438	0.055	0.002	5.1	1.3
Finland	22409	0.519	0.002	1.7	5.5
France	17253	10.906	0.063	10.7	67.1
Germany	11419	0.541	0.005	8.5	83.2
Greece	3902	25.894	0.664	15.4	10.7
Hungary	2053	4.540	0.221	9.8	9.8
Italy	9566	62.286	0.651	13.5	60.2
Latvia	3411	0.591	0.017	5.6	1.9
Lithuania	2201	0.087	0.004	6.2	2.8
Marocco	5742	2.916	0.051	17.1	37.0
North Macedonia	1001	4.433	0.443	9.8	2.1
Norway	12180	0.844	0.007	1.5	5.4
Poland	9483	2.966	0.031	7.9	38.0
Portugal	3312	144.555	4.365	15.2	10.3
Romania	6929	1.757	0.025	8.8	19.3
Russian Federation	815312	2218.100	0.272	-5.1	145.9
Slovakia	1926	0.424	0.022	6.8	5.5
Slovenia	1238	0.283	0.023	8.9	2.1
Spain	18572	95.686	0.515	13.3	47.3
Sweden	27980	5.085	0.018	2.1	10.3
Switzerland	1269	0.116	0.009	5.5	8.6
Turkey	22220	6.885	0.031	11.1	83.2
Ukraine	9690	3.625	0.037	8.3	41.7

Different investigation approaches may be considered. One method is to investigate how forest fires and temperatures have changed during history and to estimate forest fire as a function of temperature. However, the average temperature has changed rather slowly, and a long time series of detailed forest fire statistics is necessary. Such time series data do not usually exist. Furthermore, for a long time, many factors that influence forest fires may have changed, such as firefighting technology, capacity and strategies, infrastructure, forest cover, forestry methods, population size, and so on. Hence, it is not clear that estimated changes in the sizes of forest fires are results of temperature changes (Gerland et al., 2014).

Another approach is to investigate forest fires in a large number of countries with different conditions, including different average temperatures. We create a set of hypotheses that are based on fundamental factors that should explain the forest fires. Then, we try to estimate a function and see if the hypotheses can be rejected. If the function and hypotheses cannot be rejected, we may use the estimated function to answer the questions.

This latter approach has several advantages. If we use several countries in very different climate zones, we get a large variation with respect to the average temperature. This is very important if we want to get a reliable estimate of the effects of temperature on the areas of forest fires. Furthermore, we do not need a very long historical time series. This means that data sources exist and that the data comes from a relevant time period since other conditions that may influence forest fires have not had time to change dramatically. Finally, it is possible to find public, open sources of officially available statistics of high quality that can be used to estimate the functions and test the hypotheses. This is partly because large international organizations such as European Union and FAO exist and have the ambition to develop statistics with common definitions and formats to support international development and cooperation. For these reasons, the later investigation approach is selected.

The empirical data that will be used in this study are reported in Table 1. The data represent relevant conditions in 29 countries in very different climate zones. These countries have observations of fires during at least 8 years in the statistics (San-Miguel-Ayanz et al., 2019). Table 1 shows forest areas, average fire areas, average relative fire areas, average temperatures, and populations. The reader should observe that the conditions differ very much between the countries. In Portugal, as one example, more than 4% of the area burns each year on average. In Austria, Estonia, and Finland, only about 0.002% of the areas burn. Hence, Portugal's average relative fire area is more than 2000 times larger than in the other mentioned countries. Many considerable differences between countries can be observed in Table 1. The analysis in this paper will try to explain most of these differences.

2. Materials and Methods

We will now investigate if a theoretically understandable and reliable mathematical model can be defined, estimated, and empirically tested. The model should predict the average relative forest fire area in a country as a function of explaining factors. These factors should be constructed from the empirically available data.Now, we make the following definitions: A is the total forest area in a country, F is the average area of forest that burns during one year, B denotes the average value of the relative burned forest area during one year (%), T represents the average temperature, and P is the size of the population.

Equation (1) describes how A, F, and B depend on each other.

$$F = \frac{BA}{100} \tag{1}$$

Three statistically testable hypotheses were developed based on the available data. The first hypothesis is that the relative burned area is an increasing function of the average temperature for several reasons. If the average temperature increases, the time period without snow becomes longer. The air can keep more water and the fuel gets dryer. Wind speeds increase as a function of higher temperatures, which means that fires spread more rapidly and that the wind's drying effect increases.

Background to the second hypothesis: With a larger population, a country usually has a larger capacity of firefighting equipment and more firefighters. Furthermore, the amount of infrastructure is usually larger. With a higher firefighting capacity and better infrastructure, fires can be stopped earlier and more efficiently. Hence, we expect that the relative burned area is a decreasing function of the population's size, which may be viewed as a proxy for the national firefighting capacity. This is the second hypothesis.

Background to the third hypothesis: Let us consider a country with a given shape on the map. Assume that the population and the most efficient firefighting resources, such as water-bombing airplanes, are located close to the country's center. Assume that most forest areas are mainly located far away from the center of the country. Draw a straight line from the center of the country to a typical forest area. Denote this distance L. Now, assume that the country's shape remains constant but that every distance is multiplied by N. This means that the area of the country and of the forest is N^2 times larger than before. The distance to the particular forest is now N*L. When firefighting operations take place in remote areas, the average time it takes to send water bombing airplanes or other equipment to fight fires in the forests is approximately proportional to the distance from the initial location of the resources. Hence, it is reasonable to assume that the relative burned area is an increasing function of the total forest area's square root, which is approximately proportional to the time it takes to reach remote areas and fight the fires. This is the third hypothesis. The three hypotheses are found in Table 2.

Table 2. Three hypotheses. The motivations are given in the main text.

Hypothesis	Mathematical Explanation	Explanation in words
H_1	$\frac{dB}{dT} > 0$	The average relative burned area is an increasing function of average temperature.
H_2	$\frac{dB}{dP} < 0$	The average relative burned area is a decreasing function of the population's size, which may be viewed as a proxy for the national firefighting capacity.
H_3	$\frac{dB}{dA} > 0$	The average relative burned area is an increasing function of the total forest area's square root, which is approximately proportional to the time it takes for centrally stationed firefighting resources to move to forest areas to fight the fires.

The following function, equation (2), was defined to test the three hypotheses H_1, H_2, and H_3. In the regression analysis, the parameters (K_0, K_T, K_P, and K_A) are determined.

$$B = e^{(K_0+K_T T+K_P P+K_A\sqrt{A})} \tag{2}$$

In Table 3, we find the units of the explaining variables. Note in particular that the unit of $\sqrt{A}$ is 100 km since the unit of A is M ha (Million ha).

Table 3. Explaining variables, text formats, and units in the estimated regression function.

Explaining variable	Text format	Unit
T	T	Degrees Celsius
P	P	M (Million)
$\sqrt{A}$	SQRT_(A)	100 km

In order to estimate the parameters and test the hypotheses, we take the natural logarithms of both sides of the equation:

$$ln(B) = K_0 + K_T T + K_P P + K_A\sqrt{A} \tag{3}$$

Ordinary multiple regression analysis is used based on function (4). Each observation has an index, i , and a residual ε_i.

$$Y_i = ln(B_i) = K_0 + K_T T_i + K_P P_i + K_A\sqrt{A_i} + \varepsilon_i \tag{4}$$

Ordinary least squares regression analysis with 29 observations was made via Excel software.

3. Results and Discussion

Of course, the estimated model does not explain everything exactly, which means that the Multiple R, estimated to be 0.841, is less than one. (The R square is 0.707, and the adjusted R square is 0.672).

As we see in equation (4), residuals are representing national deviations from the regression line. The standard deviation of these residuals is estimated to be 1.24. These residuals are caused by all possible relevant characteristics of the different nations that are not described via the three factors and different random elements.

In Table 4, we find that all of the three factors under analysis obtained parameter values with very high absolute t-values. Hence, the probabilities that the estimated parameters obtained the incorrect signs are very low, which is clear from the very low P-values. Of particular relevance to the effects of global warming, we can conclude that the probability that an increasing value of the average temperature, T, does not imply an increasing relative fire area is approximately $6 \cdot 10^{-8}$. If the relative fire area increases, the fire area also increases. We note that the estimated degree of certainty is very high: The probability that an increasing average temperature will not increase the fire area is less than one in 10 million.

Table 4. Parameter statistics from the regression analysis based on the logarithmic version of the function in equation (4).

Parameter	Estimated value	Standard Error	t-value	P-value
K_0	-7.556784807	0.649653609	-11.63202159	1.39626E-11
K_T	0.436094188	0.057418758	7.594977775	5.97838E-08
K_P	-0.031821302	0.012207803	-2.606636244	0.015193428
K_A	0.460127404	0.097563843	4.716167264	7.77542E-05

In order to make sure that a functional form describes the empirical data well, it is important to inspect the residual plots in different dimensions. Figs. 1, 2, 3 shows that the estimated function describes the empirical data in a nonbiased manner. It is not possible to find any unexplained nonlinearities. Furthermore, the residuals do not indicate heteroscedasticity.

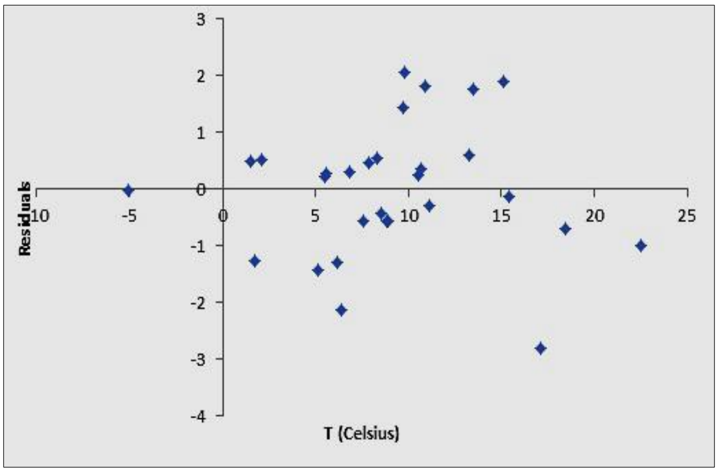

Fig. 1. Residuals from the regression line in equation (4) with T as an independent variable.

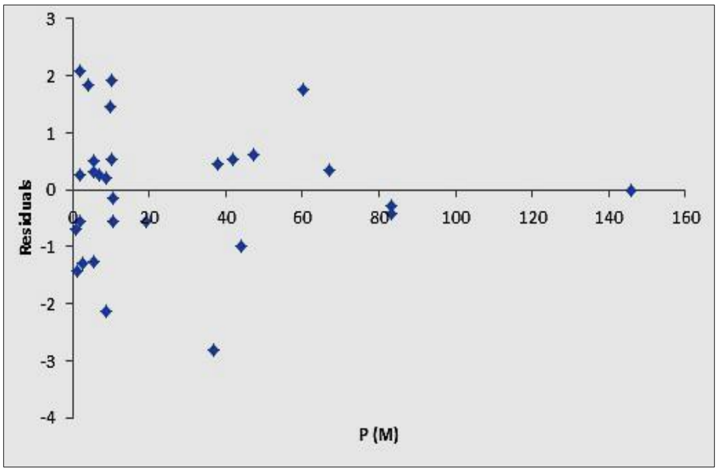

Fig. 2. Residuals from the regression line in equation (4) with P as an independent variable.

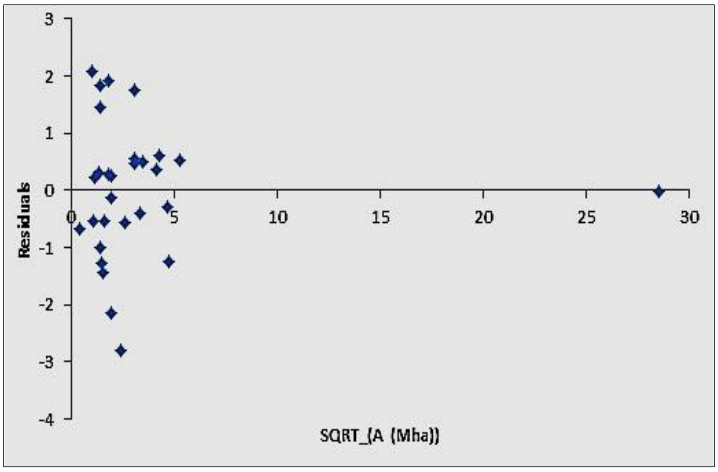

Fig. 3. Residuals from the regression line in equation (4) with $\sqrt{A}$ as an independent variable.

After these analyses, we accept equation (5) as it is. The parameter signs are $K_0 < 0$, $K_T > 0$, $K_P < 0$ and $K_A > 0$. They do not contradict the hypotheses.

$$B_i = e^{K_0 + K_T T_i + K_P P_i + K_A \sqrt{A_i} + \varepsilon_i} \tag{5}$$

Now, when the function has been estimated, it is possible to determine the properties.

3.1. The effect of the average temperature on the relative burned area

First, we determine the derivative of the average relative burned area with respect to the average temperature. This is found in equation (6).

$$\frac{dB}{dT} = K_T e^{K_0 + K_T T + K_P P + K_A \sqrt{A}} \tag{6}$$

Since we know the signs of the parameters, we find that the average relative burned area is a strictly increasing function of the average temperature, as we see in equation (7).

$$\frac{dB}{dT} = K_T B(.) > 0 \tag{7}$$

Equation (8) shows that the average relative burned area increases by approximately 44% per temperature unit (degree Celsius) if the average temperature marginally increases.

$$\frac{\left(\frac{dB}{dT}\right)}{B(.)} = K_T \approx 0.436 \tag{8}$$

However, if the temperature increases by one degree Celsius, this is not exactly a “marginal” increase. Compare equation (9).

$$e^{0.436} \approx 1.5465 \tag{9}$$

Hence, a temperature increase by 1 degree Celsius will increase the average relative burned area by more than 54% (Compare with Fig. 4).

3.2. The effect of the average temperature on the burned area

The average burned area's derivative with respect to the average temperature is strictly positive, as found in equation (10).

$$\frac{dF}{dT} = K_T B(.) A \frac{1}{100} > 0 \tag{10}$$

Equation (11) shows that the average burned area increases by approximately 44% per temperature unit (degree Celsius) if the average temperature marginally increases.

$$\frac{\left(\frac{dF}{dT}\right)}{F} = K_T \approx 436 \tag{11}$$

However, if the temperature increases by one degree Celsius, this is not a “marginal” increase. Hence, a temperature increase by 1 degree Celsius will increase the average burned area by more than 54%. Compare equation (9). The burned area is a strictly convex function of the average temperature. Compare equation (12). It increases with an increasing speed if the average temperature increases (Figs. 4, 5, 6).

$$\frac{d^2F}{dT^2} = (K_T)^2 B(.) A \frac{1}{100} > 0 \tag{12}$$

3.3. The effect of population size on the relative burned area

The average relative burned area's derivative with respect to the population is found in equation (13). This is strictly negative.

$$\frac{dB}{dP} = K_P B(.) < 0 \tag{13}$$

Equation (14) shows that the average relative burned area decreases by approximately 3% if the population's size increases by 1 million people.

$$\frac{\left(\frac{dB}{dP}\right)}{B(.)} = K_P \approx -0.0318 \tag{14}$$

Hence, the relative burned area is a strictly decreasing function of the population size. This is understandable if we assume that the firefighting capacity is a strictly increasing function of the size of the population (Fig. 6).

3.3.1. The effect of the total forest area on the relative burned area

The derivative of the average relative burned area with respect to the total forest area is found in equation (15). This is strictly positive.

$$\frac{dB}{dA} = \frac{1}{2}K_A A^{-\left(\frac{1}{2}\right)} B(.) > 0 \tag{15}$$

Equation (16) shows that the average relative burned area strictly increases if the total forest area's size increases.

$$\frac{\left(\frac{dB}{dA}\right)}{B(.)} = \frac{K_A}{2\sqrt{A}} > 0 \tag{16}$$

The effect of the total forest area on the average relative burned area is clearly seen in Fig. 5.

3.4. The effects of population size on the marginal effect of temperature on the relative burned area

In equations (17) and (18), we note that the derivative of the average relative burned area with respect to the average temperature is a strictly decreasing function of the size of the population.

$$\frac{d^2B}{dTdP} = K_P K_T e^{K_0 + K_T T + K_P P + K_A \sqrt{A}} < 0 \tag{17}$$

$$\frac{d^2B}{dTdP} = K_P K_T B(.) < 0 \tag{18}$$

Hence, if the population is large and the firefighting capacity is high, the average relative burned area is less sensitive to an increasing average temperature. This is also seen in Fig. 6. Equation (19) shows that, if the population is large and the firefighting capacity is high, the average total burned area is less sensitive to an increasing average temperature.

$$\frac{d^2F}{dTdP} = K_P K_T B(.) A \frac{1}{100} < 0 \tag{19}$$

3.5. The effects of the size of the total forest area on the marginal effect of temperature on the relative burned area

In equations (20) and (21), we find that the average relative burned area's derivative with respect to the average temperature is a strictly increasing function of the total forest area.

$$\frac{d^2B}{dTdA} = \frac{1}{2}K_T A^{-\left(\frac{1}{2}\right)} K_T e^{\left(K_0 + K_T T + K_P P + K_A A^{\left(\frac{1}{2}\right)}\right)} > 0 \tag{20}$$

$$\frac{d^2B}{dTdA} = \frac{1}{2}K_A A^{-\left(\frac{1}{2}\right)} K_T B(.) > 0 \tag{21}$$

If the total forest area is large and the distances are long, the average relative burned area is more sensitive to an increasing average temperature (Fig. 5. illustrates this fact). The average total burned area can be expressed as in equation (22).

$$F = e^{\left(K_0 + K_T T + K_P P + K_A A^{\left(\frac{1}{2}\right)}\right)} A \frac{1}{100} \tag{22}$$

The average total burned area's derivative with respect to average temperature is strictly positive, which is found in equation (23).

$$\frac{dF}{dT} = K_T e^{\left(K_0+K_T T+K_P P+K_A A^{\left(\frac{1}{2}\right)}\right)} A \frac{1}{100} > 0 \tag{23}$$

In equations (24) and (25), we see that the average total burned area's derivative with respect to average temperature is a strictly increasing function of the total forest area.

$$\frac{d^2F}{dTdA} = \frac{1}{2} K_A A^{-\left(\frac{1}{2}\right)} K_T B(.) A \frac{1}{100} + K_T B(.) \frac{1}{100} \tag{24}$$

$$\frac{d^2F}{dTdA} = \frac{\left(\frac{1}{2} K_A \sqrt{A} + 1\right) K_T B(.)}{100} > 0 \tag{25}$$

Thus, if the total forest area is large and the distances are long, the total burned area is more sensitive to an increasing average temperature than if the total area is small. In Fig. 4, we see how the average relative burned area is affected by increasing average temperature, according to the estimated function. It is assumed that the total forest area and the size of the population remain constant. The graph clearly shows that the average relative burned area is a strictly increasing and strictly convex function of the average temperature.

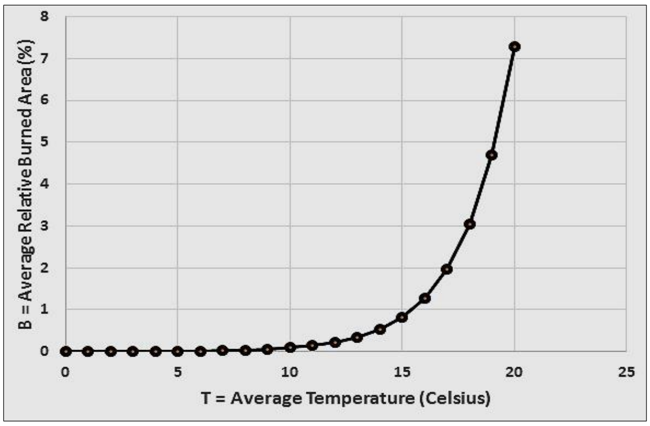

Fig. 4. The average relative burned area, B, as a function of the average temperature, T. A = 10 and P = 20.

Fig. 5 illustrates how the average relative burned area is affected by the average temperature for different forest area levels if the population (and firefighting capacity) remains constant. Note that an increasing average temperature leads to a higher average relative burned area if the total forest area is large. The logic behind this result is that it is more difficult to efficiently fight fires in many remote areas with a given amount of resources.

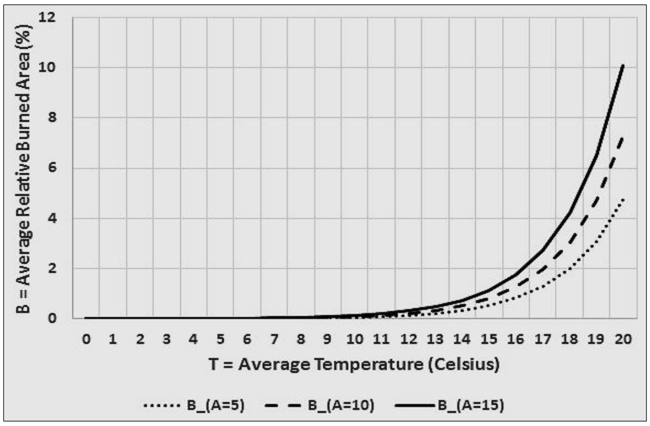

Fig. 5. The average relative burned area, B, as a function of the average temperature, T, for different levels of A. In all cases, P = 20.

Fig. 6 illustrates how the average relative burned area is affected by the average temperature for different levels of the size of the population (and firefighting resources), if the total forest area remains constant. Note that an increasing average temperature leads to a higher level of average relative burned area if the size of the population (and the firefighting capacity) is small. The logic behind this result is that it is more difficult to efficiently fight fires with less firefighting resources.

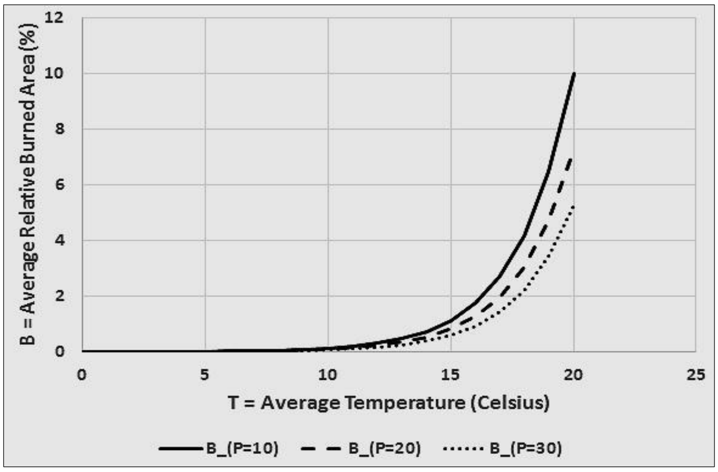

Fig. 6. The average relative burned area, B, as a function of the average temperature, T, for different levels of P. In all cases, A = 10.

3.6. National predictions of climate change consequences

Now the time has come to derive predictions of the sizes of fire areas in the future in the different countries under analysis under the influence of alternative levels of global warming. As we saw above, the average relative burned area increases by approximately 44% per temperature unit (degrees Celsius) if the average temperature marginally increases. If the temperature increases by one degree Celsius, this is not a marginal increase. A temperature increase by 1 degree Celsius will make the relative burned area increase by approximately 54.65%. Compare equation (9). This result will be used in Tables 5 and 6. There, for each of the 29 investigated countries, we find predictions of average relative fire areas and average fire areas, under the influence of alternative levels of change of the average temperatures.

In each country, the average relative fire areas and the fire areas are the same as in Table 1, in case the average temperature does not change at all (dT = 0). The average relative fire areas and the average fire areas are predicted to increase by 54.65 % in case the average temperature increases by 1 (dT = +1) degree Celsius. A repeated procedure gives the corresponding predictions for dT = +2 and dT = +3. Note that all of the predictions in Tables 5 and 6 are based on the model developed in this paper and the assumption that all other conditions in the different countries, such as the total forest areas, the sizes of the population and the national residuals from the estimated equation, remain constant.

Forest fire problems have also in earlier research publications been assumed to be increased by global warming. Several examples of this have been described in the introduction. Studies of forest fires changes have often been made based on statistical time series of fires in some countries or regions. In this paper, however, we studied the influence of temperature on fire, via data from 29 countries. This made it possible to obtain very large variation in the data, including average temperatures and other dimensions of relevance to the fires. Clearly, a warmer climate will most likely increase the problems with forest fires (Tahvonen, 2016).

The question is now what should be done to improve the situation. One obvious strategy is to invest in larger and more efficient firefighting capacity. Such efforts are also made in some countries. This is consistent with the new model results, since the fire area function derived in this paper shows that the fire areas are reduced if the population increases, which means that the firefighting capacity also increases. The derived function also shows that the burned forest area is an increasing function of the total forest area's square root, which can be seen as a proxy for distance from national centers to the forests. With expanded and improved roads and faster and larger water bombing air planes and helicopters, fires can be more rapidly managed, also in remote areas. Such investments are also typical in several countries.

Table 5. Predictions of average relative fire areas as functions of the level of change of the average temperature.

	dT= 0	**dT= +1**	**dT= +2**	**dT= +3**
Country	**Average Relative Fire Area (%)**	**Average Relative Fire Area (%)**	**Average Relative Fire Area (%)**	**Average Relative Fire Area (%)**
Algeria	1.647	2.548	3.940	6.093
Austria	0.002	0.003	0.004	0.007
Bulgaria	0.134	0.208	0.321	0.497
Croatia	0.632	0.977	1.511	2.336
Cyprus	0.967	1.495	2.313	3.576
Czech Republic	0.012	0.019	0.029	0.045
Estonia	0.002	0.004	0.005	0.008
Finland	0.002	0.004	0.006	0.009
France	0.063	0.098	0.151	0.234
Germany	0.005	0.007	0.011	0.018
Greece	0.664	1.026	1.587	2.455
Hungary	0.221	0.342	0.529	0.818
Italy	0.651	1.007	1.557	2.408
Latvia	0.017	0.027	0.041	0.064
Lithuania	0.004	0.006	0.009	0.015
Marocco	0.051	0.079	0.121	0.188
North Macedonia	0.443	0.685	1.059	1.638
Norway	0.007	0.011	0.017	0.026
Poland	0.031	0.048	0.075	0.116
Portugal	4.365	6.750	10.439	16.144
Romania	0.025	0.039	0.061	0.094
Russian Federation	0.272	0.421	0.651	1.006
Slovakia	0.022	0.034	0.053	0.081
Slovenia	0.023	0.035	0.055	0.085
Spain	0.515	0.797	1.232	1.906
Sweden	0.018	0.028	0.043	0.067
Switzerland	0.009	0.014	0.022	0.034
Turkey	0.031	0.048	0.074	0.115
Ukraine	0.037	0.058	0.089	0.138

Since the increasing temperatures drive the fire problems to a large extent, a key question is how global warming can be avoided or at least reduced. For this reason, a number of forest management solutions was suggest for mitigating climate change in the United States (Malmsheimer et al., 2008). They indicated that forests and forest products can prevent greenhouse gas emissions through wood substitution, biomass substitution, modifications of wild-fire behavior, and avoided land-use change. Other research formally proves that increasing use of forest raw materials, substituting fossil fuels in combination with an expanding area of actively managed forests, is a rational way to handle the greenhouse gas problem (Lohmander, 2020b). These effects have also been derived and described via a differential function of the CO_2 concentration in the atmosphere, with a forcing function representing fossil emissions that could be adjusted to represent increasing forest area management (Lohmander, 2020c). However, irrespective of the selected CO_2 control strategy, the CO_2 level and global warming are predicted to continue to increase for several decades. The author suggests that climate change and fire problems are more intensively investigated. The optimal combination of different methods to handle and control these global key problems must soon be determined if we should all avoid a very difficult future.

Table 6. Predictions of average fire areas as functions of the level of change of the average temperature.

	dT= 0	**dT= +1**	**dT= +2**	**dT= +3**
Country	**Average Fire Area (kha)**	**Average Fire Area (kha)**	**Average Fire Area (kha)**	**Average Fire Area (kha)**
Algeria	32.105	49,651	76,786	118.750
Austria	0.072	0.111	0.171	0.265
Bulgaria	5.227	8.084	12.502	19.334
Croatia	12.248	18.942	29.293	45.303
Cyprus	1.673	2.587	4.001	6.187
Czech Republic	0.328	0.507	0.784	1.213
Estonia	0.055	0.086	0.132	0.205
Finland	0.519	0.802	1.241	1.919
France	10.906	16.867	26.084	40.340
Germany	0.541	0.837	1.294	2.002
Greece	25.894	40.046	61.931	95.778
Hungary	4.540	7.022	10.859	16.794
Italy	62.286	96.326	148.970	230.383
Latvia	0.591	0.913	1.413	2.185
Lithuania	0.087	0.134	0.208	0.321
Morocco	2.916	4.510	6.974	10.786
North Macedonia	4.433	6.856	10.603	16.398
Norway	0.844	1.306	2.019	3.123
Poland	2.966	4.588	7.095	10.972
Portugal	144.555	223.555	345.730	534.674
Romania	1.757	2.717	4.201	6.497
Russian Fed.	2218.100	3430.311	5305.007	8204.239
Slovakia	0.424	0.655	1.013	1.567
Slovenia	0.283	0.438	0.678	1.048
Spain	95.686	147.979	228.851	353.921
Sweden	5.085	7.864	12.162	18.809
Switzerland	0.116	0.180	0.278	0.429
Turkey	6.885	10.648	16.468	25.468
Ukraine	3.625	5.606	8.670	13.408

4. Conclusions

a) The areas of forest fires in different countries can be explained via a function based on fundamental factors. The function has been empirically estimated and tested based on detailed data from 29 countries and the level of reliability is very high.

b) The forest fire area, divided by the total forest area, increases with the average temperature and the size of the total forest area. The ratio decreases with the size of the population, which is a proxy for the national firefighting capacity.

c) The estimated model predicts that global warming will increase the areas of forest fires. The future developments of expected forest fire areas in 29 countries have been predicted for alternative global warming levels.

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Appendix

Table A1. Excel file used in the multivariate regression analysis.

Country	**B (%)**	**LN (B(%))**	**T (Celsius)**	**P (M)**	**SQRT (A (Mha))**
Algeria	1.64726783	0.499118055	22.5	43.942956	1.396065901
Austria	0.001838078	-6.299034743	6.35	8.901064	1.974588565
Bulgaria	0.134269487	-2.007906405	10.55	6.951482	1.973068676
Croatia	0.631665807	-0.459394811	10.9	4.058165	1.392479802
Cyprus	0.966923571	-0.033635824	18.45	0.888005	0.415932687
Czech Republic	0.012248371	-4.402362339	7.55	10.693939	1.636154027
Estonia	0.002271329	-6.087390175	5.1	1.328976	1.56140962
Finland	0.002315042	-6.068327418	1.7	5.525292	4.73381453
France	0.063213483	-2.761237662	10.7	67.098824	4.153673073
Germany	0.004739664	-5.35178905	8.5	83.166711	3.379201089
Greece	0.663619796	-0.41004589	15.4	10.709739	1.975348071
Hungary	0.221156032	-1.5088868	9.75	9.769526	1.432829369
Italy	0.651122029	-0.429058205	13.45	60.244639	3.092895084
Latvia	0.017316525	-4.056094033	5.6	1.907675	1.846889277
Lithuania	0.003945176	-5.535261602	6.2	2.79409	1.483576759
Morocco	0.050785634	-2.980141757	17.1	36.960921	2.396247066
North Macedonia	0.442901543	-0.814407784	9.8	2.076255	1.000499875
Norway	0.006931217	-4.971719878	1.5	5.36758	3.489985673
Poland	0.031281709	-3.464721736	7.85	37.958138	3.079448002
Portugal	4.364573269	1.473520423	15.15	10.295909	1.819890107
Romania	0.02535078	-3.674945775	8.8	19.317984	2.632299375
Russian Fed.	0.272055376	-1.301749646	-5.1	145.941556	28.55366877
Slovakia	0.021991462	-3.817100998	6.8	5.457873	1.387804021
Slovenia	0.022895351	-3.776821405	8.9	2.095861	1.112654484
Spain	0.515217053	-0.663167005	13.3	47.329981	4.309524336
Sweden	0.01817449	-4.007736332	2.1	10.327589	5,289612462
Switzerland	0.009149812	-4.694021974	5.5	8.606033	1.126499001
Turkey	0.030987599	-3.474168195	11.1	83.154997	4.7138095
Ukraine	0.037410847	-3.28579458	8.3	41.732779	3.112876483

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