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Spatio-Temporal Dynamics of Forest Fires in Poland and Consequences for Fire Protection Systems: Seeking a Balance between Efficiency and Costs

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Abstract: An important issue from the forest fire protection system perspective is forecasting fires and maintaining a high readiness of firefighting units at a low cost. In Poland, the level of fire protection is defined by the degree of forest fire risk, based on forecasts made for 1 March to 30 September, i.e., the risk period (the so-called fire season). In this paper, based on classical statistical and spatial analysis, we positively verify the research hypothesis that the fire season in Poland changes in terms of start and end dates depending on the region. We therefore propose a modification to the forecasting period, adapted to local conditions and calculated annually on the basis of the previous period. Then, using network analysis, we negatively verify the hypothesis that the size of the burned area is related to the distance from fire brigades, which proves that the reasons for such a differentiation in the number of fires should be sought elsewhere than in the system used for allocating fire units. On the basis of cluster analysis, attention is drawn to areas where large fires break out more often.

Keywords: spatio-temporal analysis; wildfires; forest fires; seasonality; fire protection; Poland; sustainability

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1. Introduction

Forest fires affect almost every European country [1], and although the fire regime mainly affects the countries of the Mediterranean region (in terms of both the number of fires and the size of the area burned), the problem itself is widespread [2]. Every year, fires destroy large forest areas in various European countries—for example, in Bulgaria, an average of over 10,500 hectares is burned per year [3]. According to European reports [1], in the 2008 to 2017 period, the number of annual forests fires ranged from 91 (Slovenia) to almost 19,000 (Portugal), and the size of the burned area ranged from 72 ha (Austria) to 136,000 hectares (Portugal) per year. The annual average for all European countries is almost 2500 fires, covering a total area of over 15,500 hectares. The region of southwestern Europe is the most vulnerable to fires, with most fires breaking out in the Iberian Peninsula and Italy. However, Poland also has a large number of forest fires. When it comes to burned area, the countries of the Mediterranean basin are still the leaders, while Poland has nearly the lowest average area burned per fire (Figure 1). In Poland, relatively small burned areas are recorded [4]. The effect of scale (i.e., a large number of fires) presents a threat and challenge to Polish fire protection. At the same time, Poland is the region with the largest concentration of event hotspots related to drought conditions and fires [5], and climate models predict a significant increase in the risk of fire events in the future [6].

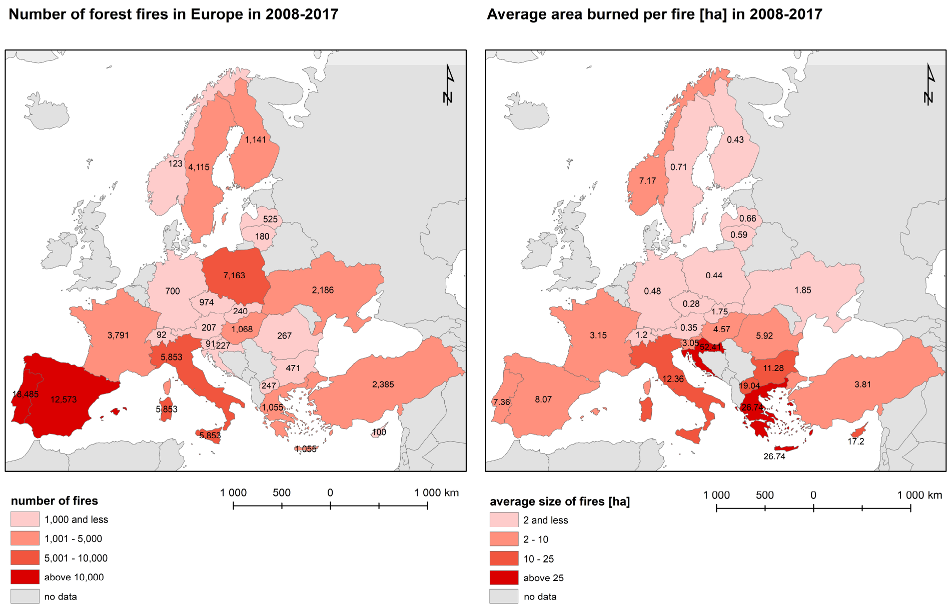

Figure 1. Number of forest fires (**left** map) and sum of area burned (**right** map) in Europe from 2008 to 2017.

At the same time, there is temporal and spatial differentiation in the number of forest fires, resulting from changing fire regimes. In the Czech Republic, the largest number of fires occurs in spring (April, May) and summer (July to August) [7,8]. Summer is the most dangerous period in Greece, as most fires occur in July and August [9]. In Spain, there are different fire peaks depending on the region [10]. For example, most of the fires in Galicia in the years 2001 to 2006 occurred between February and the first half of October, while in Asturias, the second half of October is an important period for fires. The fire regime is thus different in the two regions. In both cases, there are two fire peaks, one in March and the other in summer. However, in Asturias, the March peak is more important than the summer peak, while in Galicia, the summer peak is the most important [10]. The existence of this regional variability complicates effective forest fire forecasting.

The results of research conducted in Finland [11] suggest that in the case of continental boreal forests, the number of large fires may double or even triple over the course of this century. This would increase the risk of occurrence of large-area fires, which have almost been eliminated in Finland thanks to active and effective efforts. Attention has been drawn to the projected increase in the number of large fires in the summer months as a result of drought [12] and the changing characteristics of forest fires [13].

The decrease in the number of fires in the Mediterranean region reported by some [14] is explained by more effective firefighting and more efficient crisis management. This shows how important prevention is in reducing major damage to property, lives, and the environment.

Poland's fire protection system consists of three components: detection, firefighting, and forecasting [15]. Forest fire protection is adapted to the categories (KZPL) and degrees (SZPL) of forest fire risk. KZPL is a relatively permanent component; it includes forests with a similar level of susceptibility to fire, established over 10 years based on climatic conditions, tree stand conditions (age, habitat type, species), and anthropogenic factors. SZPL is a dynamic element indicating the probability of a fire's occurrence on a given day, depending on dynamic weather changes and litter moisture (measured twice a day). It is important to notice that SZPL is defined only in the fire season, i.e., from March 1 (or when the snow cover disappears) to 30 September [15].

KZPL and SZPL each have four categories: high risk, medium risk, low risk, no risk. Depending on the KZPL and SZPL risk categories, the regulations [15] specify observation strategies and methods, preventive actions (e.g., guidelines for creating firebreaks), and protocols for equipping units with firefighting equipment and taking additional actions (e.g., bans on access to forests). For areas with the highest KZPL, observation is required to ensure early detection of fire, notification of its occurrence, and the initiation of rescue operations [15].

During the fire season (from 1 March to 30 September), depending on the degree of a forest fire risk, calculated daily, decisions are made regarding the tasks to perform and protective measures to be implemented by the State Forests, e.g., ground patrols in particularly vulnerable regions, launching of air patrols, ensuring a degree of readiness to use firefighting equipment, and shortening the take-off time for firefighting aircraft [16]. Fire detection and firefighting are at high levels in terms of automation, procedures, and their effectiveness.

Keeping the system at a high level of readiness is associated with high costs, so it is important to maintain system efficiency and be able to react quickly to fire outbreaks while keeping costs as low as possible. Therefore, the question arises whether the adoption of the current fire season time interval corresponds to the actual frequency distribution of fires during the year. An additional but equally important issue is the recognition of spatial and temporal patterns of fire occurrence, as it can be suspected that the territorial extent of and variability in Poland's environmental conditions may determine the differences between individual regions. Recognizing the dynamics and spatial structure of fires will make it possible to concentrate firefighting efforts more effectively and, perhaps, to modify the period of readiness to match local conditions. Therefore, we formulated a research hypothesis that the fire season in Poland varies between different regions of the country in terms of its start and end dates and its duration. The aim of this work is therefore to propose a universal method for determining the local fire season and to recommend its use in order to involve formal resources at the lowest possible cost in order to prevent forest fires in the most effective way.

Recognition of the fire regime, also in terms of the size of the burned area, is a key aspect of this approach. Poland, as mentioned previously, is distinguished by a large number of fires, but with a relatively small burned area. Since any small fire can, under the right circumstances, turn into a large fire, potential causes must be considered when interpreting the results. In this paper, we consider one of the possible reasons for this trend, which is directly related to the effectiveness of the fire protection system. We do not discuss the causes behind the large number of fires (this requires additional studies), but we do consider the small size of the area burned in these fires. We hypothesize that small fires testify to the effectiveness of the fire detection and firefighting system, so we claim that the size of the burned area depends on the distance from fire brigade units. Positive verification of this hypothesis would make it necessary to pay special attention to areas with extended response times from firefighting services. Negative verification requires paying more attention to environmental conditions (including weather and habitat conditions) and to take them into account in the fire hazard forecasting system.

2. Materials and Methods

2.1. Data Acquisition and Preparation

Fire data come from the National Forest Fire Information System (NFFIS) from the 2007 to 2017 period in the form of point shapefiles, including the date, coordinates, type of fire, possible fire cause, fire duration, and area burned. These sets of information come directly from firefighters' reports [4]. This approach is more accurate than data from satellites, which, due to their spatial resolution, are not able to register all fires, especially small ones. In the case of Poland, data from MODIS satellites (more precisely: MODIS/Aqua+Terra Thermal Anomalies/Fire locations 1 km FIRMS V0061 NRT; MODIS 2023) recorded 9984 fire incidents in the 2007–2017 period; in the same period, there were 44,670 fires registered by Polish firefighters. It is clearly apparent that the MODIS data do not include all fire incidents. Analyses of the occurrence of fires based on point data were previously carried out, among other studies, in Italy [17]. The first step of the analysis was to clean the data of mistakes and errors, and any further analyses were performed on a reduced set of data.

Road data (line shapefiles, representing all public road networks in the country) were obtained from the Head Office of Geodesy and Cartography, Poland.

In order to verify the two formulated research hypotheses, methods of classical and spatial statistics and network analysis were used.

2.2. Statistical Analysis

In order to check the time variability, basic descriptive statistics [4] were calculated: number of fires and size of burned area in individual years and periods of the year, as well as broken down by voivodeships (the highest level of administrative division in Poland). In this paper, the year is divided into quarters: Quarter I (Q1)—01.01–31.03; Quarter II (Q2)—01.04–30.06; Quarter III (Q3)—01.07–30.09; and Quarter IV (Q4)—01.10–31.12. We are aware that such a division is quite arbitrary, but it allows us to refer to the fire protection system currently existing in Poland, and therefore draw conclusions on whether and how the system should be modified to more effectively reduce the number of fires breaking out.

Fires were divided into three arbitrarily determined size classes: small (up to 0.5 ha), medium (with an area of at least 0.5 ha and up to 5 ha), and large (5 ha and above). Then, the distribution of these size classes in the individual quarters was checked. Particular attention was paid to large fires as the greatest potential threat to people and property.

The key issue when proposing modifications to the fire forecasting period is finding the balance between the costs associated with the increased level of firefighting units' readiness and the benefits from extending the period during which this readiness is maintained. The approach we propose is based on determining the percentage of fires (based on percentile values), taking into account the actual jump in the number of fires during the season. Based on data from the 2007–2017 period, we considered three percentile ranges to determine the fire season: 5–95 (90% of fires), 2.5–97.5 (95% of fires), and 1–99 (98% of fires).

The study of spatial distribution was performed using Getis-Ord local statistics. The local Getis-Ord Gi statistic [18,19] allows the detection of a local concentration of high and low values (in this case, the size of the burned area) in neighboring objects (fire points) and reveals the statistical significance of that dependence. The analysis was performed using the inverse distance method, with a default distance threshold.

2.3. Network Analysis

Network analyses in GIS can be successfully used to determine the shortest path between fires and fire brigades. The road network model and the representation of units and fires as points enable the simulation of the route from the fire units to the location of the fires. This type of analysis is used in the study of optimal routes in many areas of life. For example, [20–22] studied the shortest possible routes to medical facilities from accident sites, ref. [23] analyzed the optimal routes for transporting timber between designated points, and [24] analyzed the optimal routes between fire locations and Cologne's fire departments. Network analyses were also used by [25–27], and their research aimed to determine the most optimal transport routes. Therefore, there have been many applications of network analyses to determine the shortest possible paths. The most common problems associated with network analyses are related to determining the path passing through given points. To a lesser extent, spatial dependencies between two groups of places are described in the literature, such as occurrences of incidents (fires) and the location of the facilities (fire units). Among the works listed, the analyses by [20,21,27] were based on such assumptions. The studies clearly defined the locations of incidents and objects between which the shortest routes had to be established, with the closest facility to be chosen for each incident. Multiple incidents could be assigned to one facility. This approach was also used in this work. The Network Analyst extension in ArcMap 10.7.1 software [28] was used to perform the analysis. Before starting the actual analyses, points (fires) were moved to the road network in such a way that the shift disturbed the actual situation as little as possible (the Near tool was used for this purpose). The next step was to create a geodatabase and a network file consisting of shifted points and polylines (routes between fires and fire stations) and verify the correctness of the topology. The New Closest Facility tool was used to calculate the distance between each pair of points: the fire and the nearest fire station.

On the basis of consultations with firefighters, the only administrative barriers to the movement of fire units were considered to be the borders of the voivodeships, which results from the accepted practice of dispatching units for fires within the same administrative units. In each province, the distances between fires and the nearest fire station were calculated (by road, based on BDOT10k [29], additionally verified with Open Street Map data when connecting isolated road sections). An example network for the Opolskie voivodeship (SW Poland) is shown in Figure 2. Then, the burned area and the distance to the nearest fire station were correlated (using Spearman's correlation).

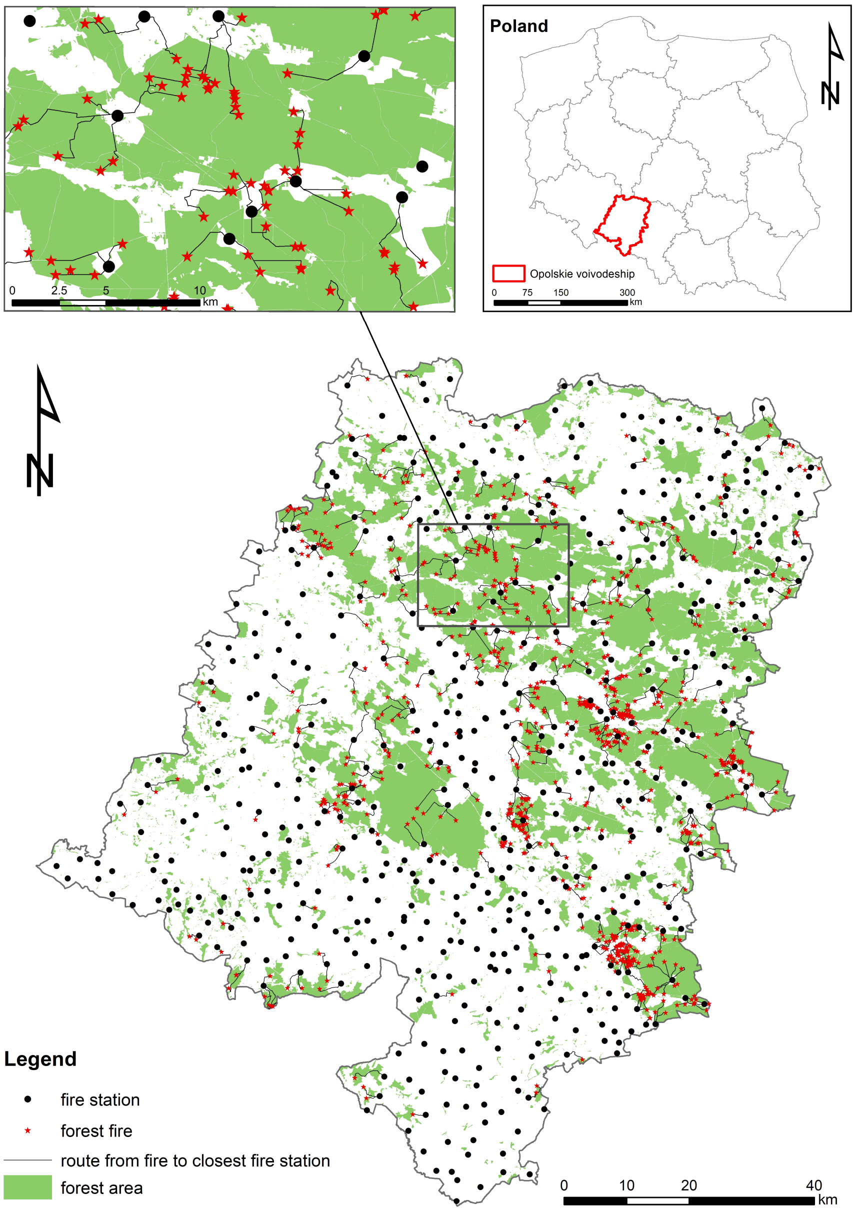

Figure 2. Road network connecting forest fires with the nearest fire station in Opolskie voivodeship, Poland. Upper maps: Poland divided by voivodeships (**right** map), a close-up of a sample fragment of the network (**left** map).

Spatial analyses were performed in ArcMap software 10.7.1 [28]. Calculations and visualizations were made using spreadsheets (OpenOffice) and the R program. Maps were made in ArcMap 10.7 and CorelDraw v. 24.

3. Results

3.1. Variation in the Number of Fires and Size of Burned Area over Time

The number of forest fires breaking out in individual years in Poland varied. The total annual number of forest fires in the 2007 to 2017 period oscillated between 2094 and 7476 (average 4051.8, which was significantly increased by the large number of fires in 2015), and the sum of the burned area ranged from 667.23 ha to 4373.85 ha (average 1833.8 ha). Most fires broke out in Q2 and Q3, respectively, and the fewest broke out in Q4 (Figure 3).

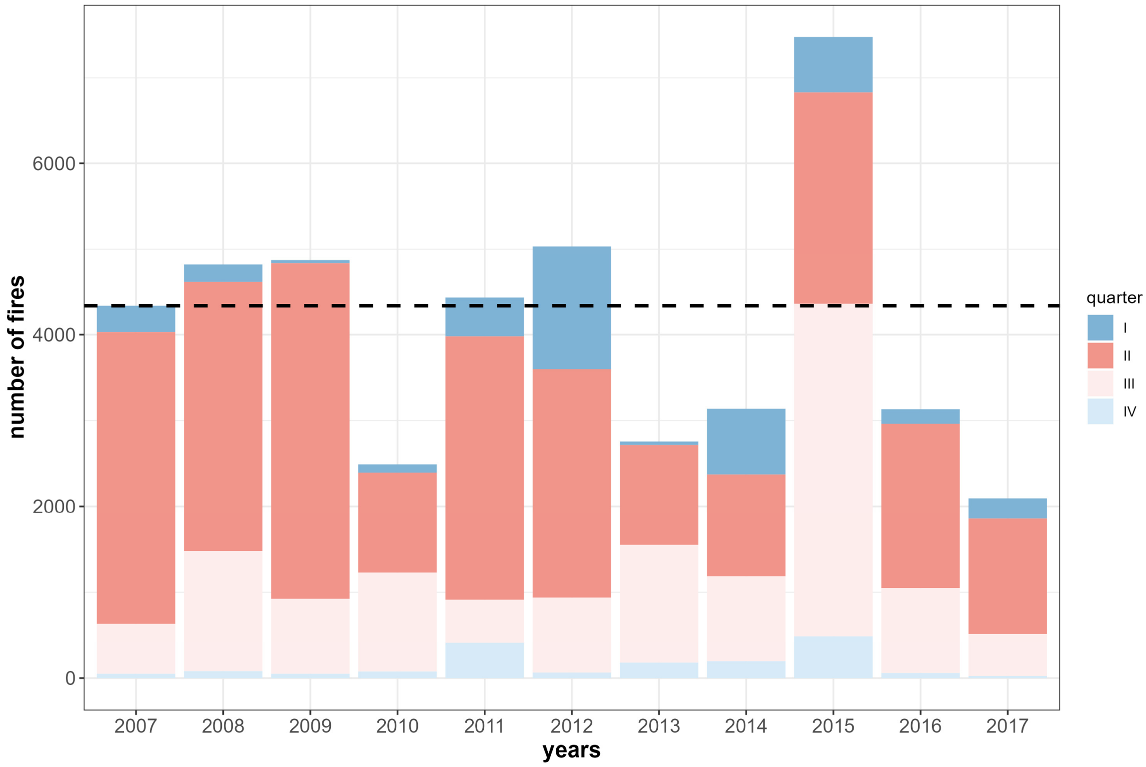

Figure 3. Number of forest fires in the 2007 to 2017 period (divided into quarters). The dotted line shows the median number of fires in the period.

The spring and summer periods (Q2 and Q3) usually had the most fires (57% of the total fires in the 2007 to 2017 period occurred in Q2, 29% in Q3; in Q1, it was 10% and in Q4, 4%). However, if we look at the size of the burned area, we notice that while in Q2 the largest total forest area was burned (51%), Q1 (26%) came second, followed by Q3 (19%), and finally Q4 (3%). In the years 2007 to 2017, approximately 13% of fires broke out in the autumn and winter periods (Q4–Q1) and approximately 29% of the area burned down during these quarters.

The trendlines (linear function) between the size of the burned area and the number of fires in individual years (Figure 4) show that the relation in Q1 has the highest slope, about twice as high as in the case of other quarters. In addition, in Q1, the best matching of the trendline to the points is observed (i.e., the smallest dispersion of values in relation to the estimated equation). The increase in the number of fires in Q1 resulted in a two- to threefold increase in the relative burned area.

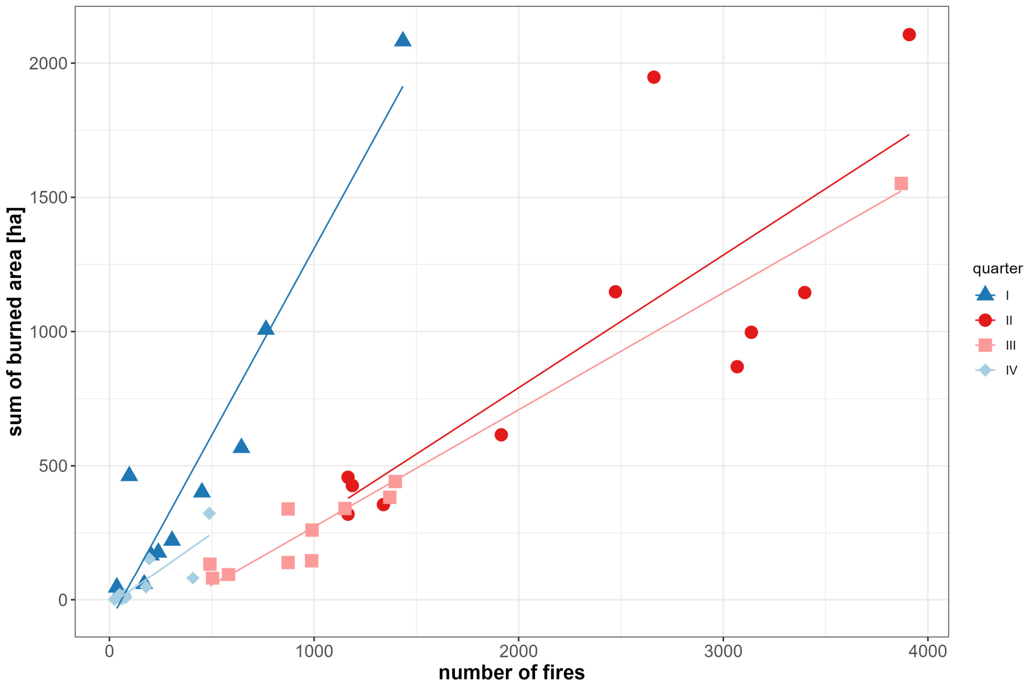

Figure 4. The relationship between number of fires and burned area in the 2007 to 2017 period for each quarter.

Overall, the burned areas of almost 55% of fires in the 2007 to 2017 period were smaller than 0.1 ha, and 80% were smaller than 0.5 ha. Fires with a burned area of at least one hectare accounted for a total of 9.8% of fires, among which fires with an area of at least five hectares accounted for 1.3% of the total (Table 1).

Table 1. Frequency of small, medium, and large forest fires. Q1–Q4—quarters.

Fire Size Class	Burned Area (ha)	Frequency in Quarters				Frequency	% of Overall Frequency
		Q1	Q2	Q3	Q4		
Small	<0.1	1504	12,834	7692	1166	23,196	54.45
	≥0.1–<0.2	408	2896	1379	159	4842	11.37
	≥0.2–<0.5	704	3639	1640	150	6133	14.40
Medium	≥0.5–<1	619	2412	1031	101	4163	9.77
	≥1–<5	801	2042	768	85	3696	8.88
Large	≥5–<20	179	232	80	9	500	1.17
	≥20–<100	33	21	8	2	64	0.15
	≥100	1	4	0	2	7	0.02
		4249	24,080	12,598	1674	SUM: 42,601	

The 213 largest fires (those over 5 ha) broke out in the period between 1 January and 31 March (37.3% of all fires of this size). In Q2 and Q3, 257 (45%) and 88 (15.4%) large-area fires broke out, respectively. Q4 saw 13 large-area fires (less than 2.3%). Thus, large fires that broke out at the beginning of the year accounted for quite a large percentage of the total number (Table 1).

The average size of the area burned during an individual fire event was the largest in Q1, with values between 0.7 and 3 ha. These differences are two to four times greater than those in the remaining quarters (Figure 5), where this value is usually below 0.5 ha.

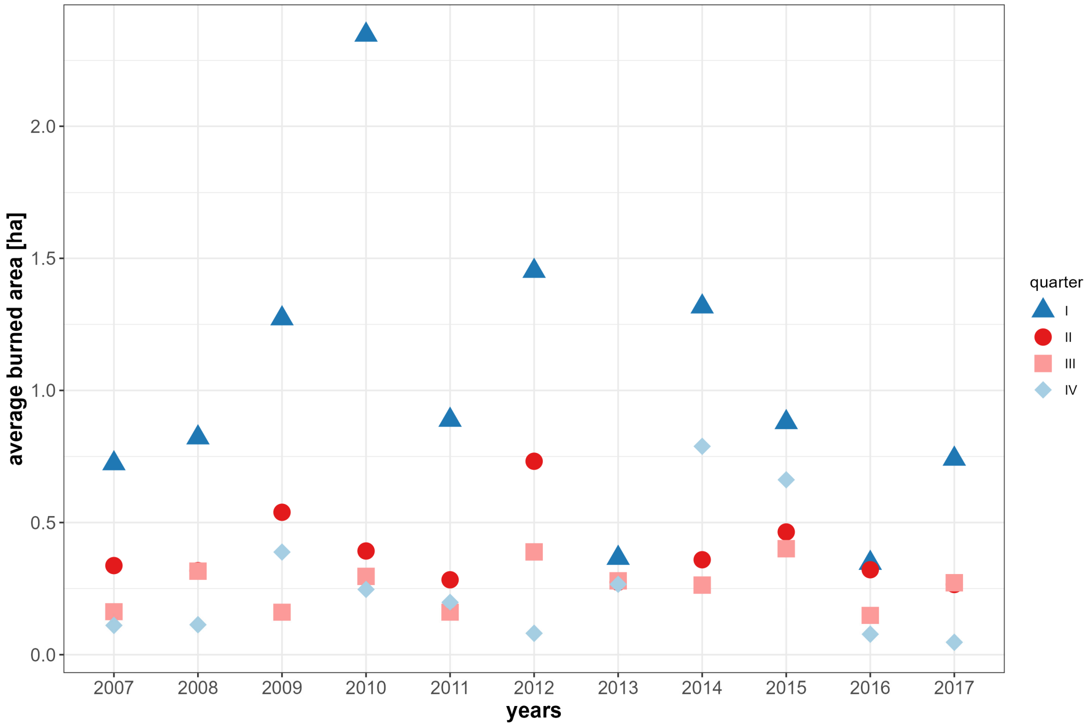

Figure 5. Average area burned in particular quarters and years.

3.2. Spatial Variation in the Number of Fires and Size of Burned Area

Both in terms of the size (Figure 6) and the number of fires (Figure 7), one can see differences between individual voivodeships. The largest number of fires in each of the voivodeships broke out in Q2 and Q3, while in terms of burned area, the results are already slightly different—in the Warmińsko–Mazurskie voivodeship (W-M; NE Poland), the largest values were recorded in the autumn and winter quarters. In addition, a relatively large total burned area was observed in Q1 in several other voivodeships—Dolnośląskie (DŚ; SW Poland), Świętokrzyskie (ŚW), and Podkarpackie (PODK; SE Poland). By far the largest areas burned as a result of forest fires were in the southeastern and central regions of the country.

3.3. Determination of the Fire Season

With the most restrictive approach (covering 98% of fires), the fire season for all of Poland should start in week 10 (currently, it is in the middle of week 9) and end in week 44 (the current end date is week 40). With the most liberal approach (covering 90% of fires), these dates will be weeks 12 and 39, respectively. With a moderate approach (covering 95% of fires), the fire season should start in week 11 and end in week 41 (Figure 8).

Based on the histograms for individual voivodeships, it can be concluded that although the fire frequency distribution looks slightly different, for most regions, the largest increase in the value at the beginning of the season takes place when the reference threshold for determining the fire season is taken as 98% of fires (Figure 9). The fall in the value at the end of the season usually occurs in the week when the number of fires reaches 90 or 95% of the total number and depends on the voivodeship. In half of the voivodeships (i.e., eight), in the case of the most restrictive approach (98% of fires), the start of the season falls in the 9th week (similarly to the current forecasting period), but in four voivodeships, it is the 11th week, and in two voivodeships, it is week 8 and week 10.

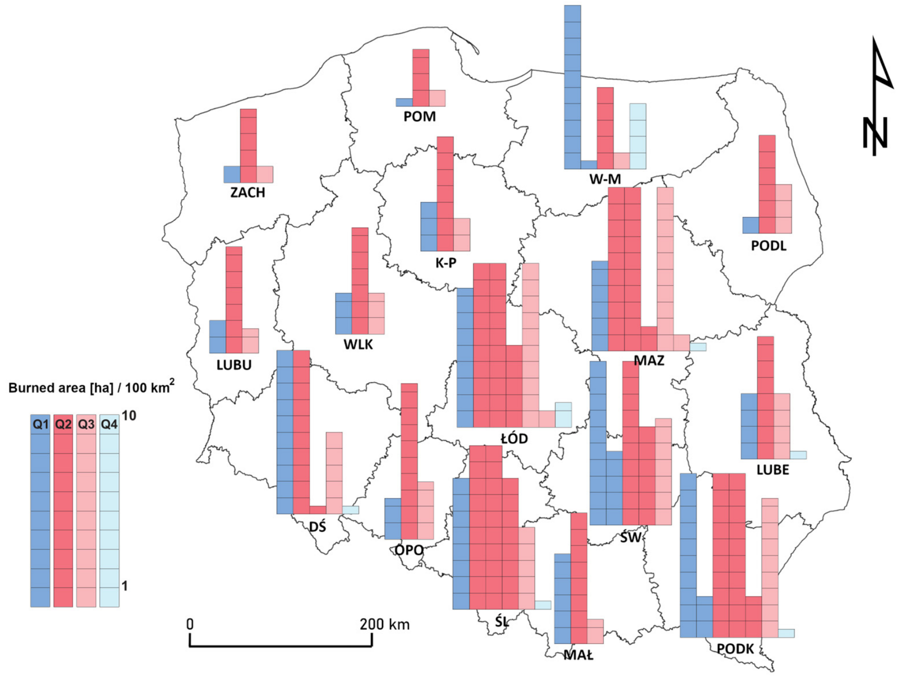

Figure 6. Burned area per 100 km^2 of forest in individual quarters of the year (Q1 to Q4) by voivodeship (data for the 2007 to 2017 period). One square = 1 hectare of burned area. Abbreviations refer to the names of voivodeships: DŚ—Dolnośląskie; K-P—Kujawsko–Pomorskie; LUBE—Lubelskie; LUBU—Lubuskie; ŁÓD—Łódzkie; MAŁ—Małopolskie; MAZ—Mazowieckie; OPO—Opolskie; PODK—Podkarpackie; PODL—Podlaskie; POM—Pomorskie; ŚL—Śląskie; ŚW—Świętokrzyskie; W-M—Warmińsko–Mazurskie; WLK—Wielkopolskie; ZACH—Zachodniopomorskie.

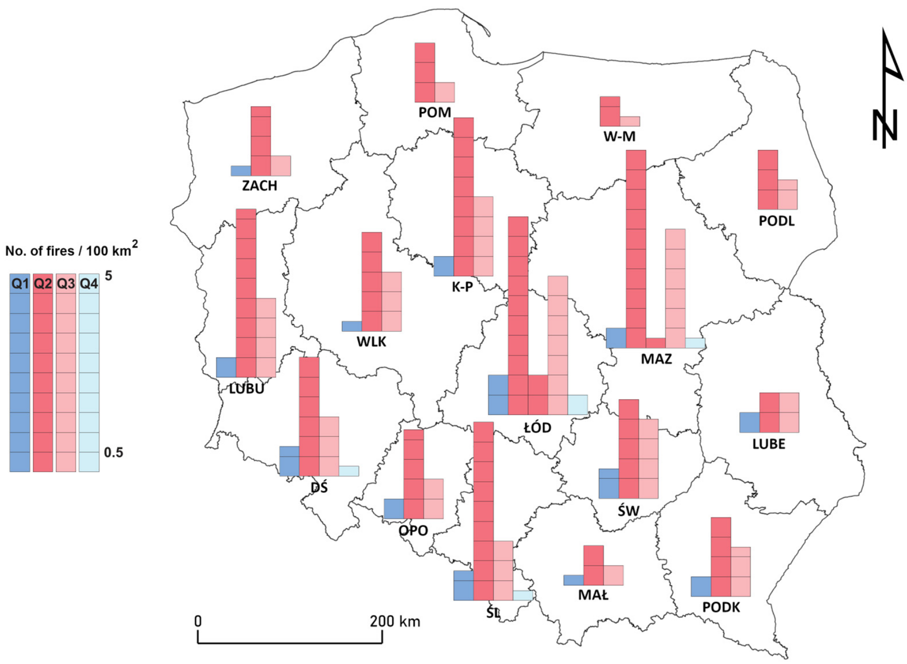

Figure 7. Number of fires per 100 km^2 of forest area in individual quarters of the year (Q1 to Q4) by voivodeship (data for the 2007 to 2017 period). One square = 0.5 fire. Abbreviations refer to the names of voivodeships: DŚ—Dolnośląskie; K-P—Kujawsko–Pomorskie; LUBE—Lubelskie; LUBU—Lubuskie; ŁÓD—Łódzkie; MAŁ—Małopolskie; MAZ—Mazowieckie; OPO—Opolskie; PODK—Podkarpackie; PODL—Podlaskie; POM—Pomorskie; ŚL—Śląskie; ŚW—Świętokrzyskie; W-M—Warmińsko–Mazurskie; WLK—Wielkopolskie; ZACH—Zachodniopomorskie.

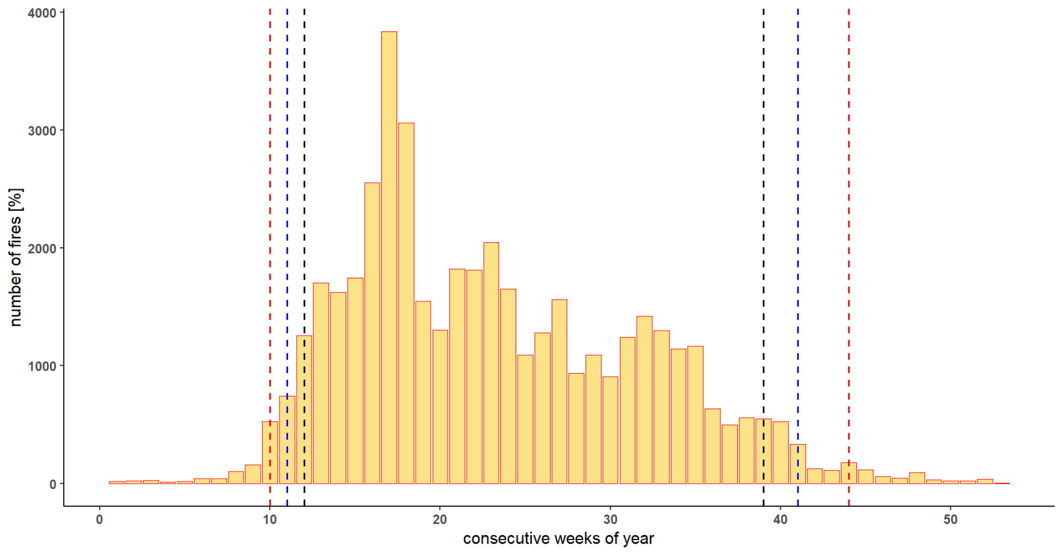

Figure 8. Frequency of forest fires in Poland in individual weeks of the year (data for the 2007 to 2017 period). The vertical lines (respectively, black, blue, red) define the range of 90, 95, and 98% of the total number of fires.

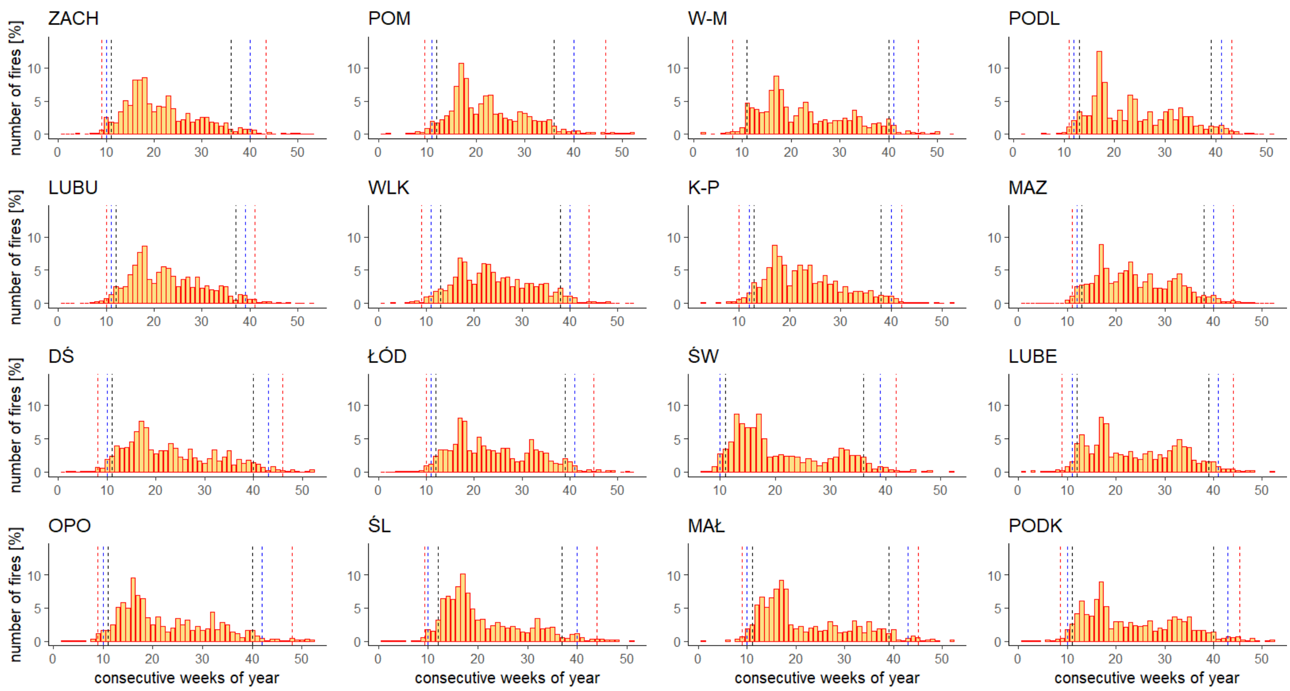

Figure 9. Frequency of forest fires in voivodeships in Poland in individual weeks of the year (data for the period 2007 to 2017). The vertical lines (black, blue, and red, respectively) represent 90, 95 and 98% of the total number of fires. The charts for individual voivodeships are consistent with their topological relation to each other. Abbreviations refer to the names of voivodeships: DŚ—Dolnośląskie; K-P—Kujawsko–Pomorskie; LUBE—Lubelskie; LUBU—Lubuskie; ŁÓD—Łódzkie; MAŁ—Małopolskie; MAZ—Mazowieckie; OPO—Opolskie; PODK—Podkarpackie; PODL—Podlaskie; POM—Pomorskie; ŚL—Śląskie; ŚW—Świętokrzyskie; W-M—Warmińsko–Mazurskie; WLK—Wielkopolskie; ZACH—Zachodniopomorskie.

3.4. Distribution of the Largest Fires

The fewest hotspots were reported in 2010, the year in which there were the fewest fires (slightly more than 2000, with the annual average for the whole period at the level of 4052). The remaining years with fewer hotspots were usually also years with numbers of fires below the annual average (2013, 2014, 2016, 2017). However, this is not a strict relationship, as the number of hotspots was also low in the extremely fire-prone year of 2015, during which almost 7500 fires broke out. Regardless of this, there is a clear spatial trend in the distribution of large fires. Large burned areas occurred mainly in the southeastern part of the country, and this tendency was maintained in most years of the analyzed period (Figure 10).

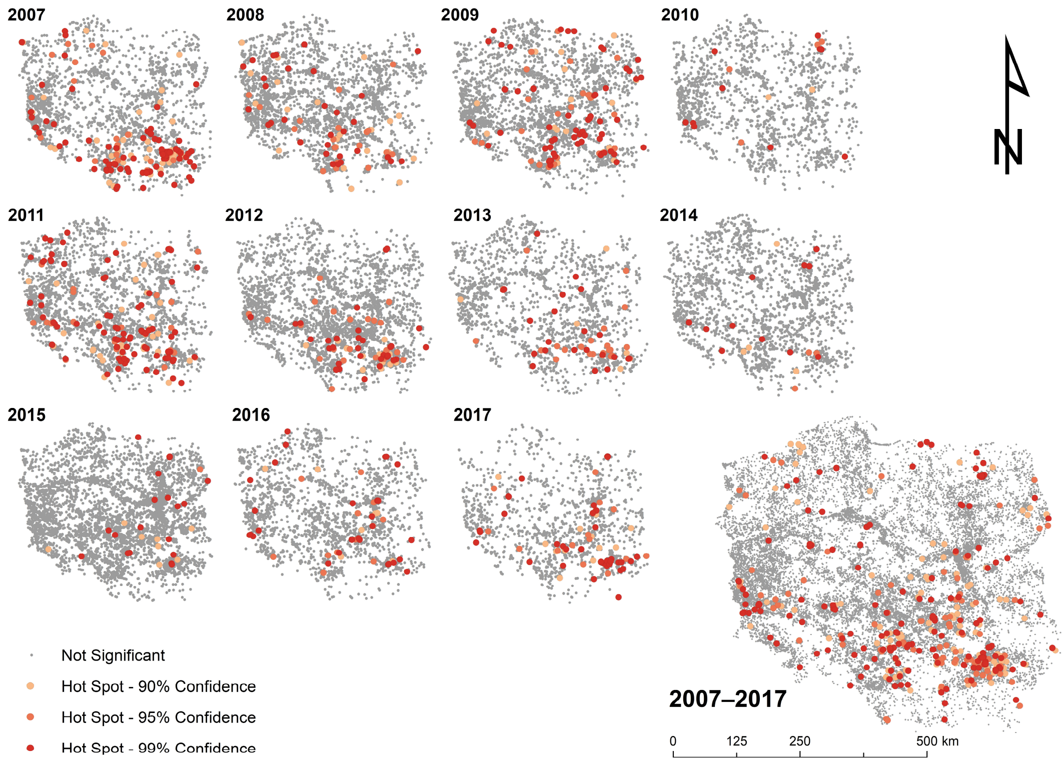

Figure 10. Statistically significant hotspots of burned area according to local Getis-Ord statistics.

This indicates the existence of regional dependencies affecting the size of fires. As the aim of the work is to indicate ways to increase the effectiveness of the existing fire protection system, it was decided to check whether the spatial distribution of the size of the burned area depends on the distance of fires from the nearest fire station.

3.5. Relationship between the Number and Size of Forest Fires and the Allocation of Firefighting Units

In addition to spatial differences in the number and size of fires in individual voivodeships, one can also notice a difference in the number of fire units and in the average distance between the fire and the nearest unit (Figure 11). Despite this, the results of the network analysis and correlation show that there is no relationship between the size of the fires and the distance to the nearest fire station. Spearman's correlation for individual voivodeships (reference units) ranges from 0.00 to 0.18 (Table 2).

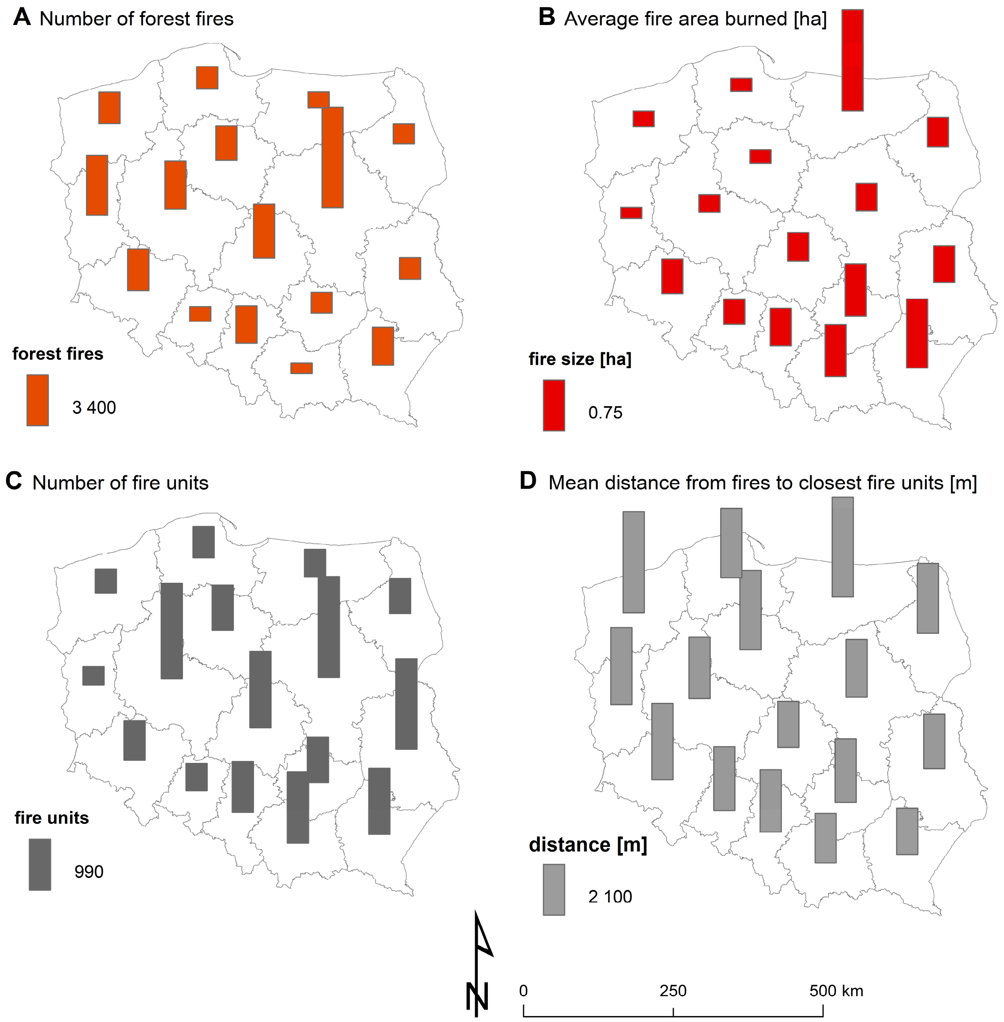

Figure 11. Characteristics of fires (numbers (**A**); sizes (**B**)), number of firefighting units (**C**), and distances between the fires and nearest units (**D**) for individual voivodeships.

Table 2. Correlations between the size of fires and the distance to fire units.

Voivodeship	No. of Fires	No. of Units	Spearman's Correlation S (Area vs. Distance)
Dolnośląskie (DŚ)	2784	762	0.02
Kujawsko–Pomorskie (K-P)	2337	877	0.08
Łódzkie (ŁÓD)	3623	1483	0.04
Lubelskie (LUBE)	1459	1761	−0.03
Lubuskie (LUBU)	4008	357	0.05
Małopolskie (MAŁ)	717	1389	0.00
Mazowieckie (MAZ)	6759	1974	0.06
Opolskie (OPO)	982	535	−0.05
Podkarpackie (PODK)	2519	1289	0.01
Podlaskie (PODL)	1347	679	0.06
Pomorskie (POM)	1475	620	0.15

Table 2. *Cont.*

Voivodeship	No. of Fires	No. of Units	Spearman's Correlation S (Area vs. Distance)
Śląskie (ŚL)	2467	996	0.00
Świętokrzyskie (ŚW)	1405	896	−0.18
Warmińsko–Mazurskie (W-M)	1034	540	0.16
Wielkopolskie (WLKP)	3201	1864	0.11
Zachodniopomorskie (ZACH)	2082	465	0.11

The number of fires in individual voivodeships for the years 2007–2017 ranged from 717 in Małopolskie (MAŁ) to 6759 in Mazowieckie (MAZ), which is more than a six-fold difference in the number of fires. The number of fire brigades varies from 357 in Lubuskie (LUBU) voivodeship to 1974 in MAZ. In MAŁ, where there were the fewest fires, the number of brigades is 1389, which is the fifth highest number in the Polish voivodeships. The burned area corresponds poorly to the number of fires. The largest average burned area was in Warmińsko–Mazurskie (W-M, 1.5 ha) and the smallest in Lubuskie (LUBU, 0.16 ha, where there are few brigades). The distances between the fire and the nearest fire brigade ranged from 1890 m in Łódzkie (ŁÓDZ) to 4160 m in Zachodniopomorskie (ZACH).

There was also no statistically significant correlation between the number of fires and the number of fire units in individual voivodeships (Spearman's correlation S = 474, p-value = 0.2534).

4. Discussion

Poland has significantly more fires and a larger total burned area compared with neighboring countries, despite having a similar percentage of forest area—approximately 30% of the country. For comparison, the average numbers of fires in the 2007 to 2016 period in Germany and the Czech Republic were 735 and 958 fires, respectively (in Poland, it was over 4000), and the average annual burned area in the 2007 to 2016 period in those countries was 319 and 287 ha, respectively [1], while in Poland, it was 1833.8 ha. Generally speaking, despite the relatively large number of fires breaking out in Poland compared with other countries in Europe (Figure 1), the vast majority of these being small and very small fires testifies to the country's generally good firefighting efficiency, high level of detection, and good fire protection solutions (from legal tools to implementing them in the field, e.g., in the field of fire protection) [15]. There is adequate security and dense distribution of State Fire Service units and volunteer fire brigades—over 16,000 units, an average of 1030 per voivodeship (Figure 11). As the results of this study show, a large proportion of fires break out in the autumn and winter seasons (Q1, Q4) in Poland, accounting for as much as one-third of all fires (Figure 3); at the same time, the highest average burned area is recorded in this period (Figure 5). This was the reason why we decided to investigate the spatio-temporal diversity in the number of fires and the size of the burned area. As in Poland (90%), the vast majority of fires in the Czech Republic (88.9%) are small fires of less than 1 ha [7]. In the years 1992 to 2004, most fires in the Czech Republic broke out in the summer (July and August) and spring months (April and May), i.e., in Q2 and Q3, which is consistent with the results of this study. In the Czech Republic, the largest burned area was noted in April, constituting about 45% of the total [7]. Similarly, in Poland, Q2 included 51.5% of the total annual number of fires. Differences can be seen in the winter months: in the Czech Republic, about 10% of fires broke out in Q4 and Q1 [7,8], while in Poland, fires during these quarters made up 29% of the total number, not to mention that the average burned area of fires in winter is higher than in other periods of the year. However, it is difficult to state clearly what the reasons for these differences may be; they are probably due to the lower preparedness of firefighting services in the winter as a result of the forest fire risk level not being calculated during this period [15], as it is calculated only in the fire season. It might be worth looking at changes in the occurrence of fires over time and forecasting throughout the year, which we strongly recommend. This conclusion is also supported by the results of fire studies from Fujian province in China in the 2001 to 2016 period [30], where the incidence of forest fires first increased and then decreased over the years, but the percentage of forest fires declined during the fire prevention season. The number of forest fires increased significantly in spring and summer, exceeding the number of forest fires occurring during the 2010 fire prevention period [30]. The spatial distribution of forest fires also changed: the number of fires decreased from northwestern to southeastern coastal areas, and the number of forest fires in the northwestern mountainous areas declined rapidly in autumn and winter. Recent studies from China [31] show that there is seasonal and spatial variability in fire hazards, and differences in fire drivers across seasons reflect the delayed impact of climatic factors on fires, leading to significant differences in the extreme effects of seasonal fires.

There are a number of studies from various parts of the world, in various types of forest environments, emphasizing the importance of seasonal variability in forest fires, especially in the context of climate change. In Portugal [32] in the years 1980 to 2007, the presence of excessive fire densities in certain periods was observed; the largest fires (>5000 ha) always occurred in the months of July to September [33]. The authors of these works also emphasize the importance of temporal analyses for efficient fire management. Research conducted in the Mediterranean region on the differences in the size of fires depending on the season and type of soil [34] shows that the results can be used, for example, to better manage resources to detect and extinguish fires in well-defined areas that change depending on the time of year and prioritize fire-prone areas. In Iran [35], based on historical data and the current situation, it has been found that the largest fires break out in July, which is the hottest and driest month. In the aforementioned countries, the highest percentage of fires occurs in the summer season, similarly to Poland. On the other hand, in Poland, the largest average burned area occurs in the winter period, which is mostly not covered by forecasting. In our opinion, this proves the importance of the fire protection system in preventing large losses caused by fire in the summer.

The spatial differentiation of fires may have various causes [36]. In Indonesia, the distribution of fires is associated with the presence of peat bogs [36]. In France, in turn, the areas where wild and urbanized areas meet (the so-called WUI) are the most vulnerable [37]. Spatial variability of fires has also been found, e.g., in Finland [38] and Canada [39]. In Poland, the causes of fires are almost entirely of anthropogenic origin [4]. The most important anthropogenic factors that may affect the occurrence of fires are considered to be population density, the density of local roads in forest areas, the density of contact lines between residential complexes and forests, and the distance of forests from buildings and communication lines [40–42].

Certainly, in the future, it will be worth looking at the areas where the largest fires are grouped, paying attention to the distribution of clusters of high values and taking actions related to the allocation and readiness of fire protection units in the regions of central Poland. In southeastern Poland, few fires break out (Figure 7) but cause large burned areas (Figure 6), so these are mainly large fires. In the central part, the burned area is large, but there is a large number of fires, which means small (or at least smaller) fires are more common. This corresponds to what is shown in Figure 11. At the same time, it is worth bearing in mind the results from Greece [43], where in the 1990 to 2003 period, there were 84 fires with an area of >1000 ha (0.37% of the total number of fires in the analyzed period). No unique characteristics of large fires have been found to distinguish them from smaller fires, leading to the conclusion that any fire can become large under certain circumstances. It has also been shown [44] that edge fires mainly concern suburban regions and are of medium size (approx. 8 ha). In Portugal, unlike in Poland, the largest fires (>5000 ha) have always occurred in the months from July to September [33], which may indicate differences in fire prevention. Mapping and analyzing hotspots can be crucial in the context of effective response, which was also emphasized by Swedish researchers [45], who also found regional differences in their country.

A pan-European analysis of cascading dry hazards related to drought and fires shows that Poland is one of the most vulnerable regions of the continent [5], but at the same time, the spatial pattern of fire occurrence analyzed at the national level is different in this work compared with the results of [5]. This is due to the fact that the analyses in that study were carried out on a larger dataset than in this work (1990 to 2018), which may suggest that the spatial characteristics of fires in Poland change over time and are different now. It is also worth noting that the analyses of [5] were conducted only on data from the summer seasons, so they may not show the full picture. In the context of the national fire safety system, detailed analyses based on data from the entire season are important.

The research hypothesis that the size of the burned area is related to the distance from the nearest fire unit was negatively verified. It was found that the size of the fire is not related to the fire service network. Possible reasons include late fire detection, especially outside the fire season, socio-economic conditions, and/or natural conditions, such as metrological factors (wind speed, precipitation and thus available soil moisture) or the type of fuel (understood as the soil composition—branches, leaves, needles—of the forest floor); the latter can be indirectly inferred based on the type of forest stand in which fires break out.

While natural causes were not considered in this work, it was shown that it is possible to modify the period of forecasting and maintaining the readiness of the firefighting system based on the analysis of the fire situation in previous years. It has been shown that the fire season in Poland changes in terms of start and end dates and in terms of the length of the period depending on the region of the country—thus, the second research hypothesis was confirmed.

Our proposal to modify the fire protection system is twofold:

(1) Continuous fire forecasting should be conducted to address the possibility of large fires in the winter. Forecasting should be maintained all year round and forecasters should react ad hoc on individual days during the winter, sending warnings to the public and a signal to fire units. As we have proven, in periods not currently covered by forecasting (late autumn and winter), not only do a relatively large number of fires break out (which, in practice, means economic, social, and other losses), but they are also, on average, larger than fires in other periods of the year. Extending the forecast period to the whole year will allow units to be dispatched faster, as at-risk areas can be identified on an ongoing basis, even in winter.

(2) The fire season should be modified, i.e., the period during which firefighting units are kept on standby in order to allocate human resources and firefighting equipment quickly enough. Based on the analysis of the histograms of the frequency of fires in individual weeks of the year, we propose possible approaches to changing the fire season depending on the region of the country. The optimal solution seems to be the adoption of the first percentile as the beginning of the fire season, because then there is a high increase in the frequency of fires. At the same time, we suggest a local approach and modification for each voivodeship due to the spatial variability within the country. In half of the voivodeships, we suggest extending or shortening the fire season in order to adapt to real fire conditions. The concentration of fires in specific regions of Poland indicates a need for targeted interventions and resource allocation in those areas to mitigate the risks and prevent large losses caused by fire.

Our proposed modification of the forecasting period (the fire season) includes the beginning of the season at the moment when the first percentile is exceeded, and the end of the forecasting on 30.09 (Figure 12).

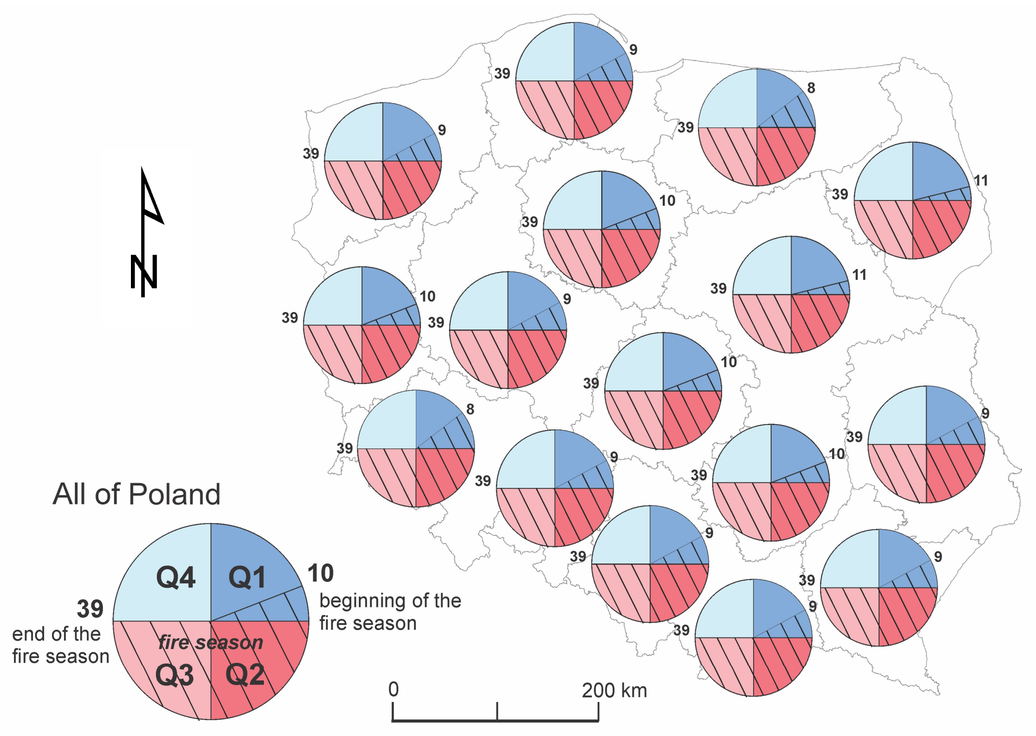

Figure 12. Start and end of the proposed forecasting period (the fire season), taking into account the first percentile of the number of fires as the beginning and 30.09 as the end, by voivodeships. The numbers at the beginning and end of the fire season indicate the weeks of the year. Data for the 2007 to 2017 period. The current forecasting period is from week 9 to week 39. Q1–Q4 are individual quarters of the year.

Taking into account the flattening of the edges of the histograms in autumn for both the whole of Poland and for individual voivodeships, as well as the average number and average size of fires recorded in Q4, it can be assumed that 30 September is an appropriate date for the end of the fire season, understood as the period of keeping firefighter units on standby. This is a reasonable balance between the percentage of fires that are included in the forecasting and the cost of keeping the system ready. This is a relatively universal method, recommended by us, of determining the fire season, which will allow us to engage formal resources at the lowest possible cost in order to prevent forest fires in the most effective way.

It should be noted that the values adopted by us are based on data from an 11-year period—we strongly recommend calculating the start and end dates of the fire season anew every year, based on a systematically expanded data set, which will allow us to flexibly respond to changes in fire trends. In conclusion, due to the statistical distribution of the frequency of fires breaking out in individual weeks of the year and local shifts related to spatial distribution, we propose that the fire season (related to higher readiness of firefighting services) should be adjusted according to the analysis of histograms from previous years and modified depending on the voivodeship.

The number of fires (including the largest fires) does not result from the location of fire brigades; further analysis of the causes is necessary in order to focus attention on areas particularly exposed to fire, including in winter. Particular attention should also be paid to the distribution of large fires, which tend to occur in specific regions of the country, especially since—as can be seen from the diagram maps—there is no simple relationship that states the more fires there are, the larger the burned area will be.

In our opinion, the large number of small-area fires can be related to the degree of penetration of forest areas by people. In Poland, there is a common and strongly rooted tradition of spending free time in forests and collecting fruits and mushrooms, either for personal consumption or for direct sale. Moreover, it has been proven that forest fires in Poland are largely dependent on human pressure on the forest environment, by analyses conducted at both the district [40] and forest district [41] levels. Population, road network density, and socio-economic data, regardless of the adopted reference level, turn out to be important for forecasting the outbreak of fires. Taking into account that fires break out all year round and that in Poland there are practically no natural causes of fires [4], it seems that humans and their activity are the direct cause of ignitions; other factors (weather, type of forest habitat) can only constitute a favorable background. For this reason, it is even more important to adequately adapt to the local situation for modeling firefighting behavior, concentration of effort, and decision making. Taking into account the local factors in forecasting the moment of increase in the number of fires could influence the decisions of local forest districts to issue warning messages and bans on access to the forest (currently, such decisions are issued based on the degree of fire risk, which is less accurate and does not take into account local conditions).

5. Conclusions

In this work, we present data proving the temporal and spatial diversity of forest fires in Poland, based on data from 2007 to 2017. It has been shown that fires break out all year round, including outside the "fire season", which lasts from 1 March to 30 September and during which the fire risk is constantly monitored and appropriate remedial actions are accordingly taken. Furthermore, it has been shown that the area burned as a result of fire is at its largest outside this period of continuous forecasting, which may lead to significant damage and losses. Both the number of fires and their size vary depending on the region of Poland (voivodeship). The number of fires in consecutive weeks of the year also varies depending on the voivodeship.

Based on the data presented, we argue that it is necessary to consider switching the system to continuous forecasting, which, in our opinion, will allow some of the losses to be avoided. The beginning, end, and duration of the fire season in Poland is region-dependent, so we also proposed modifying the start and end dates of the "fire season", setting them for each voivodeship separately based on the frequency distribution from the years preceding the current season. This approach will enable a more flexible response by fire services depending on local conditions and the local fire risk, possibly making the fire protection system more effective.

In our work, we did not focus on finding the causes of such a spatio-temporal pattern of fires. The only reason considered was that related to the effectiveness of firefighting services, i.e., the number of fire brigade units and their distance from the fire. We proved that the sizes of fires in Poland do not depend on the allocation of firefighting units.

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