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Original scientific paper

SPATIAL-STATISTICAL ANALYSIS OF FOREST FIRE DISTRIBUTION IN THE REPUBLIC OF SERBIA

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Abstract: Fires represent a significant ecological disturbance which affects the structure and dynamics of forest ecosystems, whereby their spatial distribution depends on the combination of climatic, vegetational and anthropogenic factors. The objective of this research is the analysis of the spatial distribution of fire detections in the territory of the Republic of Serbia, at the level of administrative units (municipalities) in the period from 2012 to 2026, restricted to areas classified as forest-related by the CORINE Land Cover classification (classes 2, 3, 4 and 5). The research was conducted using the data obtained through VIIRS sensors available through NASA FIRMS system of satellite data on active fires, in combination with CLC+ Backbone data. Also, Fire Radiative Power (FRP) was analyzed in order to estimate variability of the radiation power of fires and their classification. The analysis of FRP included 504 forest fire detections. The results show pronounced variability of radiation power of forest fire detections, whereby the majority of detections belong to the lower and interquartile ranges of the FRP distribution, while a smaller number of events reaches extreme values (up to 300 MW). For identification of spatial patterns, the methods of spatial statistics were used, including Moran's *I* index, as well as Getis-Ord *G*_i^{*} statistics, which enables identification of local clusters with statistically significantly high (hot spot) and low (cold spot) values. The distribution of fire detections is characterized by pronounced spatial heterogeneity, whereby the majority of municipalities records a small number of fire detections, while in a smaller number of municipalities increased frequency occurs. Statistically significant spatial clusters are identified, with the most pronounced zones in southern and southeastern parts of Serbia. The results obtained indicate that the fire risk assessment should not be based solely on their frequency, but also on FRP values. The application of integrated approach, which combines satellite data on occurrence of fire detections and classification of land cover, enables reliable identification of risk areas and it represents the basis for improving the monitoring system and planning of fire protection measures.

Keywords: forest fire detections distribution in Serbia; VIIRS; CORINE Land Cover, Fire Radiation Power FRP, Moran's *I*, hot spot analysis.

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PROSTORNO-STATISTIČKA ANALIZA RASPOSTRANJENOSTI ŠUMSKIH POŽARA U REPUBLICI SRBIJI

Sažetak: Požari predstavljaju značajan ekološki poremećaj koji utiče na strukturu i dinamiku šumskih ekosistema, pri čemu njihova prostorna distribucija zavisi od kombinacije klimatskih, vegetacionih i antropogenih faktora. Cilj ovog istraživanja je analiza prostorne distribucije detektovanih šumskih požara na teritoriji Republike Srbije, na nivou administrativnih jedinica (opština) u periodu 2012–2026, sa posebnim fokusom na vegetacione klase definisane CORINE Land Cover klasifikacijom (klase 2, 3, 4 i 5). Istraživanje je sprovedeno korišćenjem podataka dobijenih putem VIIRS senzora, dostupnih kroz NASA FIRMS sistem satelitskih podataka o aktivnim požarima, u kombinaciji sa CLC+ Backbone podacima. Takođe je analiziran Fire Radiative Power (FRP) u cilju procene varijabilnosti radijacione snage požara i njihove klasifikacije. Analiza FRP obuhvatila je 504 detekcije šumskih požara. Rezultati pokazuju izraženu varijabilnost radijacione snage detektovanih šumskih požara, pri čemu većina detekcija pripada nižem i srednjem delu raspodele FRP vrednosti, dok manji broj dostiže ekstremne vrednosti (do 300 MW). Za identifikaciju prostornih obrazaca korišćene su metode prostorne statistike, uključujući Moran's I indeks, kao i Getis-Ord Gi* statistiku, koja omogućava identifikaciju lokalnih klastera sa statistički značajno visokim (hot spot) i niskim (cold spot) vrednostima. Distribucija detektovanih šumskih požara karakteriše se izraženom prostornom heterogenošću, pri čemu većina opština beleži nizak broj detekcija, dok se u manjem broju opština javlja povišena frekvencija. Identifikovani su statistički značajni prostorni klasteri, sa najizraženijim zonama u južnim i jugoistočnim delovima Srbije. Dobijeni rezultati ukazuju da procena rizika od požara ne treba da se zasniva isključivo na njihovoj frekvenciji, već i na FRP vrednostima. Primena integrisanog pristupa, koji kombinuje satelitske podatke o detekcijama šumskih požara i klasifikaciju zemljišnog pokrivača, omogućava pouzdanu identifikaciju rizičnih područja i predstavlja osnovu za unapređenje sistema monitoringa i planiranja mera zaštite od šumskih požara.

Gljučne reči: distribucija šumskih požara u Srbiji; VIIRS; CORINE Land Cover (CLC); radijaciona moć požara (FRP); Moran's I; analiza žarišta

1. INTRODUCTION

Forests represent an important ecosystem resource that influences human health, improvement of life quality, climate change, and other key ecosystem functions (Cervinka et al., 2014; Psistaki et al., 2024). According to the data of the Second national forest inventory of the Republic of Serbia the area under the forests amounts to approximately 36.81% of the total territory. The forest structure is dominated by deciduous forests, conifer stands and mixed coniferous and deciduous forests are much less represented (The Directorate of forests of the Republic of Serbia, 2023).

Fires are ecological disturbances which affect the structure and dynamics of forest ecosystems (Smith et al., 2008). The spatial distribution and activity of fires is determined by a combination of climatic, vegetation and anthropogenic factors (Harrison et al., 2025; Park et al., 2021). Frequency, size, and intensity of fires determine their spatial and temporal patterns (Liu & Wimberly, 2015).

The effect of fires reflects in soil changes that include pH value, organic matter, microorganisms, thus influencing the changes in the ecosystem after the fire

(Liu et al., 2024; Smith et al., 2008). In addition to the impact on the soil, the impact of fire is reflected in the effect on vegetation and organic layers (Yang et al., 2022). According to Durlević et al., (2025), the distance from roads and settlements significantly affects the probability of fire occurrence, with events occurring more frequently in their immediate vicinity.

The development of satellite technologies enabled detailed monitoring of fires at the regional and global level (Justice et al., 1993). The data obtained through the visible infrared radiometer sensor (VIIRS) available through National Aeronautics and Space Administration Fire Information for Resource Management System (NASA FIRMS) is particularly noteworthy and enables detection of active fires of high spatial and temporal resolution (NASA/USGS, 2018). By combining the data of land cover classification, such as CORINE Land Cover (CLC) (EEA, 2020; Tešić, 2022), with the data of VIIRS sensor, the analysis of the connection between the type of surface and the occurrence of fire, as well as the identification of spatial patterns of their distribution, is enabled.

Similar research in Europe was conducted by Parente et al., (2016) who analyzed the spatial and temporal distribution of forest fires in Portugal. The research of Lorent et al. (2025) includes CORINE Land Cover (CLC 2018) data as one of the parameters, while VIIRS data was used for validation of the model of forest ecosystems sensitivity to fires in the territory of Romania. Pausas and Fernández-Muñoz (2012) have examined changes in forest fire regimes in the provinces of Valencia (Spain, Eastern Iberian Peninsula, Western Mediterranean Basin), by unification of 130 year of data, whereby a significant change was identified around the 1970s, with a doubling of fire frequency. In the research of Wang and Wang (2025) spatial and temporal activity of fires in China was analyzed, for the period from 2003 to 2024, using Moderate Resolution Imaging Spectroradiometer (MODIS) data, available through NASA FIMRS system.

Studies that dealt with this subject link the occurrence of an increased number of fires on the territory of the Republic of Serbia to climate change (Durlević et al., 2025; Vranić & Mišić, 2024). Novković et al., (2021) and Čurić et al., (2022) examined susceptibility of forest stands to occurrence of forest fires. The research that relates to forest fires in Serbia also used CLC data (Gigović et al., 2019; Gajović and Todorović, 2013), as well as the combination of CLC and FIRMS data, conducted by Milanović et al., (2021). At the level of the entire territory of the Republic of Serbia two studies were identified which analyzed the occurrence of fires: Brovkina et al., (2020), with the focus on post-fire forest scars in Serbia using Sentinel-2 data, and Gajović and Todorović (2013), who carried out spatial and temporal analysis of fires for the period from 2000 to 2013.

The objective of this research is the analysis and quantification of spatial distribution of detected forest fires, with a special focus on their spatial patterns. The emphasis is placed on the identification of spatial clusters and areas with an increased frequency of detected forest fires.

Radiative power of fires was observed through Fire Radiative Power (FRP), which represents the measure of energy emitted during biomass burning. The main contributions include integration of VIIRS and CLC+ Backbone data, the analysis of frequency of detected forest fire occurrence at the municipal level and classification of detections based on the FRP values.

2. MATERIALS AND METHODS

2.1. The Study Area

The research was conducted on the territory of the Republic of Serbia, latitude $43^{\circ} 11' 13''$ - $46^{\circ} 11' 25''$ N, and longitude $19^{\circ} 40' 00''$ - $23^{\circ} 00' 47''$ E (Figure 1). The Republic of Serbia is located in the central part of the Balkan Peninsula and along the southern margin of the Pannonian Basin, covering an area of 88,499 km² (Manić et al., 2022). The country is characterized by pronounced geographical diversity, with relief conditions ranging from the lowlands of the Pannonian Plain in the north to mountainous regions in the south and east. It is situated in a predominantly highland-mountain zone intersected by numerous river basins, while its geographical position has made it an important migration and transportation corridor connecting Southwest Asia with Central and Western Europe (Manić et al. 2022). About 2,854,955 ha or 36.81% of the total area of the territory of Serbia is under forests, 1,191,466 ha or 41.73% of which are state-owned and 1,663,489 ha or 58.27% are private-owned (The Directorate of forests of the Republic of Serbia, 2023). The distribution of annual precipitation in Serbia is uneven, with lower values recorded in the northern and northeastern lowlands (500–600 mm) and substantially higher amounts, exceeding 1000 mm, occurring in the mountainous areas of southwestern Serbia (Živanović & Gocić, 2022). The annual precipitation regime in Serbia is characterized by a maximum occurring predominantly in June and a minimum in February across the majority of meteorological stations (Milovanović et al., 2017).

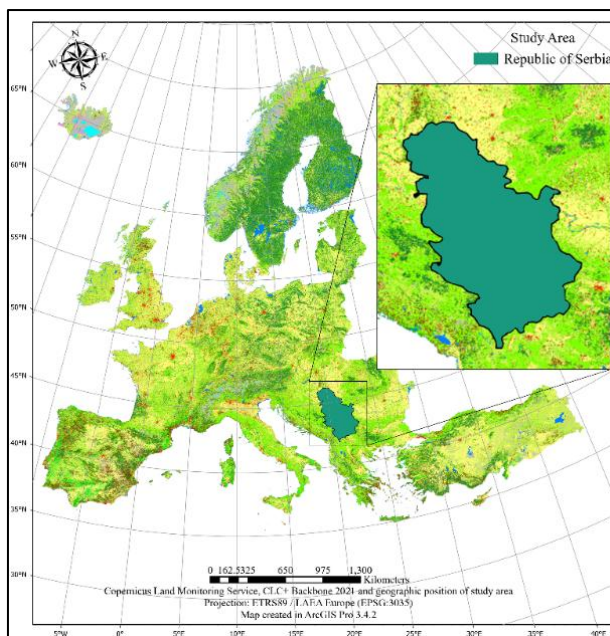


Figure 1: Study area of the Republic of Serbia with the layer of CLC2021

2.2. Data Collection

The data necessary for realization of the research is collected from several sources. The file that contains administrative border of the Republic of Serbia as well as borders of administrative units (municipalities) was downloaded from online platform GeoSrbija in shapefile format (Republic Geodetic Authority). Vegetation and land cover data were obtained from the CLC+ Backbone raster for period from 2020 to 2022 (CLC 2021) dataset (<https://land.copernicus.eu/en/products/clc-backbone/clc-backbone-2021>) with 10 m resolution, projections ETRS89 / LAEA Europe (EPSG:3035). Fire detection data were obtained from NASA FIRMS, using the VIIRS 375 m Active Fire product (Suomi NPP, Collection 2).

The primary focus of the research was on forest classes 2, 3, 4 and 5 according to CLC classification.

- Class 2: Woody needle-leaved trees
- Class 3: Woody broadleaved deciduous trees
- Class 4: Woody broadleaved evergreen trees
- Class 5: Low-growing woody plants

For segregation of classes 2, 3, 4 and 5 Geographic Information System Professional ArcGIS Pro (Esri, 2024) was used into which CLC 2021 raster was imported, as well as shapefile administrative borders of the Republic of Serbia. Both data sets are in identical coordinate reference system, and they have same spatial settings, which is necessary to provide methodological consistency in further spatial analysis.

Due to the spatial limitation, only pixels that are spatially located within the state border of the Republic of Serbia were selected. During this procedure, attribute tables of new files were also checked, whereby it was verified if the raster retains all classes and attributes present in the original dataset. This confirmed that no loss or alteration of the source data occurred during the selection process thus ensuring consistency between the original and the created dataset.

It should be emphasized that the CLC+ Backbone 2021 dataset was not used as a historical representation of land cover conditions throughout the entire study period (2012–2026). Instead, the dataset served exclusively as a reference layer for identifying forest-related land cover classes and restricting the analysis to fire detections located within areas classified as forest ecosystems. Therefore, the objective of this study was not to reconstruct historical land-cover dynamics, but to analyze the spatial distribution of forest fire detections within forest environments identified by the CLC+ Backbone 2021 dataset.

The used dataset includes period from 20 January 2012 to 17 March 2026. The source VIIRS dataset was reprojected in order to be aligned with the coordinate system of CLC+ Backbone data and administrative borders. The focus is on spatial distribution of fire detections, and dataset was used solely as spatial indicator of sites. The table of attributes includes information on the level of confidence for each fire detection (low, nominal, high). Only detections marked with "h" more than 80% - high confidence, (EEA, 2024) were used in this research. The table of attributes also includes information on the fire detection location (geographic coordinates), time of detection (date and time), as well as the value of FRP which represents the measure

of energy emitted by the detected fires in the form of thermal radiation, expressed in megawatts (MW) (NASA Earthdata, 2025).

2.3. Data Processing

CLC2021 raster was filtered to select only CLC classes 2, 3, 4 and 5, while other values were treated as NoData. After that, the value of the CLC class the detected fire was in, was assigned to each of them. The detections with the value NoData (-9999) were eliminated from further analysis, which resulted in a set of detections located exclusively on forest areas according to the CLC classification.

For the analysis of spatial distribution of detected forest fires Spatial Join tool was used, by which an attribute of forest fire location was assigned to each of the municipalities. As a result, the Join Count field was obtained, which represents the total number of forest fire detections within each municipality. For each of the municipalities geometry was calculated in km², which served as a basis for calculation of fire detections density per km². Based on this data the values of Moran's I (row-standardized) were obtained, which is used for identification of spatial clusters (Vranić & Mišić, 2024). For the purposes of the test (contiguity edges corners) was used, often called *Queens Case* which includes adjacent polygons based on common borders and common vertices. The values of this test range between -1 and 1, where the values close to -1 indicate that spatial autocorrelation is negative, while values that are closer to 1 have positive correlation, i.e. the results with similar values tend to group in space. After Moran's I test hot spot analysis was applied using Getis-Ord Gi* spatial statistics which graphically showed areas with "hot" and "cold" values by municipalities (Guerri et al., 2021).

2.4. Statistical Analysis

Statistical analysis was carried out using the software for statistical analysis SPSS ver 26 (IBM Corp., 2019). The research was carried out using descriptive statistics with a focus on FRP value of detections, whereby quartiles were used as the basis for classification. The selection of quartile classification was based on the need to avoid introduction of arbitrary fixed thresholds, considering that there is no single limit for the classification of FRP values in the literature. The methods of descriptive statistics which consist of arithmetic mean (Mean), standard deviation (SD), minimum and maximum value were used. The distribution of the number of forest fire detections by municipalities was analyzed, as well as the frequency of fire occurrence for each municipality individually. Based on the ratio between mean value and standard deviation, the variability of the distribution was estimated.

3. RESULTS AND DISCUSSION

3.1 Analysis of FRP data

Based on the classification of fires according to FRP values, the fire detections are classified in three classes:

- Lower-quartile FRP events (<9.34 MW);
- Interquartile FRP events (9.34 – 20.95 MW);
- Upper-quartile FRP events (>20.95 MW).

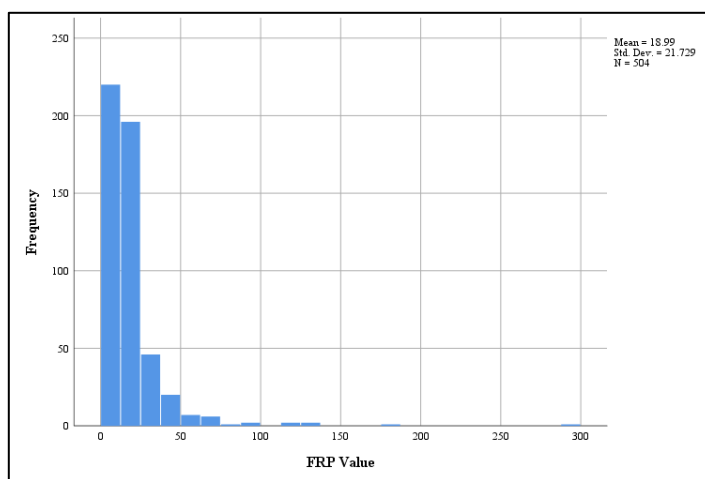
The results of these analyses are presented in Table 1.

Table 1. *The analysis of FRP values*

Percentiles		5	10	25	50	75	90	95
Weighted Average	FRP	5.75	6.94	9.33	13.42	21.04	33.88	47.89
Tukey's Hinges	FRP			9.34	13.42	20.95		

The lower quartile (Q1) was used to distinguish detections belonging to the lower quartile of the FRP distribution, the interquartile range (Q1-Q3) for detections within the interquartile range, while values above the upper quartile (Q3) were treated as detections belonging to the upper quartile of the FRP distribution. The above classification does not represent absolute assessment of fire intensity, but enables comparative analysis of variability of FRP values within the detected forest fires in the territory of the Republic of Serbia. The classification is therefore dataset-specific and intended solely for comparative analysis within the analyzed sample. Also, it is important to emphasize that the FRP values represent the radiative power at the moment of detection, and not the total energy released during the entire duration of the fire.

The results of the descriptive statistics of FRP presented in Histogram 1 indicate pronounced variability of fire radiative power (Mean = 18.99 MW; SD = 21.73 MW). The distribution of FRP values shows pronounced right asymmetry, which indicates the domination of occurrence of detections concentrated within the lower part of the FRP distribution, while smaller number of fires reaches very high values (up to 300 MW). This pattern confirms the presence of fewer fire detections belonging to the upper part of the FRP distribution, which may indicate relatively higher combustion energy compared to other events within the analyzed sample.



Histogram 1: *Fire occurrence frequencies in relation to FRP values*

Although this analysis does not include directly spatial distribution of FRP values, identified hot spot regions do not represent only the areas with larger number of fire detections, but indicate potential areas with increased risk of fire with higher values of radiative power. Based on the results obtained, fire risk assessment should not be based solely on their frequency, but also on radiative power expressed through FRP values. Fire detections belonging to the upper quartile of the FRP distribution may indicate events with comparatively greater combustion energy and potentially greater ecological significance compared to other detections within the analyzed sample. Such events may be associated with greater ecological effects, as suggested by previous studies, where fires can lead to significant changes in landscape, thereby triggering structural and functional adaptations of forest ecosystems (Lee et al., 2025). FRP values are directly connected with the quantity of the biomass burned (Wooster et al., 2005). These data provide information on potential impact of forest fires on ecosystem, which makes them an important parameter in radiative power analysis and fire risk assessment.

3.2 Analysis of Forest Fire Distribution

The analysis of forest fire detection distribution (Table 2) showed that the number of forest fire detections by municipalities ranges from 0 to 28, with a mean value of 2.56 detections and standard deviation of 4.57.

Table 2. Analysis of forest fire occurrence distribution

Descriptive Statistics	N	Minimum	Maximum	Mean	Std. Deviation
Join Count	197	0	28	2.56	4.570
Valid N (listwise)	197				

The high value of standard deviation compared to arithmetic mean indicates pronounced spatial variability of the number of fires, i.e., uneven distribution of fire detections between analyzed spatial units.

The results of spatial autocorrelation (Table 3) (Moran’s I = 0.435) indicate statistically significant positive spatial dependance of the forest fire detection density at the level of municipalities (Z = 10.15; p < 0.001). The obtained value deviates from the expected value for a random distribution (I = -0.005), which confirms there is a positive spatial autocorrelation. The result shows that the municipalities with similar values of forest fire detections density are grouped spatially.

Table 3. Moran’s I Summary

Moran’s I Summary	Moran’s Index	Expected Index	Variance	z-score	p-value
	0.434860	-0.005102	0.001881	10.145626	0.000000

The results obtained indicate there are pronounced cluster patterns, i.e. spatial concentrations of forest fire detections, whereby certain areas represent the zones of increased risk. The result of Moran’s I test confirms that fire detection distribution is not random, but spatially structured, which is in accordance with the findings of Gajović and Todorović (2013), who determined similar grouping of the occurrence of fires in the southern, southeastern and eastern parts of the Republic of Serbia. Previous studies have shown that the frequency and distribution of fire

detections are conditioned by a combination of factors such as the type of vegetation, season, climatic conditions, and specificities of local conditions (Ray et al., 2023). Although climatic, vegetation, topographic and anthropogenic variables were not directly analyzed in this study, previous research suggests that these factors may contribute to the observed spatial patterns of forest fire detections. Higher concentration of forest fires can be associated with unfavorable climatic conditions, such as higher temperatures and more pronounced periods of drought, as well as specific structure of vegetation which contributes to higher flammability (Park et al., 2021). In addition to climatic conditions, anthropogenic factors also have a significant role, since areas with more intensive agricultural activities and more frequent burning of plant residues are characterized by an increased frequency of fires, especially in transition zones between agricultural and forest areas (Ga et al., 2025). On sites where fires occur there may be changes in the nutrient cycle, because biological elements from biomass can return to the soil in the form of ash, which can cause losses in macroelements and organic matter (Yang et al., 2022). The results are consistent with the findings of Shazard et al., (2026), which suggest that even a slight increase in fire intensity can cause significant losses in ecosystem productivity, which is especially significant considering that dense forest stands have a slower regeneration compared to less dense stands and areas covered with grass vegetation (Lee et al., 2025). Spatial distribution of fires varies throughout different regions, and it is conditioned by natural characteristics of the space (Archibald et al., 2013).

The results presented in Table 4 indicate that the largest share of municipalities are without detected forest fires (47.7%), while with one forest fire detection there are 15.7% of municipalities, and with two forest fires detection 9.1%. All other categories individually participate with significantly smaller percentages (below 5%).

Table 4. *The analysis of frequencies and percentage share of forest fire detections on classes 2, 3, 4 and 5*

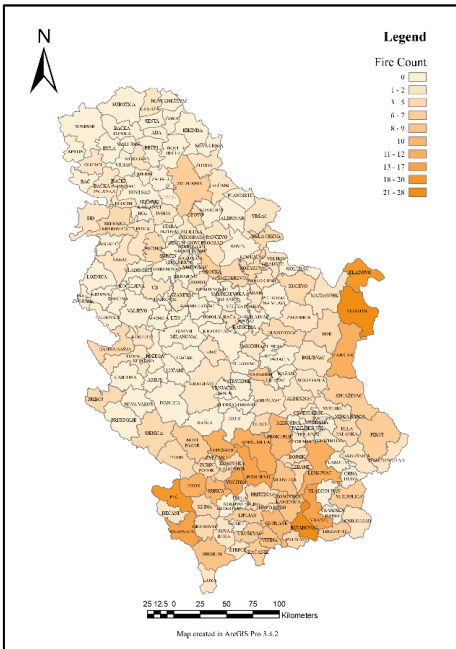
Number of detections	Frequency	Percentage	Cumulative percentage
0	94	47.7	47.7
1	31	15.7	63.5
2	18	9.1	72.6
3	7	3.6	76.1
4	10	5.1	81.2
5	6	3.0	84.3
6	9	4.6	88.8
7	2	1.0	89.8
8	2	1.0	90.9
9	2	1.0	91.9
10	3	1.5	93.4
11	3	1.5	94.9
12	2	1.0	95.9
15	1	0.5	96.4
16	1	0.5	97.0
17	2	1.0	98.0
18	1	0.5	98.5
20	1	0.5	99.0
26	1	0.5	99.5
28	1	0.5	100.0
Total	197	100.0	100.0

The cartographic representation (Map 1) shows that 10 municipalities with the highest frequency of detections are Bujanovac (28) and Negotin (26), then Peć (20), Kladovo (18), as well as Podujevo and Vranje with 17 detected forest fires in each. High values were detected also in municipalities Vučitrn (16), Đakovica (15), Istok (12) and Leposavić (12). These results indicate that the zones with the most pronounced fire detections in forests are mostly grouped in southern, southeastern, and partly in eastern parts of the researched space.

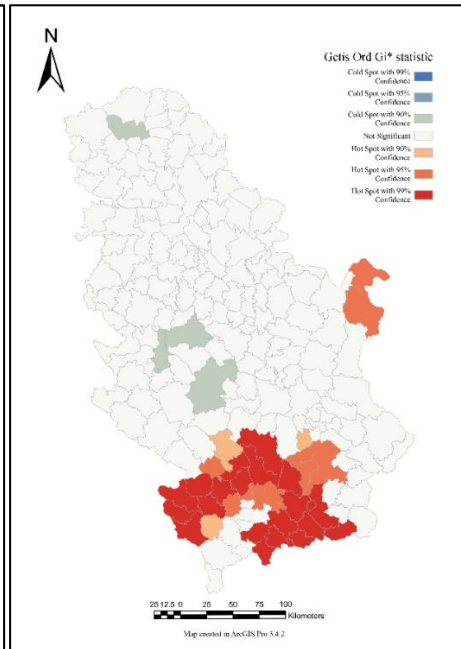
Getis-Ord Gi* analysis identified statistically significant spatial clusters of forest fire detection density (Map 2). The most pronounced hot spot regions are observed in southern and southwestern parts of the country, where municipalities with a high-density detection of forest fires are spatially grouped and form continuous zones of increased risk.

On the other hand, a large number of municipalities of central, western, and northern Serbia show very low number of forest fires detection or complete absence of registered events. Such pattern confirms the presence of pronounced positive asymmetry of distribution, where a small number of municipalities carries the main part of the total activity.

The cartographic representation additionally confirms the spatial concentration. The municipalities with the highest values are clearly distinguished as hot spots, the border municipalities, and hilly-mountainous municipalities of southeastern Serbia, as well as some municipalities of eastern Serbia, stand out in particular.



Map 1. Frequency of forest fire detections by municipalities



Map 2: Getis-Ord Gi* hot spot analysis

Map 1 and Map 2 show that forest fire detections are spatially concentrated in limited zones, while the largest part of the territory is affected with a significantly lower intensity. The similar result which shows grouping of clusters in southern and eastern parts of the Republic of Serbia was established by Gajović and Todorović (2013) using Moran's I and Getis Ord G_i^* . Hot spot regions identify spatial clusters with increased frequency of fire detections, while the assessment of their radiative power requires additional analysis of FRP values. This is important information considering that previous studies have shown that frequent forest fires significantly change microbiological structure of soil and decrease ecosystem productivity (Smith et al., 2008).

4. CONCLUSION

The identified hot spot regions indicate that forest fire detections are not randomly distributed but tend to be spatially clustered. Previous studies have shown that repeated fire occurrence within the same areas may contribute to cumulative changes in soil and vegetation.

The results of the analysis show pronounced spatial heterogeneity of forest fire detection distribution, where the majority of municipalities have a low number of detections, while in the smaller number of municipalities zones of high concentrations occur, which is confirmed through spatial autocorrelation (Moran's I), as well as by Getis-Ord G_i^* hot spot analysis.

By focusing the analysis on CLC classes 2, 3, 4 and 5 a more precise overview of the distribution of fire detections within forest ecosystems is enabled, whereby the results provide an overview of the spatial distribution of fire detections occurring within forest-related CLC classes. Such finding emphasizes their importance in the context of risk assessment and planning of protection measures.

The results obtained indicate that the assessment of the risk of forest fire should not be based solely on their frequency, but on the values of the radiative power. Although detections belonging to the upper quartile of the observed FRP distribution are less frequent, they may represent events with comparatively greater combustion energy and therefore deserve special attention in fire risk assessments.

Based on the identified spatial patterns it can be concluded that for the efficient management of forest fires the organization of protection system at the regional level is necessary, whereby preventive and protection measures should be directed to the identified hot spot zones as a matter of priority.

The application of integrated approach, using VIIRS and CLC, proved to be an effective tool for analyzing the spatial distribution of forest fire detections and identification of risk areas, which contributes to the improvement of the system of monitoring and protection measure planning.

Although all the used data are aligned in the same coordinate system and originate from reliable sources, certain limitations continue to exist. The difference in spatial resolution between VIIRS detections (375 m) and CLC data (10 m) can influence the precision of land cover class assignment, while aggregation of data at the level of municipalities can lead to the occurrence of modifiable areal unit problem (MAUP) effect. Additionally, VIIRS detections can be limited by the recording conditions, such as cloudiness and radiative power of forest fires.

VIIRS active fire records represent satellite detections rather than unique fire events. Consequently, multiple detections may originate from the same fire occurring during successive satellite overpasses or across adjacent pixels. Therefore, the reported frequencies should be interpreted as fire detection frequencies rather than exact counts of independent forest fires.

An additional limitation is that CLC+ Backbone 2021 represents a single reference period and does not capture potential land-cover changes that occurred between 2012 and 2026. Consequently, the results should be interpreted as a spatial analysis of forest fire detections within areas classified as forest land according to the CLC+ Backbone 2021 dataset, rather than as a reconstruction of historical vegetation conditions at the exact time of each fire event.

Despite these limitations, the research results provide insight into the spatial patterns of forest fire occurrence and represent the basis for further research. The research can be directed toward integration of climatic parameters (temperature, precipitation, drought indices) and socio-economic factors into forest fire spatial distribution models.

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SPATIAL-STATISTICAL ANALYSIS OF FOREST FIRE DISTRIBUTION IN THE REPUBLIC OF SERBIA

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Summary

Fires represent one of the key ecological factors that affect the structure and dynamics of forest ecosystems, whereby their spatial distribution depends on the combination of climatic conditions, type of vegetation, and anthropogenic influences. In the last decades, the development of satellite technologies enabled more precise monitoring and analysis of spatial distribution of fires. The objective of this research was to analyze spatial distribution of forest fire detections in the territory of the Republic of Serbia in the period from 2012 to 2026, restricted to forest-related CLC classes (2, 3, 4 and 5). The analysis was based on the data of VIIRS sensors available through NASA FIRMS system, in combination with CLC+ Backbone data, along with the application of geospatial and statistical methods. Special emphasis was placed on the assessment of the radiative power of the fire detections through Fire Radiative Power (FRP), which represents a measure of the energy emitted during combustion. The results show pronounced spatial unevenness of fire detection distribution, whereby the majority of municipalities record a low number of events or their absence, while in a smaller number of municipalities there are zones with an increased frequency. Examination of spatial autocorrelation (Moran's $I = 0.435$; $p < 0.001$) indicates statistically significant grouping of fire detections, which was confirmed also by Getis-Ord G_i^* hot spot analysis. The most pronounced clusters were identified in the southern, southeastern and eastern parts of Serbia. The analysis of FRP values shows high variability, where lower- and mid-range FRP events dominate the dataset, while a smaller number of detections belong to the upper quartile of the FRP distribution and may potentially have a greater influence on

ecosystem processes. The results obtained indicate that fire risk assessment should not be based solely on their frequency, but also on radiative power. The identified spatial patterns indicate the need for regionally oriented approach to risk management, whereby preventive and protective measures should be directed toward identified risk zones. Although data from reliable sources were used and aligned in the same coordinate system, there are certain limitations, primarily regarding the difference in spatial resolution between VIIRS detections and CLC data, as well as possible influence of the aggregation effect of spatial units (MAUP). Despite this, the application of an integrated approach that combines satellite data and land cover classification is an effective tool for the analysis and identification of risk areas and contributes to the improvement of the system of monitoring and planning of fire protection measures.

PROSTORNO-STATISTIČKA ANALIZA RASPORSTRANJENOSTI ŠUMSKIH POŽARA U REPUBLICI SRBIJI

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Rezime

Požari predstavljaju jedan od ključnih ekoloških faktora koji utiču na strukturu i dinamiku šumskih ekosistema, pri čemu njihova prostorna distribucija zavisi od kombinacije klimatskih uslova, tipa vegetacije i antropogenih uticaja. U poslednjim decenijama, razvoj satelitskih tehnologija omogućio je preciznije praćenje i analizu prostorne distribucije požara. Cilj ovog istraživanja bio je da se analizira prostorna distribucija detektovanih šumskih požara na teritoriji Republike Srbije u periodu 2012–2026, sa posebnim fokusom na šumske kategorije definisane CLC klasifikacijom (klase 2, 3, 4 i 5). Analiza je zasnovana na podacima VIIRS senzora dostupnih kroz NASA FIRMS sistem, u kombinaciji sa CLC+ Backbone podacima, uz primenu geoprostornih i statističkih metoda. Poseban akcenat stavljen je na procenu radijacione snage požara kroz Fire Radiative Power (FRP), koji predstavlja meru energije emitovane tokom sagorevanja. Rezultati pokazuju izraženu prostornu nejednačenost distribucije detektovanih šumskih požara, pri čemu većina opština beleži nizak broj događaja ili njihovo odsustvo, dok se u manjem broju opština javljaju zone sa povišenom frekvencijom. Ispitivanje prostorne autokorelacije (Moran's $I = 0.435$; $p < 0.001$) ukazuje na statistički značajno grupisanje požara, što je potvrđeno i Getis-Ord G_i^* hot spot analizom. Najizraženiji klasteri identifikovani su u južnim, jugoistočnim i istočnim delovima Srbije. Analiza FRP vrednosti požara pokazuje visoku varijabilnost, gde dominiraju detekcije koje pripadaju nižem i srednjem delu raspodele FRP vrednosti, dok manji broj detekcija pripada gornjem kvartilu raspodele FRP vrednosti i može ukazivati na događaje sa većom energijom sagorevanja i potencijalno većim ekološkim efektima. Dobijeni rezultati ukazuju da procena rizika od požara ne treba da se zasniva isključivo na njihovoj učestalosti, već i na radijacionoj snazi. Identifikovani prostorni obrasci ukazuju na potrebu za regionalno orijentisanim pristupom upravljanju rizikom, pri čemu bi preventivne i zaštitne mere trebalo usmeriti ka identifikovanim rizičnim zonama. Iako su korišćeni podaci iz pouzdanih izvora i usklađeni u istom koordinatnom sistemu, određena ograničenja postoje, pre svega u pogledu razlike u prostornoj rezoluciji između VIIRS detekcija i CLC podataka, kao i mogućeg uticaja efekta agregacije prostornih jedinica (MAUP). Uprkos tome, primena integrisanog pristupa koji kombinuje satelitske podatke i klasifikaciju zemljišnog pokrivača predstavlja efikasan alat za analizu i identifikaciju rizičnih područja i doprinosi unapređenju sistema monitoringa i planiranja mera zaštite od požara.