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THE INFLUENCE OF CLIMATIC CONDITIONS ON THE OCCURRENCE OF LARGE FOREST FIRES: A CASE STUDY OF STARA PLANINA NATURE PARK IN 2007 AND 2019

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ABSTRACT. This work investigates the relationship between the occurrence of large forest fires (more than 1,000 ha) and meteorological data. Specifically, it analyzes the characteristics of large forest fires in July 2007 (2,500 ha) and October 2019 (2,108 ha) in Serbia's Stara Planina Nature Park (NP). The results show that at these times, forest fires occurred during long heatwaves with low relative humidity and high air temperature. Dry climatic conditions in the preceding months also contributed to the occurrence of large forest fires, alongside the presence of wind. The study uses climate indices based on the combination of air temperature and precipitation. Forest drought index (FAI) data show that 2007 and 2019 were drier than the 1961–1990 climate period. According to the Lang Precipitation Factor Index (AI_{Lang}), the periods June–July 2007 and July–October 2019 can be classified as dry. The De Martonne Drought Index (Im_{DM}) shows that July 2007 and October 2019 had the characteristic of areism. These were also the periods when large wildfires were recorded. The results of this study could be used for wildfire risk assessment in protected areas and for fire prevention and suppression planning.

Keywords: climate indices; large forest fire; Serbia; Stara Planina Nature Park.

INTRODUCTION

Some studies (Dimitrakopoulos *et al.*, 2011a; Tedim *et al.*, 2013) support the hypothesis that a fire can become large under certain circumstances. Large fires, although relatively infrequent, contribute significantly to the area burned (San-Miguel-Ayanz *et al.*, 2013; Stocks et al., 2003) and play an important role in shaping many ecosystems worldwide (Moritz *et al.*, 2014). Ganteaume *et al.* (2019) note that large fires determine the trend of and annual variability in the total area burned.

Bradstock (2010) notes that the occurrence of large wildfires is driven by the presence of spatially contiguous rows of plant biomass dry enough to burn, weather conditions conducive to rapid fire spread, and the occurrence of ignitions. Fernandes *et al.* (2016) indicate that fuel structure and composition determine fire spread and thus the locations of the largest fires. Rolinski *et al.* (2016) and Song *et al.* (2017) have concluded that winds play a key role in fire spread. Ruffault *et al.* (2017) consider wind conditions to be the main factor explaining why fires become large. The rapid occurrence of a large fire can owe to certain weather systems such as cold fronts, mountain winds and instability in the upper atmosphere (Hasson *et al.*, 2009; Sharples, 2009).

Trouet *et al.* (2009) state that climate and weather are two of the most important factors influencing a fire regime. Harrison *et al.* (2010) claim that a region's climate plays a crucial role in regulating its forest fire regime. Some studies (Barbero *et al.*, 2019; Krawchuk and Moritz, 2011; Littell *et al.*, 2009; Westerling *et al.*, 2003) suggest that fire activity is closely related to the climate of the region. The climatic conditions in the months or years before a fire also contribute to the occurrence of large fires (Keeley and Zedler, 2009). Gill and Allan (2008) note that large fires occur at certain times of the year. According to Vasić (1992), forest fires can occur throughout the year, but there are three critical periods for forest fires in Serbia: early spring (March–April), summer (July–August) and autumn (September–October). With respect to forest fires, humans pose the greatest threat to forests, due to their potential to behave inappropriately (burning vegetation) and/or undertake certain activities (especially in agriculture) that risk starting a fire.

Several studies (Dimitrakopoulos *et al.*, 2011a; Massari and Leopaldi, 1998; Pellizzaro *et al.*, 2007; Ruffault *et al.*, 2018) suggest that there is a strong correlation between the flammability of Mediterranean species and their moisture content. Nolan *et al.* (2016) note that there are clear thresholds of fuel moisture associated with wildfire occurrence. Tošić *et al.* (2019) state that the most favourable conditions for fire occurrence are high air temperatures, low relative humidity and lack of precipitation. Wells *et al.* (2004) point to the influence of the seasonal movement of maximum temperature and precipitation on the frequency of fires and the extent of destruction. In longer dry seasons and especially during periods of extremely high air temperatures, fire risk increases (Tošić *et al.*, 2020). Živanović *et al.* (2020) note that in Serbia, the greatest risk of fire occurs during the summer months. In north-eastern Serbia, where Stara Planina Nature Park (NP) is located, Tošić *et al.* (2020) highlight the importance of assessing the impact of extreme climatic conditions that favour the occurrence and spread of forest fires. Furthermore, Cardil *et al.* (2014, 2015) note that extreme temperature events are known to lead to large forest fires.

A long period without rain leads to drought, which dries out existing vegetation and facilitates the burning of fuel (Pausas *et al.*, 2012), increasing the intensity of fire and the speed of its spread. With the occurrence of major droughts, forests become highly flammable (Aragao *et al.*, 2007; Bradstock *et al.*, 2014; Hasson *et al.*, 2009; Sharples, 2009). The optimal conditions for fires are hot weather, dry fuel and ignition sources (Moritz *et al.*, 2005).

Forest fires in Serbia account for a relatively small number of fires overall (about 3.5%) (Živanović *et al.*, 2018). Of particular concern is the occurrence of large forest fires in areas protected as natural assets of exceptional importance, where they often assume the character of disasters.

The aim of the present work is to determine, based on climatic conditions, the vulnerability of forest areas protected as natural assets to the occurrence of large fires. This study's results can be used to assess the risk of fires of other forest areas through defining the relevant thresholds for the responsible services.

MATERIALS AND METHODS

Study area and data sources

Stara Planina NP is located in the eastern part of the Republic of Serbia in south-eastern Europe (*Figure 1*). The park stretches along the Serbian–Bulgarian border from Vrška Čuka (Zaječar) in the north to Dimitrovgrad in the south. Its total area is 114,332 ha, about 40% of which comprises forest (Official Gazette of RS, No. 50/93).

Stara Planina NP has a temperate continental climate, which varies depending on a specific area's altitude and location. The coldest month is January while the warmest is July. The number of forest fires and burned areas that occurred in July 2007 and October 2019 were obtained from the data of the Ministry of Interior of the Republic of Serbia, Emergency Management Sector, n.d. (MIRS, 2022). Climate indices based on the combination of air temperature and precipitation were used for this study. Air temperature, precipitation and wind data were taken from the Republic Hydrometeorological Service of Serbia (RHSS, 2022).

Methodology

The diversity of climatic conditions in different periods was determined using the De Martonne Aridity Index, I_{DM} (De Martonne, 1925), the Lang Precipitation Factor Index'Lang Factor, AI_{Lang} (Lang, 1920) and the Forestry Aridity Index, FAI (Fuehrer *et al.*, 2011), based on the following *Equations* (1-3):

$$I_{DM} = \frac{P}{T+10} \quad (1)$$

$$AI_{Lang} = \frac{P}{T} \quad (2)$$

$$FAI = \frac{T_{\mathrm{VII-VIII}}}{P_{\mathrm{V-VII}}+P_{\mathrm{VII-VIII}}} c \quad (3)$$

where P is the annual mean precipitation (mm), T is the annual mean temperature (°C), $T_{\mathrm{VII-VIII}}$ is the average temperature in July and August (°C), $P_{\mathrm{V-VII}}$ is the total precipitation in the period from May to July (mm), $P_{\mathrm{VII-VIII}}$ is the total precipitation in the period from July to August (mm), and c = 100 mm/°C is the constant.

The monthly values of the Im_{DM} and the adjusted Monthly Lang Precipitation Factor Lang Index (AI_{Langm}) were determined based on the following *Equations* (4-5):

$$AIlangm = \frac{Pm}{Tm} \quad (4)$$

$$Im\,D\,M = \frac{12Pm}{Tm+10} \quad (5)$$

where T_m is the mean monthly air temperature (°C) and P_m is the mean monthly rainfall (mm).

The classification of climate according to Lang is given in *Table 1*.

Table 1 – Classification according to Lang (1920)

AI_{Lang}	Types of climate
0 – 20	Arid
20 – 40	Arid
40 – 60	Semi-arid
60 – 100	Semi-humid
100 – 160	Humid
> 160	Perhumid

The classification of the DeMartonne Aridity Index is given in *Table 2*.

Table 2 – De Martonne Aridity Index (I_{DM}) classification

Types of climate	Values of I_{DM}
Arid	$I_{DM} < 10$
Semi-arid	$10 \le I_{DM} < 20$
Mediterranean	$20 \le I_{DM} < 24$
Semi-humid	$24 \le I_{DM} < 28$
Humid	$28 \le I_{DM} < 35$
Very humid	$35 \le I_{DM} < 55$
Extremely humid	$I_{DM} > 55$

The *FAI* and the average weather conditions of four different climate categories are shown in *Table 3*.

Table 3 – Meteorological features of forestry climate categories

FAI values	Forestry climate categories
< 4.75	Beech climate
4.75–6.00	Hornbeam oak climate
6.00–7.25	Sessile oak/Turkey oak climate
> 7.25	Forest-steppe climate

Figure 1 – Location of Stara Planina NP

Based on the value of the monthly rain factor (AI_{Langm}), the climate of certain months is characterized as follows:

$AI_{Langm} < 3.3$ the climate is arid;

AI_{Langm} 3.3 - 5 climate is semi-arid;

AI_{Langm} 5 - 6.6 the climate is semi-humid;

AI_{Langm} 6.6 - 13.3 climate is humid;

$AI_{Langm} > 13.3$ the climate is perhumid.

Based on the monthly values of the De Martonne Drought Index (Im_{DM}):

$Im_{DM} < 5$ indicates distinctly desert, areic areas;

Im_{DM} of 5–10 indicates bordering desert endorheic areas;

Im_{DM} of 10–20 indicates that drainage is exorheic (external) or endorheic (internal) and the vegetation is steppe;

Im_{DM} of 20–30 indicates that drainage is exorheic and the vegetation is wooded steppe;

Im_{DM} of 30–40 indicates that drainage is exorheic and the vegetation is forest;

Im_{DM} > 40 indicates abundant exorheic drainage and that forests cover the entire area.

RESULTS AND DISCUSSION

Basic characteristics of air temperature

In the area of Stara Planina NP during the period 1961–1990, the warmest month was July, with an average daily temperature of 19.3°C, while the coldest month was January, with an average daily temperature of –1.3°C (*Table 4*). Some studies (Bajat *et al.*, 2015; Unkašević and Tošić, 2009) suggest that the highest air temperature in Serbia during this period occurred in July 2007.

The annual temperature anomaly was positive and amounted to 1.4°C in 2007 and 2.0°C in 2019 compared to the climatological normal (1961–1990). *Table 4* shows that the mean monthly air temperature values for all months in 2007 and 2019 were above the perennial average.

The largest increase in average monthly air temperatures in 2007 was 3.7°C in the month of July. In 2019, a 2.6°C increase in the average monthly air temperature in October can be observed compared to the perennial average.

During July–August 2007 and 2019, the average monthly air temperature exceeded 20°C, posing an increased risk of forest fires. The months of August, September and October 2019 were in the 'Very warm', 91st–98th percentile range. Moreover, during the heatwave of 12 to 29 October, the period from 14 to 27 October fell in the 'Extremely hot' range (RHSS, 2022).

The number of summer days (Tx ≥ 25°C) in 2007 was 97, including 28 in July. The number of tropical days (Tx ≥ 30°C) in 2007 was 47, including 22 in July and 16 in August. In 2019, the number of summer days (Tx ≥ 25°C) was 123, including 23 in October. The number of tropical days (Tx ≥ 30°C) in 2019 was 53, while there were no tropical days in October.

The numbers of tropical days in 2007 and 2019 were significantly higher than the perennial average of 21.5, including 7.2 in July and 8.7 in August. The absolute maximum temperature was 41.4°C, measured on 24 July 2007 (RHSS, 2022).

Basic characteristics of precipitation

In Stara Planina NP, the annual maximum average precipitation for the period 1961-1990 was in June (87.1 mm) and the minimum (38.9 mm) was in September (*Table 5*) (RHSS, 2022). The decrease in the amount of precipitation was particularly pronounced in certain months during the fire season. *Table 5* shows pronounced decreases in precipitation in July 2007 and March and October 2019 compared to the perennial period.

Pronounced decreases in precipitation occurred in the months of April, June and July. The lowest amount was measured in July 2007: only 7.2 mm. No precipitation occurred in the period from 12 to 31 July.

Table 4 – Monthly mean and annual mean (Ann) air temperature (°C) at Dimitrovgrad meteorological station for different periods of the analysis

Period	Month												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
1961/ 1990	-1.3	0.9	4.9	10.0	14.6	17.5	19.3	19.0	15.4	10.4	5.2	0.7	9.7
2007	3.4	4.6	7.1	10.5	16.4	20.4	23.0	20.8	13.7	10.2	3.0	-0.4	11.1
2019	-0.9	2.4	7.4	11.1	13.6	19.9	21.2	21.6	16.8	13.0	10.6	3.6	11.7

Table 5 – Monthly mean and annual mean rainfall (mm) at Dimitrovgrad meteorological station for different periods of the analysis

Period	Month												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
1961/ 1990	42.2	40.5	46.5	51.1	74.9	87.1	60.7	44.1	38.9	39.1	61.4	49.0	635.5
2007	43.4	29.5	55.0	10.0	85.2	47.2	7.2	118.6	60.5	112.0	146.7	25.3	740.6
2019	57.5	24.4	15.8	46.0	69.1	79.4	67.5	35.0	30.7	21.4	48.5	32.9	528.2

The schedule and amount of precipitation also reduced the moisture content in the air. Air humidity in July 2007 was 54%, which was 12.7% less than in the perennial period. The lowest air humidity recorded was 15%, on 24 July 2007.

This combination of extremely low relative humidity and high air temperatures over a period of several days created conditions suitable for the occurrence of fires.

The absence of precipitation was evident in the period June–July, which, in addition to high air temperatures, caused the surface layer of the soil to dry as well as a significant decrease in moisture reserves in deeper layers of the soil. It should be noted that in the period June–July, there were 11 days when precipitation exceeded 1.0 mm, although there were no days when it exceeded 10.0 mm. An evident increase in the amount of precipitation during the vegetation period occurred in the month of August compared to the standard climatological normal (1961–1990) (*Table 5*).

The amount of precipitation in 2019 was 107.3 mm less than the perennial average. It should be noted that there were as many as ten months with a negative rainfall anomaly. The rainfall values for August, September and October 2019 were within the 'Normal', 27^{th}–75^{th} percentile range. During October 2019, the total amount of precipitation was 21.4 mm, all of which fell in the first ten days of the month. During this month, one day with more than 1 mm of precipitation and one day with more than 10 mm of precipitation were recorded. The period from 7 October to 1 November 2019 did not see any measurable precipitation.

Basic characteristics of wind

The low prevalence of silence (11‰) in this research area during the period 1961–2000 (Milovanović, 2010) is particularly interesting. Southeasterly winds were the most prevalent.

Wind speeds in the area ranged from gentle breezes to strong winds, the greatest of which occurred in mountain passes and saddles. The perennial average indicated that the highest frequency was from the south-east. The greatest mean annual wind speed was from the north-west (*Figure 2*).

Comparing the data on the frequency, speed and direction of the wind, it can be concluded that in the area of Dimitrovgrad during the month of July 2007, wind most frequently came from the south-east (SE; *Figure 3*). Wind from the north-west (NW) manifested the highest average wind speed: 3.7 m/s (*Figure 3*). On 20 July 2007, a wind speed of 3 m/s was recorded near the ground, influencing the rapid development of a fire across a large forest area. Wind gusts of 4 m/s were particularly pronounced on 23 July 2007, which made it difficult to extinguish the fire and contributed to its uncontrolled spread. A decrease in wind gusts was recorded in the days from 26 July to 28 July 2007, when at certain points the wind speed fell to 1 m/s. In the Dimitrovgrad area in the month of October 2019, wind most frequently came from the south (S; *Figure 4*). This direction also produced winds with the highest average wind speed: 2.7 m/s (*Figure 4*). On 27 October 2019, the highest wind speed (6.2 m/s) was measured near the ground, influencing the rapid development of fires across large areas of forest and grass vegetation. The mean wind gust speed during the period from 27 to 31 October 2019 was within the range of 1 to 2 m/s.

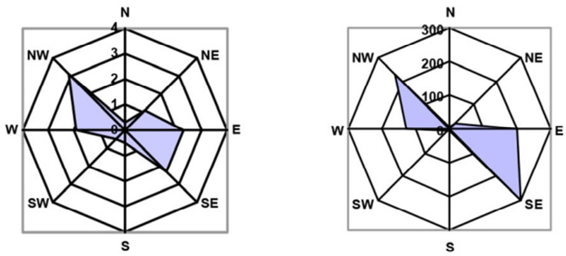
Fires in Stara Planina NP in July 2007 and October 2019

The period from 19 to 29 July 2007 was characterized by a particularly large number of forest fires in Stara Planina NP. These fires burned about 2,500 ha of low vegetation, thickets and forests in the mountainous area. On the part of Pirot Forestry, direct damage was estimated at USD 419,216.28, lost increment or profit at USD 467,256.94 and environmental damage at USD 628,824.44 (Ministry of Interior of the Republic of Serbia, Emergency Management Sector, n.d.). A large fire engulfed state forests in the Zavoj economic unit and private forests on plots in the Area of the villages of Rosomač and Slavinja. The cause of the fire was attributed to humans, i.e. the burning of organic plant remains in open areas. The fire on Mount Vidlič started in the afternoon of 20 July 2007 on south-western mountain slopes above the village of Krupac in the municipality of Pirot. The fire lasted until 30 July 2007 and affected areas at an altitude of 1,063 to 1,676 metres above sea level within the boundaries of Stara Planina NP.

On 27 October 2019, vegetation in Stara Planina NP was engulfed by a fire that spread uncontrollably from the territory of the Republic of Bulgaria. The fire lasted until 31 October 2019 and covered a total area of 2,108 ha. The fire mainly affected non-vegetated areas, i.e. pastures and meadows across a total area of 1,558 ha. The total vegetated forest area affected by the fire was 550 ha, with beech and spruce burning the most. The fire affected 276 ha of parts of the farm unit (FU) Stara planina II – Topli Do and 2 ha within the FU Stara planina II – Arbinje. Across an area of 1,365 ha, the fire affected parts of the locality 'Orlov Kamik – Kopren', where the first (I) level protection system was established. In the locality 'Sveti Nikola - Jabučko ravnište – Srebrna glava' in the territory of the cadastral municipality (CM) Topli Do and Dojkinci, the fire covered a total area of 743 ha, including parts of the area of the second level of protection (II) (Official Gazette of RS).

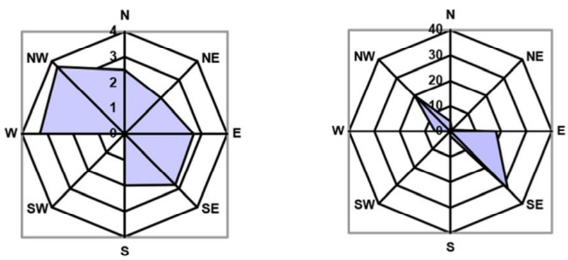
Climate indices

The FAI data revealed a significantly higher value in 2007 compared to in the period 1961–1990. An increase in drought intensity (higher index values) in the Dimitrovgrad area and thus in parts of the Stara Planina region owed to high air temperatures and lower precipitation in the summer months.



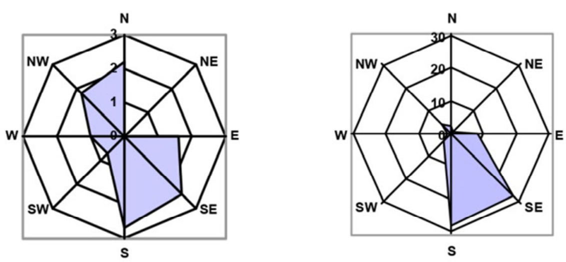
a) b)

Figure 2 – (a) Mean annual wind speed (m/s) by direction and (b) mean annual frequency of wind occurrence at the Dimitrovgrad meteorological station during the period 1961–2000



a) b)

Figure 3 – (a) Mean wind speed (m/s) by direction and (b) mean frequency of wind occurrence during July 2007 at the Dimitrovgrad meteorological station



a) b)

Figure 4 – (a) Mean wind speed (m/s) by direction and (b) mean frequency of wind occurrence during October 2019 at the Dimitrovgrad meteorological station

The drought index for 2007 and 2019 indicated a decrease in forest moisture, which created conditions suitable for the spread of fires over large areas.

The Lang Precipitation Factor (AI_{Lang}) and De Martonne Drought Index (I_{DM}) values for 2019 were significantly lower than the perennial average (*Table 6*), due to the rainfall deficit and high air temperatures. According to the I_{DM}, the moisture conditions for 2019 corresponded to those of a semi-humid climate.

The monthly values of the Lang Precipitation Factor (AI_{Langm}) and the De Martonne Aridity Index (Im_{DM}) are shown in *Table 7*. Three months in 2007 and five months in 2019 can be classified as arid. The lowest values of these indices occurred in July 2007 and October 2019, when large forest fires took place. It should also be noted that the months before these fires experienced arid conditions.

The fires analized zed occurred in inaccessible mountain areas, where they proved difficult to extinguish and so they lasted for several days. A common issue was that a fire was not detected promptly. To improve response systems in areas where forest fires periodically occur, it is necessary to install automatic terrestrial systems for their early detection and prediction. Data collected in real time can enable more effective intervention by the responsible fire protection services, thus minimizing the costs of extinguishing fires and the damage caused in forests.

This research's finding of a correlation between large fires and climate data and indices are consistent with those of other studies (Charney *et al.*, 2010; Crimmins, 2006; Dong *et al.*, 2021; Ertugrul *et al.*, 2019). Studies from other parts of the world have obtained similar findings on the relationship between large fires and drought (Chuvieco, 1999; Dennison *et al.*, 2014; Dimitrakopoulos *et al.*, 2011b; González *et al.*, 2018; Riley *et al.* 2013; Ruffault *et al.*, 2018; Russo *et al.*, 2017; San-Miguel-Ayanz *et al.*, 2013; Turco *et al.*, 2017; Urbieta *et al.*, 2015). Furthermore, the present study's results that strong winds near the ground allow fire to spread over long distances is consistent with those of Abatzoglou *et al.* (2013), Hernandez *et al.* (2015), Lahaye *et al.* (2018) and Ruffault *et al.* (2017).

This investigation has revealed the occurrence of variations in the amount of precipitation (reductions) and the air temperature (increases) as well as increases in wind speed in the months preceding large forest fires, which influenced the drying of fuel and vegetation, causing it to become more sensitive and burn more easily. In Serbia, there is no monitoring of climate parameters in high-altitude and isolated areas. Instead, climate stations are mostly located at lower altitudes and near settlements. The stations measuring climatic parameters relevant to the occurrence and development of forest fires belong to the network coordinated by RHSS, from which we took the data presented in this paper. Given that no measurements of climate parameters exist for the research area in question, we cannot show the conditions that lead to the occurrence and development of forest fires at the local level.

Table 6 – Values of the *FAI*, AI_{Lang} and I_{DM} indices for the period 1961–1990 and the years 2007 and 2019 for the Dimitrovgrad meteorological station

Period	*FAI*	AI_{Lang}	I_{DM}
1961–1990	Forest-steppe climate (*FAI* = 11.7)	Semi-humid (AI_{Lang} = 65.5)	Humid (I_{DM}=32.3)
2007	Forest-steppe climate (*FAI* = 16.5)	Semi-humid (AI_{Lang} =66.7)	Very humid (I_{DM}=35.1)
2019	Forest-steppe climate (*FAI* = 13.4)	Semi-arid (AI_{Lang} =45.1)	Semi-humid (I_{DM}=24.3)

Table 7 – Monthly AI_{Lang} and I_{mDM} values for the period 1961–1990 and the years 2007 and 2019 for the Dimitrovgrad meteorological station

Period	Index	Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1961–1990	AI_{Lang}	-	45	9.5	5.1	5.1	5.0	3.1	2.3	2.5	3.8	11.8	70
	I_{mDM}	58.2	44.6	37.4	30.7	36.5	38	24.9	18.2	18.4	23.0	48.5	55.0
2007	AI_{Lang}	12.8	6.4	7.7	1.0	5.2	2.3	0.3	5.7	4.4	11.0	48.9	-
	I_{mDM}	38.9	24.2	38.6	5.9	38.7	18.6	2.6	46.2	30.6	66.5	135.4	31.6
2019	AI_{Lang}	-	10.2	2.1	4.1	5.1	4.0	3.2	1.6	1.8	1.6	4.6	9.1
	I_{mDM}	75.8	23.6	10.9	26.2	35.1	31.9	26.0	13.3	13.7	11.2	28.3	75.8

If there were measurements, the data collected on the ground in real time would allow for more effective intervention if and when a fire occurs as well as increase the ability to predict the occurrence of a fire

CONCLUSIONS

Prolonged drought is an important predictor of large forest fires in Serbia. This case study of Stara Planina NP from 2007 and 2019 has shown that the occurrence of large forest fires is strongly influenced by weather conditions. Trend analysis of the time series revealed pronounced increases in air temperature and decreases in precipitation in July 2007 and October 2019, when large forest fires occurred. Extreme climatic conditions such as high maximum air temperatures, a large number of tropical days and nights, long heatwaves, prolonged drought and a long-term deficit in soil moisture favour the occurrence and spread of forest fires. Wind plays a key role in the uncontrolled spread of fires over large areas. The results derived from the application of drought indices have shown that more intense droughts in the summer months can create conditions suitable for the occurrence of large forest fires.

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