THE INFLUENCE OF THERMAL SOIL REGIMES ON THE FOREST FIRES FREQUENCIES

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This paper focuses on the possible impact of the thermal soil regime on the occurrence of forest fires in the Zaječar administrative district in Eastern Serbia. The study uses data on soil temperature from the Republic Hydrometeorological Service of the Republic of Serbia and the ERA5-Land gridded reanalysis dataset for monthly temperature and volumetric soil water of the soil level 1 (0-7 cm), and soil level 2 (7-28 cm) with horizontal resolution of 0.1° (approximately 12 km × 12 km) during the period of 2009–2021. Differences in soil temperature at depths of 2, 5, 10, and 20 cm at the meteorological station in Zaječar for the periods 1961–1990 and 2009–2021 are observed. By analyzing the data on the registered number of forest fires for the period 2009–2021, pronounced oscillations in the dynamics of forest fires can be observed. The minimum number of forest fires (0) is registered in 2014, when the maximum of soil moisture in the soil levels 1 and 2 is observed. A high number of forest fires corresponds to high soil temperatures in 2012 and 2017. Soils drier and hotter than the average are registered in 47.0% of all months with the fire occurrences. About 50% of fires occurred in dry and hot soils during 2012 and 2017. This percentage was zero in 2014, when there were no fires.

Key words*: soil temperature, forest fires, Zaječar administrative district (ZAD), Serbia*

1. Introduction

The characteristics of the spatial-temporal distribution of soil temperature are a significant but rarely described sign of climate warming [1]. Analysis of long-term trends in soil temperatures could provide valuable information on climate change [2]. According to Zhang and He [3], soil surface temperature is one of the basic parameters of energy exchange. Therefore, soil temperature at different depths is a unique parameter and can be useful for understanding both surface energy processes and regional ecological and climatic conditions [4]. The spatial and temporal dynamics of soil temperature strongly influence a wide range of biotic and abiotic processes in boreal forests [5]. The temperature of the soil plays a very important role in many of the chemical and biological processes that take place within it [6].

The water-holding capacity of the soil, which facilitates biomass growth between fire may exacerbate the fire regime if long dry summers become frequent [7]. Onwuka [8] states that soil temperatures affect the water content of the soil and its conductivity and availability to plants. High temperatures are usually accompanied by low soil and air humidity, which in extreme cases can lead to dehydration and drying-up of the entire plant. The heating of the surface and deeper layers of the soil depends on a number of factors in addition to geographical location: the physical characteristics of the soil, the type of cover (e.g., plants or snow), exposure, terrain, and so on [6, 9]. Vegetation affects soil temperatures [10, 11]. It improves the thermal conditions of the soil's surface layer, depending on the type of plants and the density of the cover [12]. Vegetation cover consumes significant amounts of heat for transpiration, depending on its physiological growth processes. Dark soils absorb more solar energy and heat up faster during the day than lighter soils, which have a higher albedo [13, 14]. The thermal conductivity of the soil decreases as it becomes more porous [15].

The degree of forest fire risk depends to a large extent on the substrate, that is, of the parent substrate and its soil, as well as the moisture content in the ground fuel material (e.g., needles, leaves, and branches) [16]. The type and physical properties of the soil can affect the amount of water available to the plants. Sandy soils leak water quickly, while heavy clay soils retain it. The best soils are loamy with a crumbly structure; these have the most regulated water regime [17-19]. Sandy soils heat up faster so the grass vegetation on them dries quickly and becomes flammable, even during the smallest droughts [20].

Several studies have shown that low humidity and high soil temperatures are indicators of the occurrence and extent of forest fires on the Iberian Peninsula and surrounding island [20-22]. Živanović [23] states that by drying out vegetation and reducing the moisture content in fuel material, conditions can be created for forest fires to start and spread. Many authors have revealed connections between weather conditions and the occurrence of forest fires in different areas in Serbia [23-29] and worldwide [30-36].

To protect forests from fire, it is important to know the temperature of the soil during the vegetation period, because this affects the growth and development of above-ground parts of the plant and the degree of growth and absorption of roots.

This paper aims to investigate the monthly and annual variability of soil temperature in the Zaječar administrative district (ZAD) in Eastern Serbia, and determine the periods of increased danger from forest fires.

2. Material and methods

2.1. Geographical position

The ZAD is located in the eastern part of the Republic of Serbia (Fig. 1). Based on the division of geographical regions in Serbia, the area of the ZAD is classified as Eastern (Balkans) Serbia. The total area is 3,623 km^2 and is characterized by a complex geological structure, relief, and vegetation. The forest cover of the area under investigation is 36.19%.

The climate in eastern Serbia is continental [37]. The average annual air temperature in Zaječar was 11.0°C during the period 1981–2010; the warmest month was July and the coldest January [38].

The average annual rainfall in Zajecar was 581.4 mm. The minimum amount of precipitation in Zaječar was in January, while the maximum was in May or June [38].

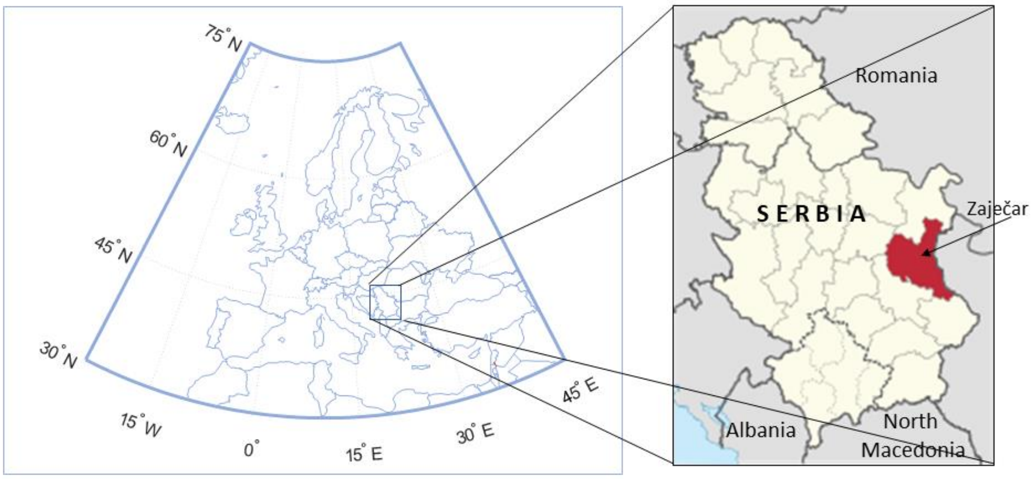

Figure 1. Location of Serbia in Europe and map of the Zaječar administrative district.

The mountains on the territory of the ZAD are built of different rocks: sandstone, limestone and volcanic rocks. The thickness of the sandstone on Stara Planina is more than 1000 m. Karstic relief forms are common in this area due to the presence of limestone. The hilly and mountainous part of the area, where there are forests, has soils with poorer characteristics (rendzina, brown acid soils, syrosem).

2.2. Data

Data on the registered number of forest fires in the area under investigation for the period 2009-2021 were obtained from the Sector for Emergency Situations of the Ministry of the Interior of the Republic of Serbia in Belgrade. Data on the area affected by these fires were not considered because it was difficult to obtain precise data.

Data on soil temperature were obtained from the Republic Hydrometeorological Service of the Republic of Serbia (RHMSS) for the meteorological station Zaječar (φ = 43° 53ʹ N, λ = 22° 18ʹ E, and h = 144 m asl). Temperatures were measured at four depths (2, 5, 10, and 20 cm) for the period 1961–1990 and 2012, 2014, and 2017. The data series were complete and quality controlled by the RHMSS.

Considering that the fire covers large forest areas (sometimes several km^2), it is impossible to measure the temperature of the soil at the location of the fire in real conditions. Hence, data from the ERA5-Land gridded reanalysis dataset for monthly surface temperature (ts), temperature (stc1) and volumetric soil water (smc1) of the soil level 1 (0-7 cm), and temperature (stc2) and volumetric soil water (smc2) of the soil level 2 (7-28 cm) were used. Soil temperatures are calculated at the middle of each layer and volumetric soil water represents the volume of water in each layer in units m^3/m^3. Horizontal resolution was 0.1° (approximately 12 km × 12 km) in regular latitude/longitude coordinates during the period of 2009–2021.

3. Results and discussion

3.1. Dynamics of forest fire outbreaks in the ZAD

The season for forest fires varies significantly from year to year. Figure 2 shows the number of forest fires during the period from 2009 to 2021. The year with the highest number, 2017, witnessed extreme weather conditions, including long periods of drought combined with high air temperatures. The years 2014 and 2018 saw the lowest number. Precipitation significantly above the long-term average values created humid conditions and reduced the risk of conflagration.

There was a negative trend in the number of forest fires in the ZAD during the period 2009-2021 (Fig. 2). The equation of the linear trend is as follows:

$$NF = -0.36264\, t + 11.2 \qquad (1)$$

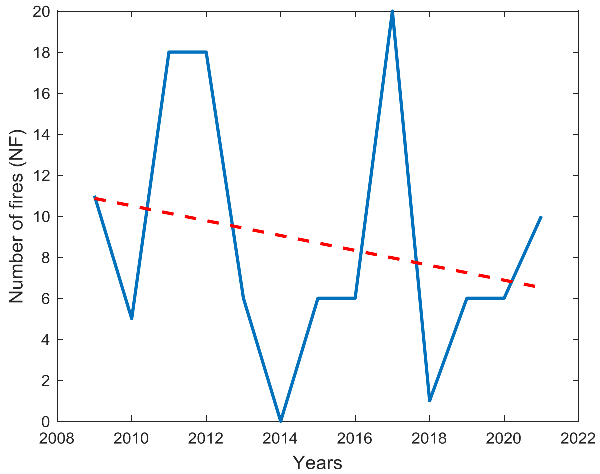

Figure 2. Number of fires on the territory of Zaječar for the period 2009-2021; linear trend is presented by dashed line.

As can be seen in Fig. 3, the forest fire season lasted from March to December. The most of the fires occurred during March (20.35% of the total) from 2009 to 2021 in ZAD, which is in agreement with the dynamics of forest fires in Serbia obtained by [25]. They concluded that forest fires usually occured in the season of agricultural works in spring.

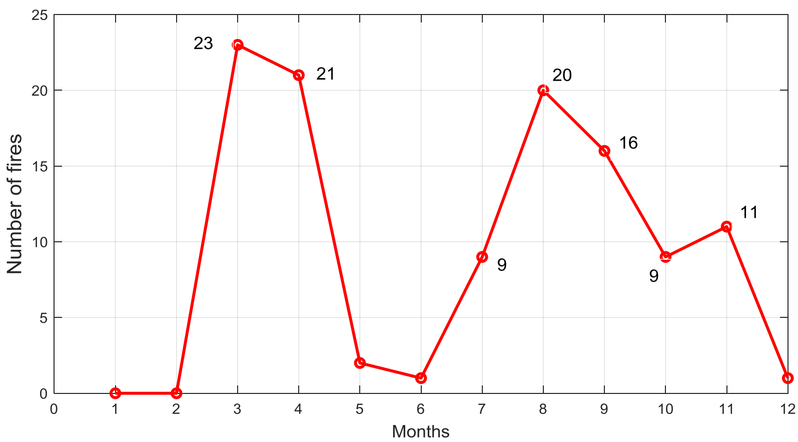

Figure 3. Number of forest fires per month in the period 2009-2021.

3.2. Analysis of soil temperature

The annual time series of soil temperature and soil moisture are calculated by averaging daily values. Spatial distribution of mean values of surface temperature (ts), soil temperature (stc1) and soil volumetric soil water (smc1) of the soil level 1 (0-7 cm), and temperature (stc2) and volumetric soil water (smc2) of the soil level 2 (7-28 cm) for Serbia during the study period 2009-2021 is presented in Fig. 4. The highest values (higher than 13 °C) of ts (Fig. 4a), stc1 (Fig. 4b) and stc2 (Fig. 4c) are observed in northern Serbia, while the minimum values (about 5°C) are recorded in mountain areas of southwestern and southeastern Serbia. Temperatures of the soil level 1 (Fig. 4b) and soil level 2 (Fig. 4c) are higher than the surface temperatures (Fig. 4a). The minimum value of smc1 (Fig. 4d) and smc2 (Fig. 4e) of about 0.14 m^3/m^3 is noted in northern Serbia, the maximum value of 0.4 m^3/m^3 is registered at the south of Serbia. According to Fig. 4, hot and wet soils prevailed in the ZAD at the eastern Serbia.

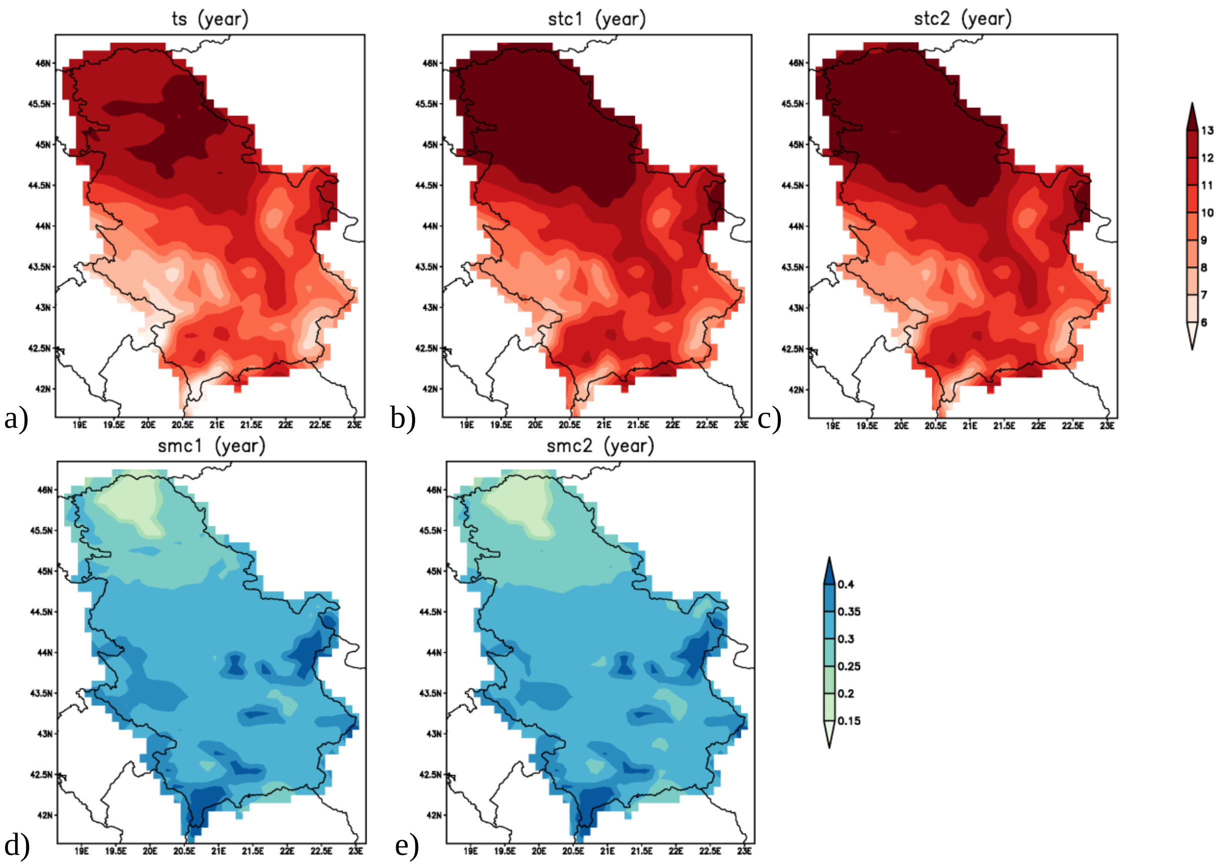

Figure 4. a) Surface temperature (ts), b) temperature (stc1) of the soil level 1 (0-7 cm), c) temperature (stc2) of the soil level 2 (7-28 cm), d) volumetric soil water (smc1) of the soil level 1 (0-7 cm), and e) volumetric soil water (smc2) of the soil level 2 (7-28 cm) in Serbia during the period 2009-2021.

Figure 5 displays measurements of the mean monthly soil temperatures at different depths in Zaječar. The highest soil temperature values were in July and the lowest in January (Fig. 5). Perennial measurement results showed that the highest mean monthly soil temperature (a value of 25.5 °C) was measured at a depth of 2 cm in July. The soil surface began to heat up in March, most intensively at a depth of 2 cm. The most pronounced increase in soil temperature was recorded in the April–May period and the most pronounced decrease in the September–October period. Higher soil temperatures were recorded in the second half of the year.

The daily fluctuation of the soil temperature decreases with depth until a constant is reached. On average, this occurs at a depth of 1 m, although it depends on the type of soil and humidity, season, and latitude. The temperature of the land surface is variable and depends on the depth of measurement and the time of day. The time lag between maximum and minimum soil temperature increases with depth. It takes time for the surface layer to heat up and for the heat to be transferred through the soil, a process that depends largely on its heat capacity.

The temperature of the deeper layers of the soil depends on the heating of the surface layer and the characteristics of the soil that affect heat transfer. The transfer of energy from the surface to the deeper layers of the soil and vice versa is more efficient in wet than in dry soil. The water content in the soil increases its thermal conductivity. In summer, the heat in moist soil is more easily conducted through deeper layers, and in winter it is released more intensively.

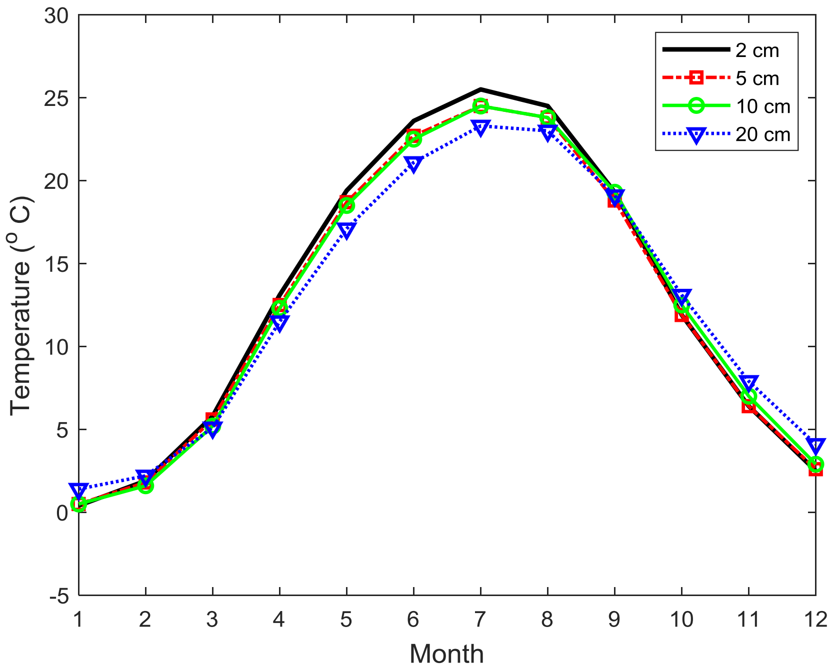

Figure 5. Mean monthly values of soil temperature (°C) at 2, 5, 10 and 20 cm depth at the Zaječar station, period 1961-1990.

Hence, annual time series of soil temperature and moisture of the soil level 1 (0-7 cm) and level 2 (7-28 cm) are presented in Fig. 6. The highest temperature of the soil level 1 and level 2 (Fig. 6a) is observed in 2012, while the peak of soil moisture of the soil level 1 and level 2 (Fig. 6b) is noted in 2014. The soil temperature and volumetric soil water of level 1 were higher than ones of level 2 (Fig. 6).

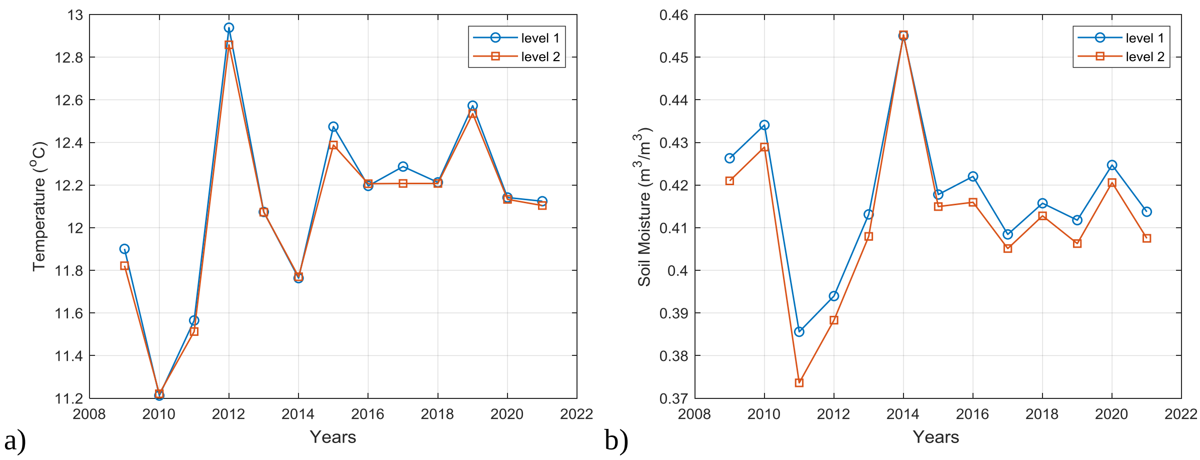

Figure 6. a) Soil temperature and b) soil moisture of the soil level 1 (0-7 cm) and the soil level 2 (7-28 cm), at Zaječar, period 2009-2021.

The monthly regime of the soil temperature at different depths for selected years (2012, 2014 and 2017) is presented in Fig. 7.

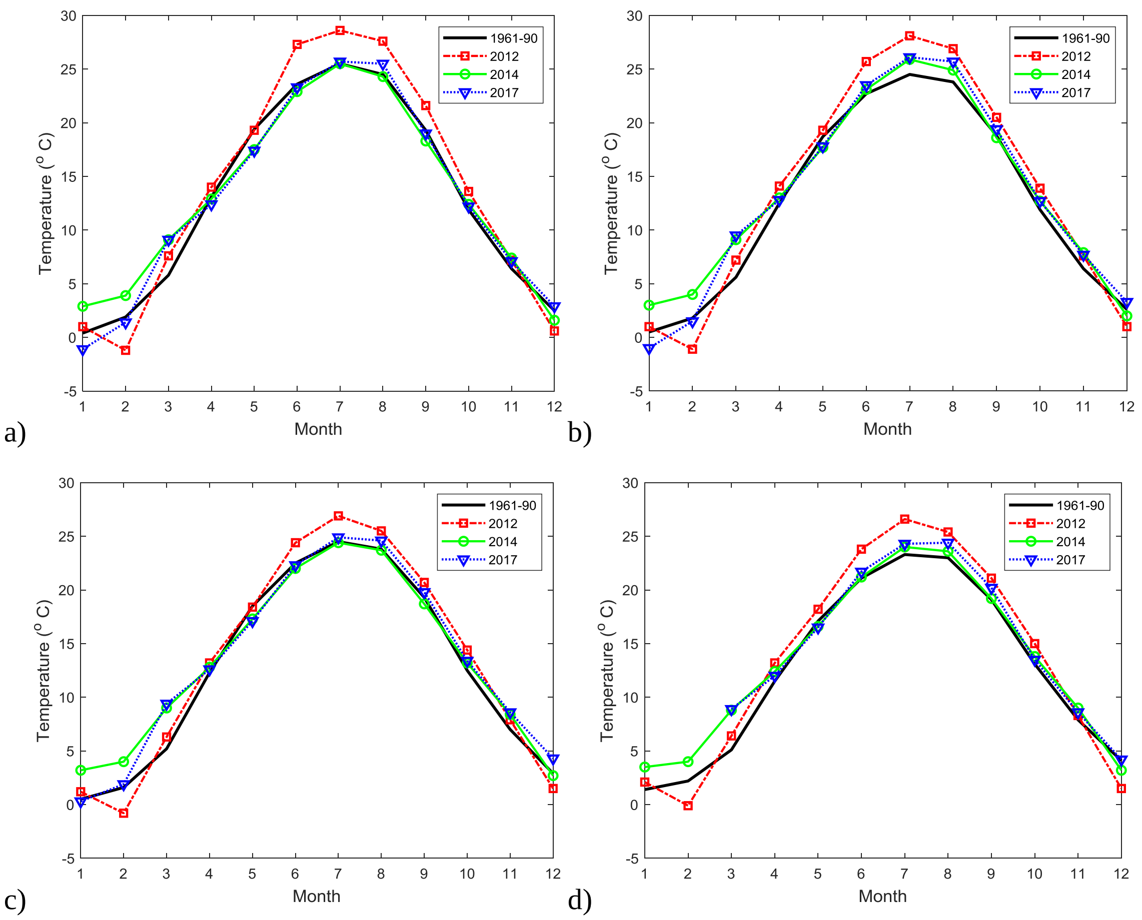

Figure 7. Mean monthly soil temperature at the Zaječar station in different time periods (1961-1990, 2012, 2014 and 2017) and at different depths: a) 2 cm; b) 5 cm; c) 10 cm; d) 20 cm.

The year of 2012 was the warmest (Fig. 6a), 2014 the wettest (Fig. 6b), and in 2017 the highest number of forest fires (Fig. 2) was recorded during the period 2009-2021. The results show that the highest mean monthly temperature (28.6 °C, at 2 cm) was measured in July 2012 (Fig. 7a). This was 3.1 °C higher than the long-term average (Fig. 7a). In addition, the maximum value of monthly temperatures is observed in 2012 at depth of 5 cm (Fig. 7b), 10 cm (Fig. 7c) and 20 cm (Fig. 7d). During the warm part of the year, the temperature decreased with depth. It increased in the cold part.

To examine conditions during the fire events in the ZAD, moisture-temperature data have been coupled and presented by months and years in Figs. 8 and 9, respectively. In order to determine which fires burned in dry and warm soils, reference values approximately defining normal moisture-temperature conditions have been stablished yearly [21]. These values were calculated as the long-term mean of both variables in the ZAD and presented by dotted lines in Figs. 8 and 9. Regarding soils moisture and temperature, soils drier and hotter than the average are noted in 47.0% (Fig. 8) of all months with the fire occurrences. These percentages varied depending on years, for example, during 2012 (Fig. 9a) and 2017 (Fig. 9b) when a higher fire frequency is registered, about 50% of fires happened in dry and hot soils. This percentage was zero in 2014, when there were no fires, and the soil moisture was high (Fig. 9c).

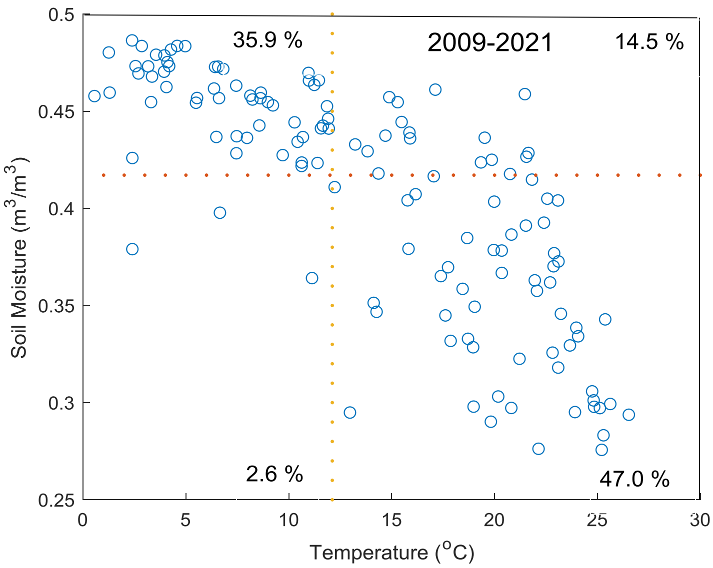

Figure 8. Mean monthly soil temperature (°C) and soil moisture (m^3/m^3) of the soil level 1 for months with fire occurrences during the period 2009-2021. Dotted lines represent the mean values of temperature and moisture in Zaječar.

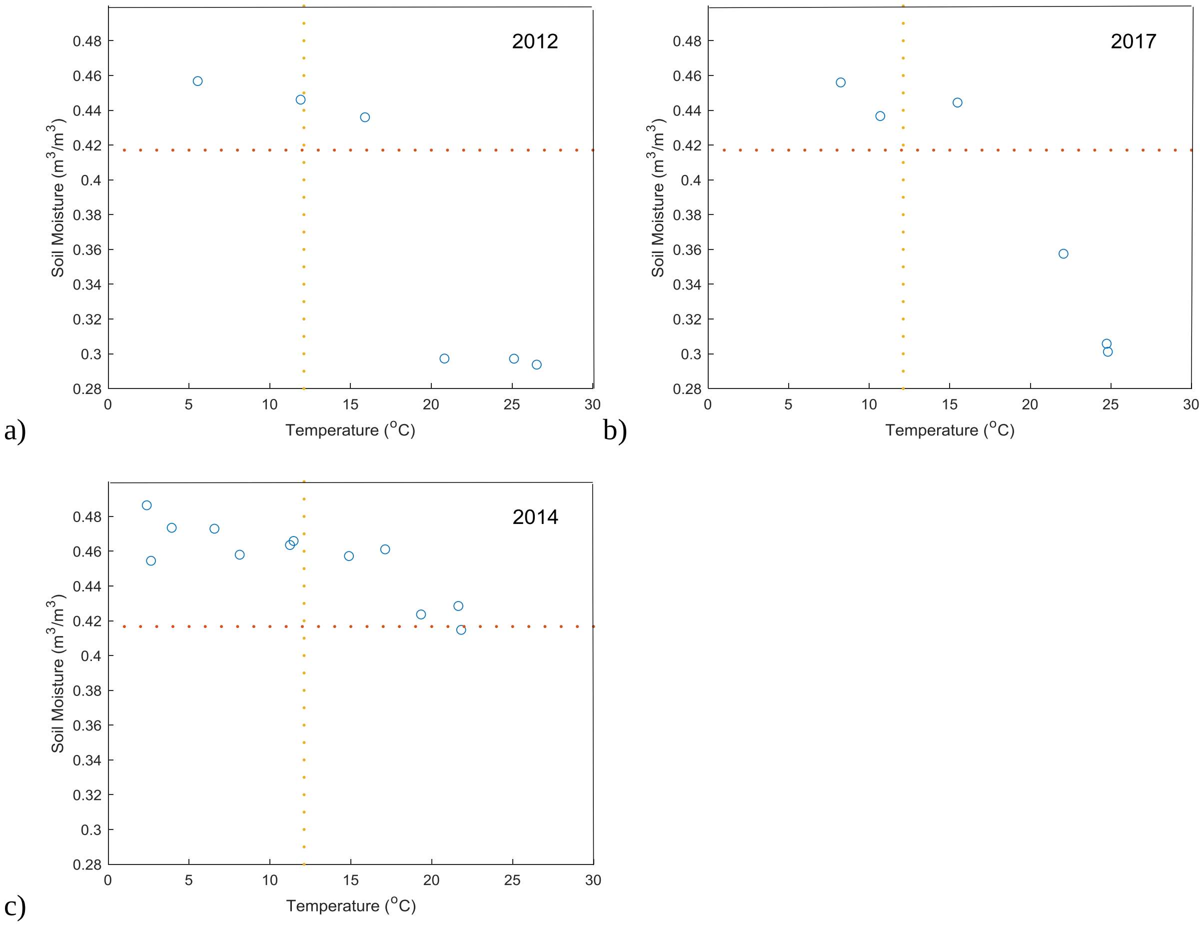

Figure 9. Mean monthly soil temperature (°C) and soil moisture (m^3/m^3) of the soil level 1 (0-7 cm), for months with fire occurrences in: a) 2012 and b) 2017; c) 2014 for all months. Dotted lines represent the mean values of temperature and moisture in Zaječar

It can be concluded that most wildfires burned when soil temperature was higher and soil moisture was lower than the overall yearly averages. Our results are in an agreement with [21], who analysed the relationship of forest fires with soil moisture and temperature patterns in the Iberian Peninsula and the Balearic Islands between 2010 and 2014.

Conclusions

The thermal regime of the soil is recognized as one of the important parameters for forestry development and forest protection. A comparative analysis of the values measured shows that, when compared with the reference period 1961-1990, the period 2009-2021 saw an increase in the average soil temperature at the research area. The present study demonstrates that the forests in the ZAD are vulnerable to fires between March and December. The risk of fires was highest during the months of March, April and August. High soil and air temperatures, and small amounts of precipitation were recorded during the latter. The occurrence of fires in March, when soil and air temperatures are low, points to the influence of human factors. The analysis of the 2009-2021 data shows a pronounced difference in the number of fires in 2014 (when there were none) compared with 2017 (when there were 20). To investigate conditions during the fire events, moisture-temperature data have been coupled. Regarding soils moisture and temperature, soils drier and hotter than the average are registered in 47.0% of all months with the fire occurrences during the period 2009-2021. About 50% of fires happened in dry and hot soils in 2017, while this percentage was zero in 2014, when there were no fires.

Given that the forests in the ZAD are located mostly at higher hypsometrical altitudes, stations for measuring soil temperature should be set up in the mountains. These would enable a more realistic assessment of the impact of thermal soil regimes on fire risk. The analysis of fire risk in the future should be based on soil moisture-temperature information enhanced with the application of remotely sensed land data from geostationary satellites.

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Nomenclature

N – the number of observations
NF – number of forest fires
smc1 – volumetric soil water [m^3/m^3] of the soil level 1
smc2 – volumetric soil water [m^3/m^3] of the soil level 2
stc1 – temperature [°C] of the soil level 1
stc2 – temperature [°C] of the soil level 2
t – time [years]
ts – surface temperature [°C]
φ – geographical latitude
λ – geographical longitude
h – altitude.

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