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EXPLORING LONG-TERM WILDFIRE DYNAMICS ACROSS LAND COVER TYPES IN RELATION TO CLIMATE IN THE EASTERN MEDITERRANEAN LANDSCAPES

ISTRAŽIVANJE DUGOROČNIH DINAMIKA POŽARA U RAZLIČITIM TIPOVIMA ZEMLJIŠNOG POKROVA U ODNOSU NA KLIMU U KRAJOBRAZIMA ISTOČNOG MEDITERANA

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SUMMARY

The Mediterranean region is characterized by diverse landscapes and unique climatic conditions, making this region of crucial importance in the context of wildfires. Türkiye is one of the largest countries in the Mediterranean region with remarkable ecological richness, characterized by diverse land covers encompassing a variety of ecosystems and habitats. Fires play a crucial role in shaping ecosystems in fire prone areas in the country. Understanding the relationship between vegetation composition, climatic factors and historical fire patterns is thus crucial for effective fire management and conservation efforts in the Eastern Mediterranean and the world in general. This study reports and discusses fire dynamics in Türkiye spanning from 2001 to 2020 across diverse land cover classes, employing both the ESA FireCCI51 burned area product and ground-based fire data. This study aims to provide insights into the complex relationship between wildfire activities by examining the interactions and long-term climate variables, vapor pressure deficit (VPD) and the Angström index. The analysis of FireCCI51 data revealed different spatial patterns of wildfire occurrence in different landscapes of the study area. Fires were mainly concentrated in needle-leaved and shrubland landscapes in the west and south, while broad-leaved, herbaceous, and agricultural fires were prevalent in various parts of Türkiye. Despite legal restrictions, stubble burning remains a common practice, contributing to fire occurrences, especially during dry and hot periods after harvest. Long-term climate trends, particularly increasing VPD and decreasing rainfall, significantly impact wildfire dynamics in the study area. High VPD values correlate well with increased fire activity, indicating its role in fuel moisture and burned area. The increasing trend in VPD and decreasing trend in the Angström index underscores the landscape's increasing susceptibility to wildfires, suggesting a potential impact of climate change on burned area.

KEY WORDS: wildfires, FireCCI51, land cover, vapor pressure deficit, Angström index

INTRODUCTION
UVOD

The Mediterranean region, with its diverse landscapes and unique climatic conditions, is of crucial importance in the context of wildfires (Pausas et al. 2008). This region encompasses a rich mosaic of land covers ranging from open and dense forests to shrublands, grasslands, and agricultural areas (Lavorel 1999). However, alongside its ecological rich-

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ness, the Mediterranean region is also characterized by a pronounced susceptibility to wildfires, and understanding the long-term wildfire dynamics is of great importance (Coskuner 2022b; Marchi et al. 2018).

Ecologically, wildfires play a crucial role in shaping Mediterranean ecosystems, influencing vegetation dynamics, nutrient cycling, and habitat structure and composition (Naveh 1994). Many plant species in the region have adapted to fire, with some species even requiring periodic burning for regeneration (Pausas and Vallejo 1999). However, the increasing frequency and severity of wildfires, exacerbated by factors such as land use change, urbanization and climate change pose significant challenges to ecosystem resilience and biodiversity conservation (Coskuner 2022b; Vilar et al. 2016). Moreover, stubble burning presents a significant environmental challenge, particularly prevalent in agricultural areas where post-harvest residue is abundant (Virto et al. 2007; Yakupoglu et al. 2022). It releases harmful pollutants such as particulate matter, carbon monoxide, and volatile organic compounds into the atmosphere (Das et al. 2024), which affects air quality and poses a health risk to human populations (Chanana et al. 2023). Therefore, these fires can also have profound economic and social impacts, affecting public health, livelihoods and infrastructure (Bilgili et al. 2021a).

Monitoring and analyzing long-term fire dynamics is crucial for effective fire management and mitigation strategies (Coskuner 2022a). Satellite-based remote sensing offers a valuable tool for assessing burned areas over large areas and extended time periods, providing consistent and systematic data collection at relatively low cost (Giglio et al. 2018; Lizundia-Loiola et al. 2020; Coskuner et al. 2023). In the last two decades, several satellite-based global burned area (BA) products have been developed (Alonso-Canas and Chuvieco 2015; Giglio et al. 2018; Lizundia-Loiola et al. 2020; Tansey et al. 2008), with those derived from MODIS (Moderate Resolution Imaging Spectroradiometer) data being the primary source for monitoring fire activity worldwide. The latest publicly available versions include MCD64A1 Collection 6 at a resolution of 500 meters (Giglio et al. 2018) and the ESA FireCCI51 product at a resolution of 250 meters (Lizundia-Loiola et al. 2020). These products provide comprehensive coverage over an extended period, starting from 2000 onwards, making them valuable resources for analyzing historical and recent fire dynamics (Katagis and Gitas 2022). FireCCI51 has a higher spatial resolution compared to MCD64A1 C6 and finer spatial resolution allows for more detailed mapping of burned areas and better detection of smaller fires (Lizundia-Loiola et al. 2020). Therefore, FireCCI51 BA product can be used to analyze long-term wildfire activity across land cover classes in the Mediterranean landscapes where relatively small scale fires dominate the fire regime (Pausas and Fernández-Muñoz 2012).

Climate plays an important role in shaping long-term fire activity, offering valuable insights into the environmental conditions conducive to fire occurrence and spread (Abatzoglou et al. 2018). Understanding the influence of climatic factors such as air temperature, relative humidity and rainfall patterns is crucial for assessing historical fire trends, predicting future fire occurrences and burned areas, and developing effective fire management strategies (Mueller et al. 2020; Rao et al. 2022; Bilgili et al. 2019). One important variable to effect fire activity is vapor pressure deficit (VPD) (Seager et al. 2015). It is the difference between the amount of moisture in the air and the maximum amount of moisture the air can hold at a specific temperature (Mueller et al. 2020). VPD quantifies atmospheric dryness, with higher VPD values indicating drier air conditions. Understanding VPD is important for analyzing long-term wildfire activity (Sedano and Randerson 2014) as it directly influences fuel moisture content (Bilgili et al. 2019), vegetation flammability, and fire behavior (Seager et al. 2015). High VPD values correlate with increased evapotranspiration rates, leading to the desiccation of vegetation and drying of surface fuels leading to heightened fire danger. During periods of increased VPD, vegetation becomes more susceptible to ignition, and fires are more likely to spread rapidly due to the abundance of dry fuel (Rao et al. 2022).

Fire indices are mathematical formulations used to assess fire danger and potential wildfire behavior based on various weather and environmental conditions. These indices integrate weather parameters and fuel moisture conditions to quantify the level of fire danger in a given area (Van Wagner 1987). One of the fire indices is the Angström index, which is calculated by combining air temperature and humidity (Angström 1942), and which can provide valuable information for long-term fire analysis through its association with climatic conditions and atmospheric dynamics (Wastl et al. 2012; Holsten et al. 2013). By incorporating fire indices such as Angström index and VPD into long-term wildfire analysis, researchers can identify trends, assess fire danger, and understand the underlying drivers of fire activity over time.

Some studies have been conducted to analyze fires at different geographic scales (García et al. 2022; Earl and Simmonds 2018), including the Mediterranean region and Türkiye using satellite-based burned area products (Tonbul 2024; Malkisnon et al. 2011). However, little information is available regarding the exploration of long-term fire dynamics across different land cover classes and unveiling the interactions between long-term climate variables in Türkiye. This area stands out in the Eastern Mediterranean region with remarkable ecological richness, characterized by diverse land covers that encompass a variety of ecosystems and habitats. From dense forests to arid shrublands, landscapes host a wealth of biodiversity, supporting numerous plant and animal species (Atalay et al. 2014). Fires play a crucial role in shaping the structure and composition of ecosystems in this region (Bilgili et al. 2021b).

This study aims to investigate fire dynamics in Türkiye from 2001 to 2020 across various land cover classes using the FireCCI51 burned area product and ground-based fire data, focusing on the interactions between long-term climate variables, vapor pressure deficit (VPD), and the Angström index to understand the factors driving wildfire activity. Additionally, it seeks to contribute to a holistic understanding of wildfire dynamics in the Eastern Mediterranean region, offering valuable information in the development of effective wildfire management strategies tailored to the region's specific environmental conditions and land cover characteristics.

MATERIAL AND METHODS
MATERIJAL I METODE

Study site – *Područje istraživanja*

The study area encompasses the mainland of Türkiye, situated between 35° and 43° North latitudes, and 25° and 45° East longitudes (Figure 1). Türkiye possesses a land area of 78.4 million hectares, with approximately 23.2 million hectares covered by forests, constituting around 29.7 percent of the total land area (GDF 2022). Roughly 12.5 million hectares of forested land are prone to and at risk of wildfires, with the majority of fires occurring in regions characterized by Mediterranean climate, marked by high temperatures and low rainfall during the wildfire season, predominantly in southern and western part of the country (Bilgili et al. 2021a).

In the period 1988-2022, a total of 76.931 fires burned a total of 510.097 ha of forest land. This represents 2.198 fires on 14.574 ha annually, with an average area of 6.6 hectares burned per fire (GDF 2022). These fires originate mainly from negligence and carelessness, arson, natural/lightning, and unknown causes. It is known that a significant portion of fires with unknown cause are human-caused fires (unidentified picnic fires, out-of-control fires ignited for cleaning debris, cigarettes, etc.) (Bilgili 2005). According to recent statistics (1988-2022), of the entire burned area, 10% is classified as arson, 62% as negligence and carelessness, 3% as natural/lightning and 25% as unknown, indicating that 97% of the fires are human-caused (GDF 2022).

Wildfires mainly take place in the southern and western parts (Mediterranean and Aegean region) of the country, where the majority of land areas are covered by needle-leaved forests, shrubland, mosaic tree-shrub vegetation and grassland/herbaceous areas (Figure 1). Needle-leaved forests are mainly dominated by the Turkish red pine (*Pinus brutia* Ten.) and Anatolian black pine (*Pinus nigra* Arn.) (Atalay et al. 2014). Shrublands/maquies are mainly dominated by the Mediterranean maquie vegetation (i.e., *Arbutus andrachne* L., *Quercus coccifera* L. *Laurus nobilis* L., *Pistacia terebinthus* L., *Cistus* spp. and *Myrtus communis* L.) (Coskuner 2022a).

Cropland residue burning, while strictly banned, remains a prevalent agricultural practice despite its significant environmental effects and a considerable risk as a potential cause of forest fires in the country (Bilgili 2005). The practice of burning crop residues after harvest, such as wheat and corn stalks, often occurs in proximity to forested areas, particularly during the dry summer months when vegetation is highly susceptible to ignition (Yakupoglu et al. 2022). These residue burnings can quickly escalate into uncontrolled wildfires, especially when weather conditions are favorable for fire spread. Embers carried by wind can ignite surrounding forests, leading to wildfires.

The Aegean and Mediterranean coasts experience cool, rainy winters and hot, moderately dry summers. Annual precipitation in these areas varies from 580 to 1,300 millimeters, depending on the location. The Black Sea coast receives the highest amount of rainfall, with the eastern part receiving up to 2,200 millimeters annually. It is also the only region in Türkiye that receives rainfall throughout the year (TSMS 2024).

The wildfire season typically spans from late May to mid-September across the country. However, due to the rise in average annual temperatures in recent decades (Atalay et al. 2024), the wildfire season has extended in the southern regions. Coupled with the increase in fuel continuity (Coskuner 2022b) in the region, very fast-spreading, high-intensity, and destructive fires are expected to be become more common. In 2021 alone, over a hundred thousand hectares of forested land was burned during the end of July to mid-August (Bilgili et al. 2021a; Coskuner and Bilgili 2022). Moreover, there has been an increase in the number of fires in the northeastern part of the country (Coskuner 2021). Additionally, significant fires (>50 hectares) are becoming more common in the Midwestern part of the Black Sea region.

Land cover – *Zemljišni pokrov*

The fireCCI51 burned area product classifies the burned area using ESA CCI Land Cover classification system. The land cover types of the study area were assed using the ESA CCI Land Cover classification system. The CCI-LC project delivers consistent global land cover maps at 300 m spatial resolution annually from 1992 to 2015 (ESA 2017). The CCI land cover dataset has 38 different classes both at the

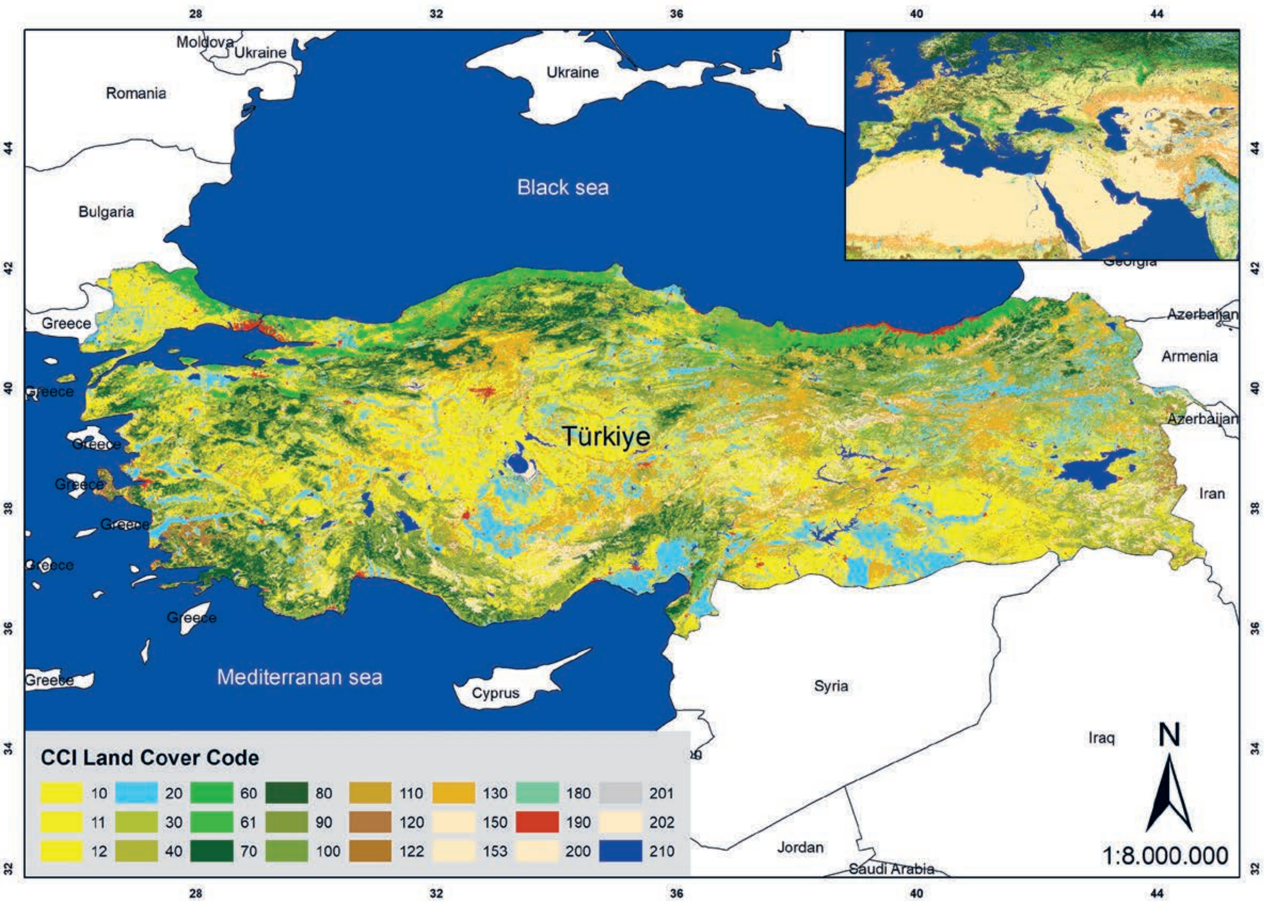

Figure 1. The location and land cover types according to the ESA CCI Land Cover classification of the study site (http://maps.elie.ucl.ac.be/CCI/viewer/index.html).

Slika 1. Lokacija i tipovi zemljišnog pokrova prema ESA CCI klasifikaciji zemljišnog pokrova na području istraživanja (http://maps.elie.ucl.ac.be/CCI/viewer/index.html).

global and regional scale. Of these, Türkiye had 24 land cover classes in 2015 (Figure 1).

The land area of Türkiye amounts to about 78.4 million hectares and 55.7% Cropland [14.0% Cropland, rain fed (LCC:10), 16.2% Cropland, rain fed herbaceous cover (LCC:11), 1.6% Cropland, rain fed, tree or shrub cover (LCC:12), 10.2% Cropland, irrigated or post flooding (LCC:20), 3.9% Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%) (LCC:30), 9.9% Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)) (LCC:40)], 24.5% Forest [(4.8% Tree cover, broadleaved, deciduous, closed to open (>15%) (LCC:60), 0.1% Tree cover, broadleaved, deciduous, closed (>40%) (LCC: 61), 5.9% Tree cover, needle-leaved, evergreen, closed to open (>15%) (LCC: 70), 0.0% Tree cover, needle-leaved, deciduous, closed to open (>15%) (LCC:80), 0.4% Tree cover, mixed leaf type (broadleaved and needleleaved) (LCC: 90), 13.4% Mosaic tree and shrub (>50%) / herbaceous cover (<50%) (LCC: 100)], 0.8% Shrubland [(0.8% Shrubland (LCC: 120), 0.0% Deciduous shrubland (LCC: 122)], 14.0% Herbaceous [(0.3% Mosaic herbaceous cover (>50%) / tree and shrub (<50%) (LCC: 110), 9.6% Grassland (LCC: 130), 3.7% Sparse vegetation (tree, shrub, herbaceous cover) (<15%) (LCC: 150), 0.3% Sparse herbaceous cover (<15%) (LCC: 153)], and 4.7% Other [(1.0% Urban areas (LCC: 190), 1.7% Bare areas (LCC: 200), 0.2% Consolidated bare areas (LCC: 201), 0.0% Unconsolidated bare areas (LCC: 202) and 1.8% Water bodies (LCC: 210)].

Burned area information – *Informacije o opožarenom području*

The FireCCI51 burned area product was used to analyze long term burned area in the study area. This product covers the period 2001-2020, and the main input for this FireCCI51 burned area product are the MOD09GQ Collection 6 images, acquired by the Terra satellite, which offer daily surface reflectance information in the red and near infrared bands of the MODIS sensor at 250 m spatial resolution (Lizundia-Loiola et al. 2020; Pettinari et al. 2021). The FireCCI51 burned area product has land cover information in each burned pixel and land cover information provided by CCI Land Cover (LC) products (ESA 2017).

The FireCCI51 monthly burned area pixel products were downloaded from The Centre for Environmental Data Analysis (CEDA) web platform (CEDA 2023) for each year in the period 2001-2020. First, the burned area raster datasets for each month of a year were clipped using the border of the study area. Then the clipped raster layers were converted into shape file polygons using grid code of land covers to calculate the burned area. The analyses were performed using a GIS software (ArcGIS® v. 10.2, ESRI, Redlands, CA, USA).

The ground-based number of fires and burned dataset covering the study periods were obtained from the General Directorate of Forestry (GDF), Forest Fire Service in Türkiye. Fires have been documented since 1988 by the GDF and include the number of fires and burned areas (ha), and annual mean values can be downloaded from the GDF website (GDF 2022).

Climate data and statistical analysis – *Klimatski podaci i statistička analiza*

Climate data were obtained from Turkish State Meteorological Service (TSMS 2024). This dataset includes monthly air temperature (°C), relative humidity (%) and rainfall (mm) from 85 different local stations in the country from 2001 to 2020. Then the mean values of the meteorological data from all stations were used for the analysis, and mean air temperature and relative humidity were used to calculate the Angström index and vapor pressure deficit (VPD).

The Angström index is simple and uses only temperature and relative humidity in its calculation (Angström 1942). This index provides an indication of fire risk and danger potential. The Angström index is calculated according to formula (1).

$$I = \left(\frac{R}{20}\right) + \left[\left(\frac{27 - T}{10}\right)\right] \quad (1)$$

where:

I = Angström index, R = relative humidity (%) and T = air temperature (°C)

The interpretation of this index is:

> 4.0	Fire occurrence unlikely,
4.0 – 2.5	Fire conditions unfavorable,
2.5 – 2.0	Fire conditions favorable,
< 2.0	Fire occurrence very likely,

The Angström index is a widely used index in determining the relationship between long-term meteorological data and wildfires (Coskuner 2021; Pérez-Sánchez et al. 2017).

Vapor pressure deficit (VPD) indicates the difference between the saturation vapor pressure and the actual vapor pressure. VPD (kPa) was calculated according to the equation below (Bonan 2008) (2):

$$VPD = 100 - (RH \times 610.7 \times 10^{((7.5 \times T)/(273.3 + T))})) \quad (2)$$

Where T is air temperature (°C) and RH is relative humidity (%).

When VPD is high, it means the air is very dry, which accelerates the evaporation of moisture from vegetation and soil. This dries out the forest fuels making them available for ignition. High VPD can also lead to increased water stress in plants, making them more prone to wilting. Furthermore, high VPD can exacerbate fire conditions by increasing the rate at which fire spread once ignited.

Correlation and regression analyses were undertaken to investigate the relationships between climatic variables and burned area in different land cover types. Before the analyses, Shapiro-Wilk normality test was conducted on all variables. All statistical analyses were performed using the statistical software SPSS, Version 26.0 (SPSS 2019).

RESULTS
REZULTATI

Analysis of the trends in yearly burned area and climatic variables – *Analiza trendova godišnje opožarene površine i klimatskih varijabli*

The analysis of FireCCI51 data between 2001 and 2020 showed that fires occurred in 8 main land cover (LC) types. These were needle-leaved (LC: 70), broadleaved (LC: 60), mixed (LC: 90), mosaic tree-shrub (LC: 100), shrubland (LC: 120, 122), wetland (LC 180) and cropland (LC: 10, 11, 12, 20, 30, 40). A total of 74721.9 ha, 12411.7 ha, 1225.1 ha, 144933.5, 23184.2 ha, 213589.9 ha, 23823.0 ha and 13564909.20 ha area burned in needle-leaved (Figure 2a), broadleaved (Figure 2b), mixed (Figure 2c), mosaic tree-shrub (Figure 2d), shrubland (Figure 2e), wetland (Figure 2f) and cropland (Figure 2h), respectively. Total burned area in FireCCI51 was 14058799.53 ha between 2001 and 2020.

The results of the ground-based GDF fire data indicated that a total of 178324.20 ha forest land area was burned in 46727 fires, with 8919 ha forest land area burned in 2336 fires annually from 2001 to 2020. The highest value was seen in 2008 with 29749 ha forest area burned, and a slightly increasing trend can be seen from 2001 to 2020 (Figure 3a). A significant linear relationship was observed between the FireCCI51 burned forest area and the GDF burned area, with overestimation particularly evident in some years (Figure 3a, b) (R^2=0.58). GDF burned area was also compared with the FireCCI51 needle-leaved, and needle-leaved plus shrubland burned area, as wildfires mainly took place in Anatolian red pine and Mediterranean maquis in the study area. Although the results indicated there was a slight underestimation in both FireCCI51 burned areas in needle-leaved (Figure 3c, R^2=0.59) and needle-leaved plus shrubland (Figure 3d, R^2=0.63), the trends in burned area in needle-leaved plus shrubland are close to

Figure 2. Representative photos of fires in FireCCI51 land covers in the study area. Fires in needle-leaved (a), broadleaved (b), mixed (c), mosaic tree-shrub (d) forested lands, and shrubland (e), herbaceous (f), wetland (g) and cropland (h).

Slika 2. Reprezentativne fotografije požara u FireCCI51 tipovima zemljišnog pokrova na području istraživanja. Požari u šumskim područjima s crnogoričnim (a), bjelogoričnim (b), mješoviti (c), mozaični drvenato-grmoliki (d) pokrovom, te grmoliki (e), travnati (f), močvarni (g) i poljoprivredna površina (h).

the ground-based GDF burned area in the country for the period 2001-2020 (Figure 3a, d).

The results in the long-term climatic data analysis on a yearly basis indicated that there was a decreasing trend in rainfall and an increasing trend in VPD for the study period. The lowest rainfall was recorded in 2008 (Figure 4a). The decreasing trend in the Angström index was also evident from 2001 to 2020 (Figure 4b).

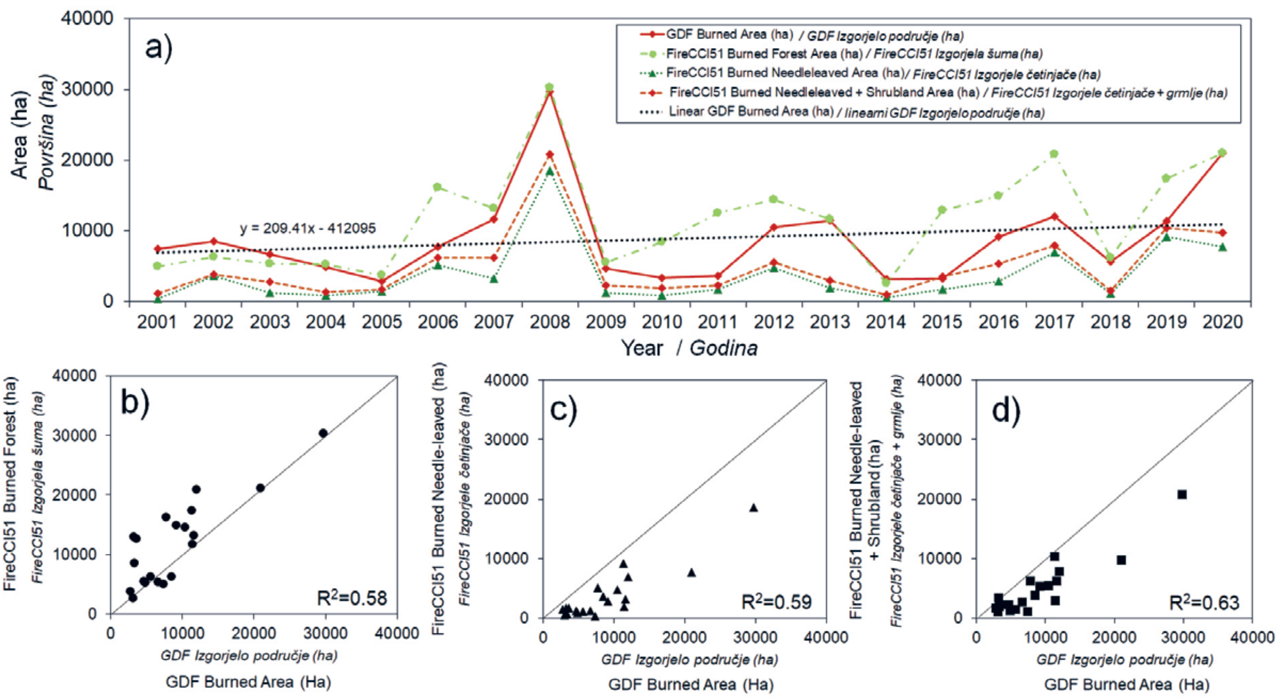

Figure 3. Relationships between GDF burned area (ha) and FireCCI51 burned areas (a) (Forest LC: 60, 70, 90 and 100) (b), needle-leaved (LC: 70) (c) and needle-leaved + shrubland (LC: 70, 120, 122) (d)) from 2001 to 2020.

Slika 3. Odnosi između opožerenih površina prema GDF (ha) i opožarenih površina prema FireCCI51 (a) (šumski zemljišni pokrov: 60, 70, 90 i 100) (b), crnogoričnih (LC: 70) (c) i crnogoričnih + grmolikih područja (LC: 70, 120, 122) (d)) od 2001 do 2020. godine.

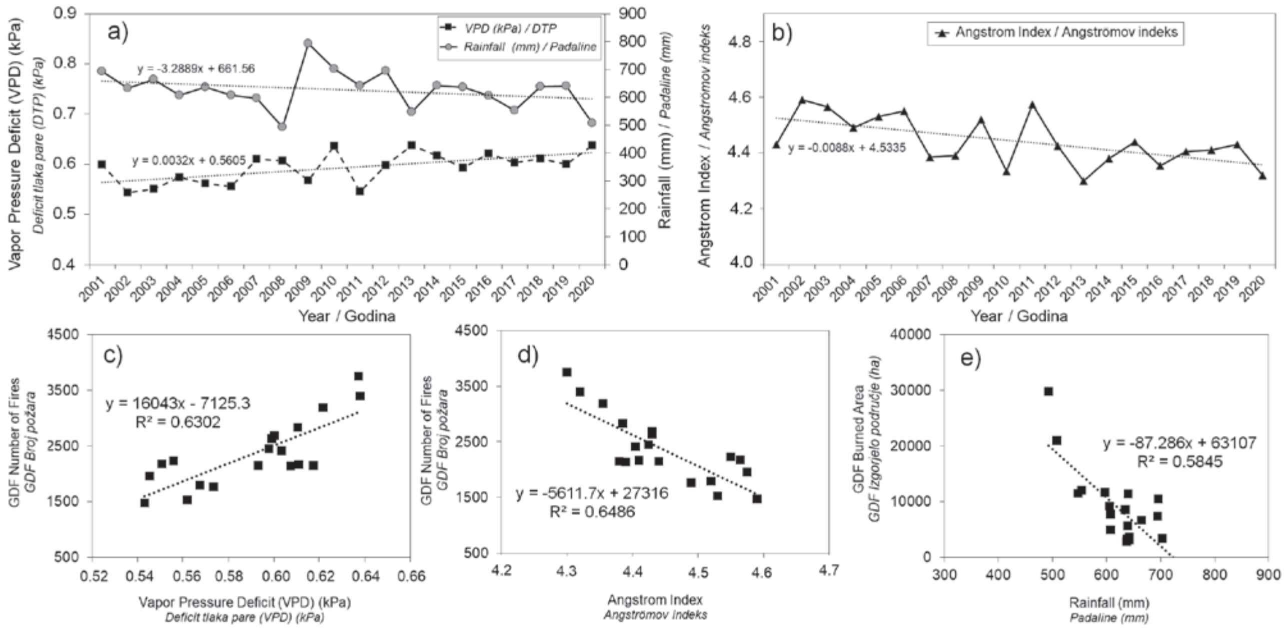

Figure 4. Temporal trends in vapor pressure deficit (VPD) (a), rainfall (a) and Angstrom index (b) from 2001 to 2020. Relationships between GDF fire number and VPD (c), and the Angström index (d) and GDF burned area and rainfall (e).

Slika 4. Vremenski trendovi Deficit tlaka pare (VPD) (a), oborina (a) i Angströmov indeks (b) od 2001. do 2020. godine. Odnosi između broja požara prema GDF-u i VPD-a (c), Angströmov indeks (d) te opožarene površine prema GDF-u i oborina (e).

The VPD explained 63% (Figure 4c) and the Angström index explained 65% (Figure 4d) of the variation in the number of fires, and rainfall alone explained 58% of variation in the burned area (Figure 4e). The correlation analysis showed there was a significant positive correlation between VPD and the number of fires (r=0.576) and negative correlation between the Angström index and the number of fires (r=-0.583) (Table 1). No significant correlation was observed between the number of fires and rainfall. Nevertheless, there was a significant negative correlation between GDF burned area and rainfall (r=-0.635) (Table 1).

The correlation analysis also indicated that ground-based GDF burned area is positively correlated with FireCCI51 needle-leaved burned area (r=0.771), forest (r=0.759), shrubland (r=0.490) and mosaic tree-shrubland (r=0.591).

Table 1. The results of the correlation analysis using average annual climatic variables, FireCCI51 burned area according to land covers and GDF number of fires and burned area in Türkiye from 2001 to 2020. (R: Rainfall, VPD: Vapor pressure deficit, ANG: Angström index, FireCCI51 burned areas (BL: Broadleaved, MX: Broadleaved and needle-leaved mixed, MTS: Mosaic tree-shrubland, NL: Needle-leaved, FOR: Forest, SHR: Shrubland, HRB: Herbaceous, WTL: Wetland, CRP: Cropland, ABR: FireCCI51 All burned), GNF: GDF fire number, GAB: GDF burned areas).

Tablica 1. Rezultati korelacijske analize prosječnih godišnjih klimatskih varijabli, FireCCI51 opožerenog područja prema zemljišnim pokrovima i broju požara te opožarene površine prema GDF-u u Turskoj od 2001. do 2020. godine. (R: Oborine, VPD: Deficit tlaka pare, ANG: Angströmov indeks, FireCCI51 opožarena površina (BL: Bjelogorično, MX: Mješovito bjelogorično i crnogorično, MTS: Mozaično drvenasto-grmoliko, NL: Crnogorično, FOR: Šuma, SHR: Grmoliko, HRB: Travnato, WTL: Močvarno, CRP: Poljoprivredna površina, ABR: FireCCI51 Sva opožarena područja), GNF: Broj požara prema GDF-u, GAB: Opožarena površina prema GDF-u)

Cor	R	VPD	ANG	BL	MX	MTS	NL	FOR	SHR	HRB	WTL	CRP	ABR	GNF	GAB
R	1														
VPD	-0.334	1													
ANG	0.369	-0.991	1												
BL	-0.035	0.008	0.000	1											
MX	-0.334	0.219	-0.211	0.425	1										
MTS	-0.527	0.318	-0.347	0.071	0.543	1									
NL	-0.594	0.036	-0.069	0.050	0.534	0.663	1								
FOR	-0.539	0.279	-0.300	0.170	0.645	0.881	0.889	1							
SHR	-0.329	0.377	-0.393	0.230	0.561	0.592	0.426	0.627	1						
HRB	0.378	0.008	-0.004	-0.044	0.082	0.379	-0.005	0.226	0.335	1					
WTL	-0.153	0.044	-0.079	0.147	0.496	0.281	0.150	0.212	0.463	0.211	1				
CRP	0.239	-0.158	0.159	0.053	-0.128	0.156	-0.299	-0.113	0.263	0.765	0.241	1			
ABR	0.147	-0.060	0.062	0.077	0.009	0.284	-0.195	0.017	0.377	0.779	0.344	0.977	1		
GNF	-0.341	0.576	-0.583	0.095	0.305	0.505	0.362	0.490	0.559	0.257	0.098	-0.012	0.087	1	
GAB	-0.635	0.353	-0.391	0.208	0.268	0.591	0.771	0.759	0.490	-0.122	0.042	-0.319	-0.227	0.635	1

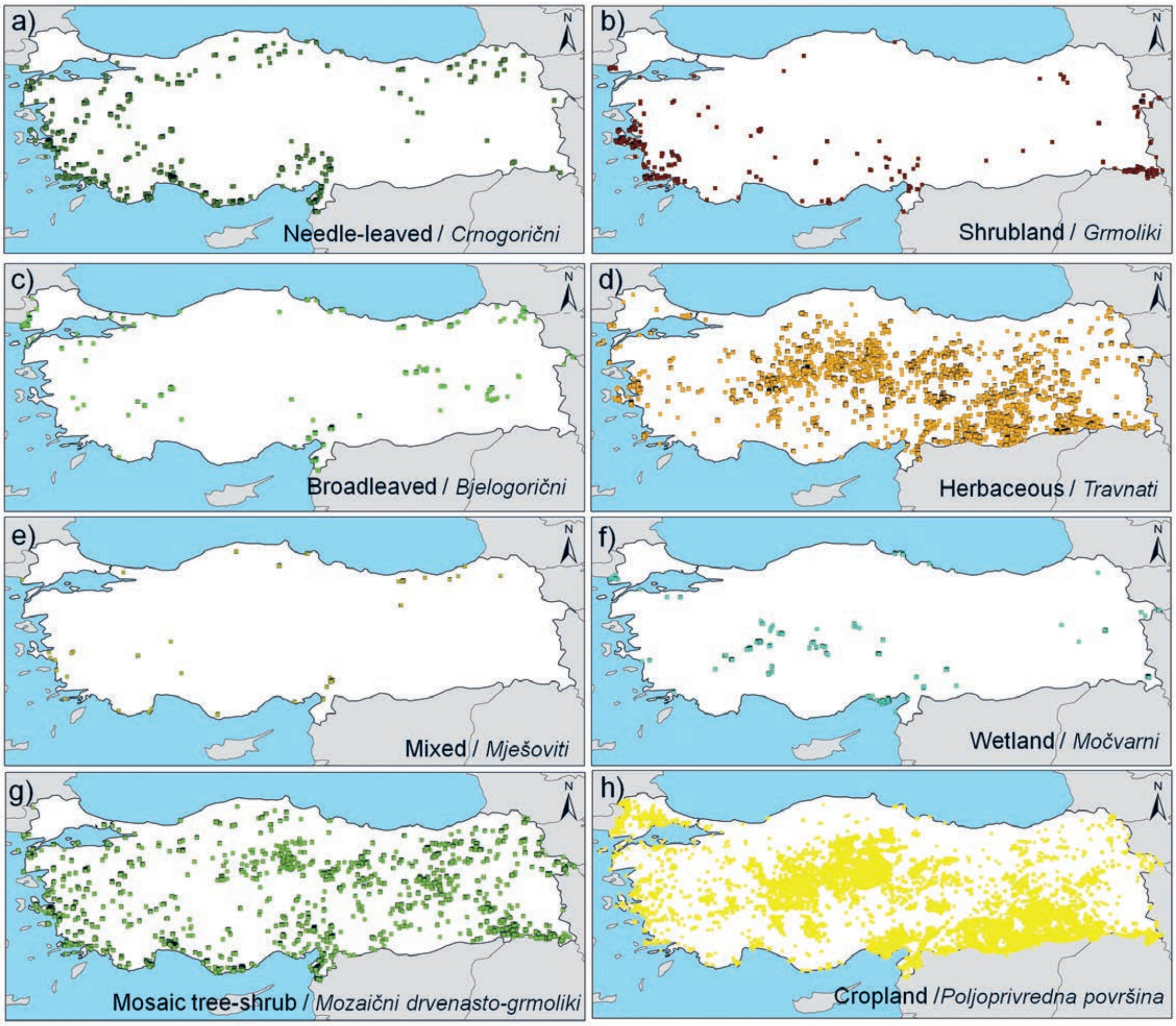

Figure 5. Spatial distribution of FireCCI51 burned areas across land cover types (Forest (Needle-leaved (a), Broad-leaved (c), Mixed (e) and Mosaic tree-shrub (g)), Shrubland (b), Herbaceous (d), Wetland (f) and Cropland (h)) from 2001 to 2020.

Slika 5. Prostorna raspodjela opožarenog područja prema FireCCI51 kroz tipove zemljišnog pokrova od 2001. do 2020. godine (Šuma (crnogorični (a), bjelogorični (c), mješoviti (e) i mozaični drvenasto-grmliki (g), grmoliki (b), travnati (d), močvarni (f) i poljoprivredna površina (h).

There was no correlation observed between GDF burned area and broadleaved, mixed, herbaceous, wetland, cropland and all burned area in FireCCI51 on a yearly basis.

The distribution of fires in FireCCI51 showed that fires in needle-leaved and shrubland were mainly in the western and southern part of the country where Anatolian red pine and Mediterranean maquis are the main vegetation cover (Figure 5a, b). The broad-leaved burned areas were mainly in the northern parts of the country, whereas herbaceous areas were in the central and the southeastern part of the country (Figure 5c, d). The burned area in the mixed and wetland areas was relatively low compared to other land covers (Figure 5e, f), whereas mosaic tree-shrub and cropland areas (Figure 5g, h) were common in different parts of the study area. Especially, cropland fires were concentrated in the northwestern (Thrace), central Anatolian and southwestern part (Figure 5h) of the country where large agricultural fields are prevailing (Figure 1).

Analysis of monthly FireCCI51 burned areas according to land cover with climatic variables – *Analiza opožarenog područja FireCCI51 na mjesečnoj razini prema zemljišnom pokrovu i klimatskim varijablama*

FireCCI51 provides monthly burned area dataset. The data obtained from monthly burned areas according to land cover types were analyzed using monthly mean climatic variables. The results indicated that VPD and the Angström index were well correlated with all land cover classes except monthly burned area in broadleaved, mixed and wetland cover types (Table 2).

The scatter plots showed that there was a negative exponential relationship between the Angström index and five major land cover types, namely forest (Figure 6a), shrubland (Figure 6b), herbaceous (Figure 6c) and cropland (Figure 6e) except wetland (Figure 6d). The fires mainly concentrated around 2.5 and 6.5 index values. It can be cle-

Table 2. The results of correlation analysis using monthly mean climatic variables and FireCCI51 burned area according to land covers from 2001 to 2020. (R: Rainfall, VPD: Vapor pressure deficit, ANG: Angström index, FireCCI51 burned areas (BL: Broadleaved, MX: Broadleaved and needle-leaved mixed, MTS: Mosaic tree-shrubland, NL: Needle-leaved, FOR: Forest, SHR: Shrubland, HRB: Herbaceous, WTL: Wetland, CRP: Cropland, ABR: FireCCI51 All burned)).

Tablica 2. Rezultati korelacijske analize mjesečnih srednjih klimatskih varijabli i opožarenog područje prema FireCCI51 u odnosu na zemljišne pokrove od 2001. do 2020. godine. (R: Oborine, VPD: Deficit tlaka pare, ANG: Angströmov indeks, FireCCI51 opožarena površina (BL: Bjelogorično, MX: Mješovito bjelogorično i crnogorično, MTS: Mozaično drvenasto-grmoliko, NL: Crnogorično, FOR: Šuma, SHR: Grmoliko, HRB: Travnato, WTL: Močvarno, CRP: Poljoprivredna površina, ABR: FireCCI51 Sva opožarena područja)).

Cor	R	VPD	ANG	BL	MX	MTS	NL	FOR	SHR	HRB	WTL	CRP	ABR
R	1												
VPD	-0.807	1											
ANG	0.810	-0.999	1										
BL	-0.215	0.176	-0.179	1									
MX	-0.148	0.105	-0.103	0.430	1								
MTS	-0.597	0.652	-0.655	0.488	0.292	1							
NL	-0.527	0.557	-0.556	0.536	0.400	0.810	1						
FOR	-0.581	0.630	-0.632	0.610	0.381	0.961	0.879	1					
SHR	-0.595	0.673	-0.676	0.482	0.280	0.739	0.717	0.767	1				
HRB	-0.609	0.719	-0.722	0.372	0.166	0.827	0.661	0.806	0.780	1			
WTL	-0.298	0.355	-0.356	0.548	0.276	0.534	0.516	0.586	0.582	0.567	1		
CRP	-0.523	0.623	-0.625	0.394	0.142	0.732	0.615	0.734	0.722	0.871	0.612	1	
ABR	-0.525	0.626	-0.628	0.411	0.160	0.756	0.640	0.764	0.733	0.883	0.616	0.996	1

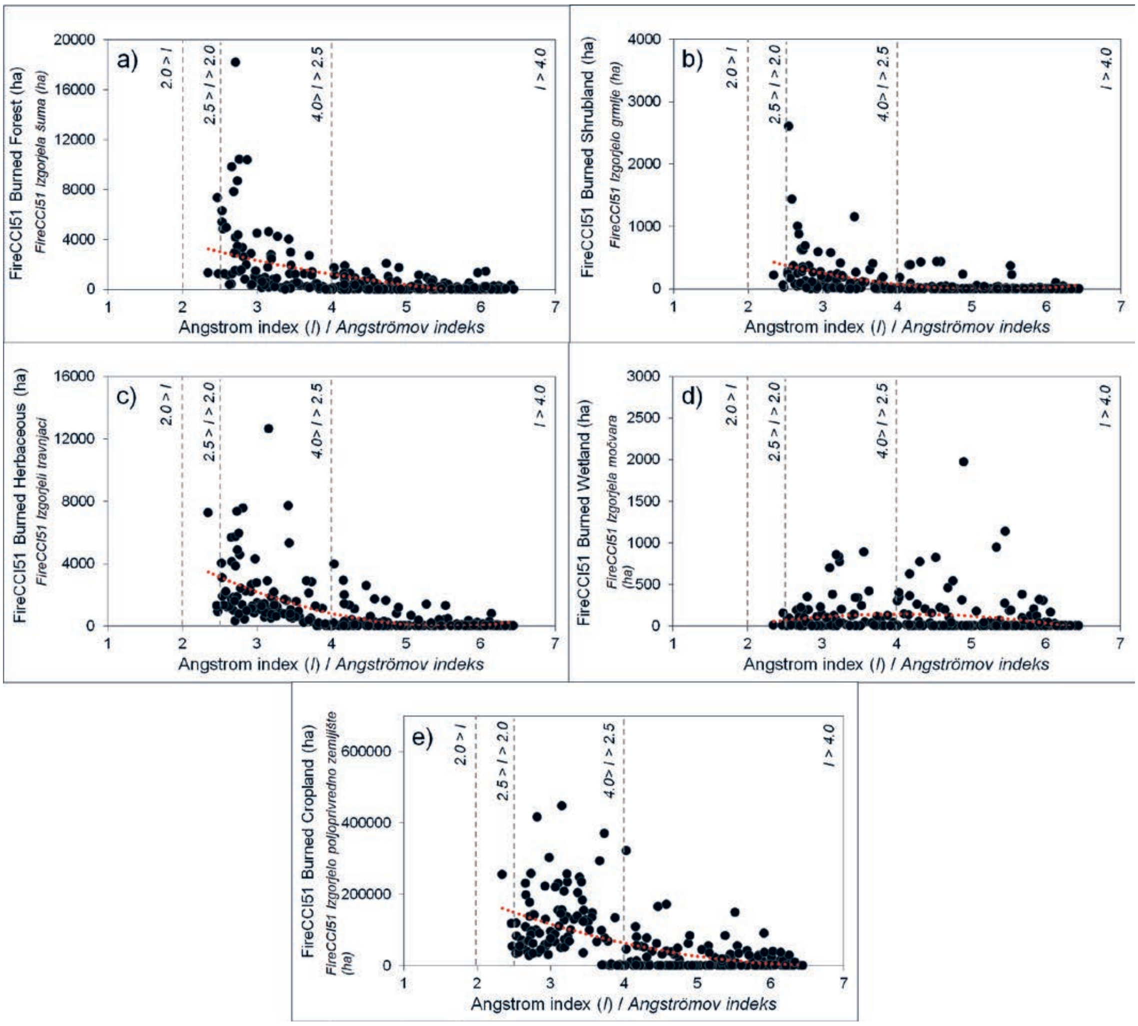

Figure 6. Relationships between the Angström index and FireCCI51 burned total areas (Forest (a), Shrubland (b), Herbaceous (c), Wetland (d) and Cropland (e)) from 2001 to 2020.

Slika 6. Odnosi između Angströmovog indeksa i ukupnih opožarenih površina prema FireCCI51 od 2001. do 2020. godine (šuma (a), grmlje (b), travnato područje (c), močvara (d) i poljoprivredno zemljište (e))

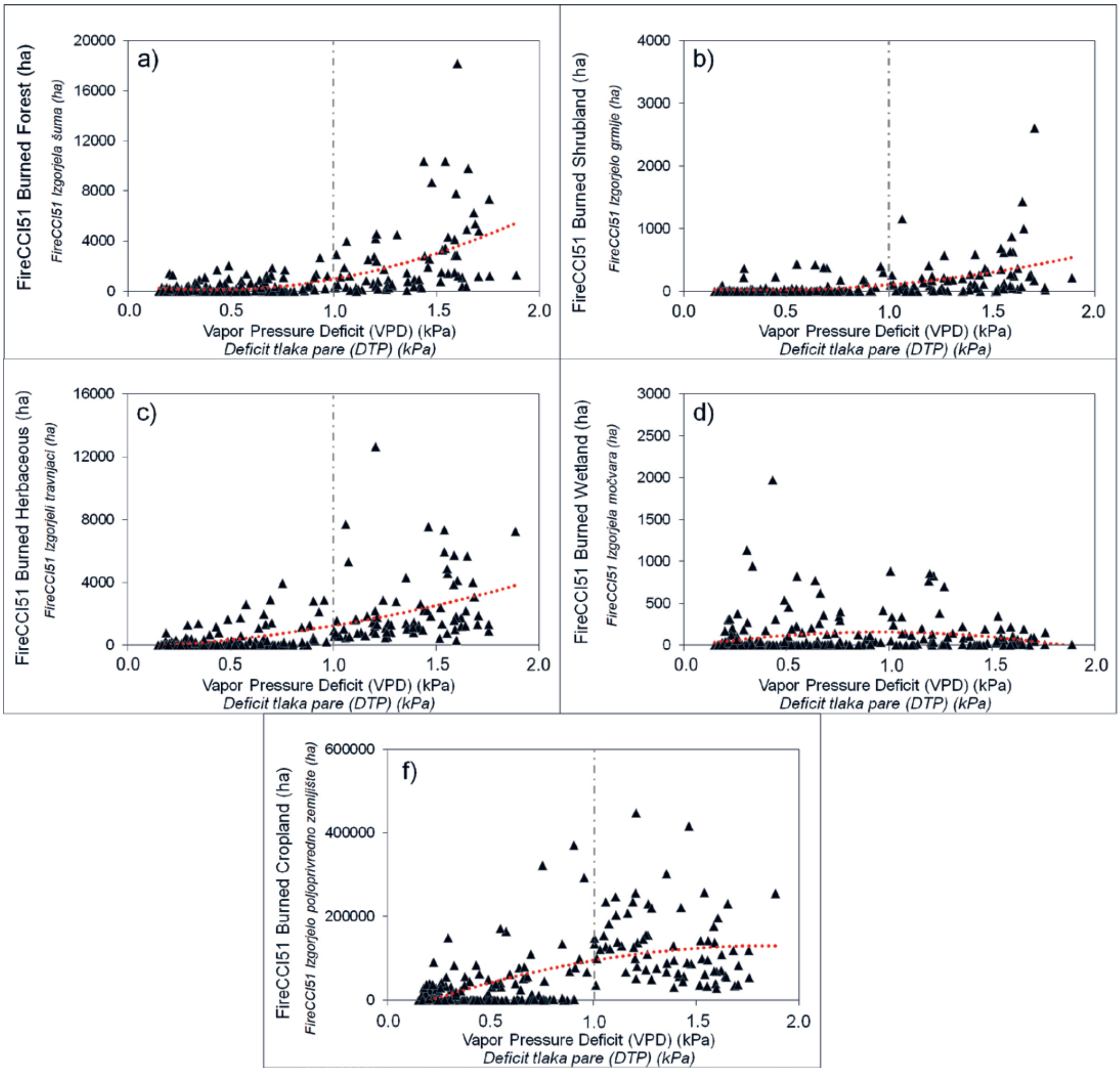

Figure 7. Relationships between vapor pressure deficit (VPD) (kPa) and FireCCI51 burned areas (Forest (a), Shrubland (b), Herbaceous (c), Wetland (d) and Cropland (e)) from 2001 to 2020.

Slika 7. Odnosi između deficita tlaka pare (VPD) (kPa) i opožarenih površina prema FireCCI51 od 2001. do 2020. godine (šuma (a), grmlje (b), travnato područje (c), močvara (d) i poljoprivredno zemljište (e))

arly seen that the burned area was comparatively lower over the index values of 4.0 (Figures 6a, b, c, e).

The scatter plots showed that the burned area increased exponentially with increasing VPD in three major land covers, namely forest (Figure 7a), shrubland (Figure 7b), and herbaceous (Figure 7c). There was no relationship evident in cropland (Figure 7e) and wetland (Figure 7d). The increase in the rate of burned area was notable when the VPD was over 1.0 kPa (Figures 7a, b, c, e).

The monthly distribution of burned areas showed that there was a significant correlation between VPD and FireCCI51 burned forest (Figure 8a), shrubland (Figure 8b), herbaceous (Figure 8c), cropland (Figure 8e) and all burned area (Figure 8f) except wetland (Fig. 8d). The fires mainly took place from May to November in forest, shrubland and herbaceous land cover, with the highest value being in burned areas in August (Figures 8a, b, c). The majority of the burned areas in all FireCCI51 dataset were cropland fires (Figure 8e) and the monthly distribution of burned areas in cropland was similar to those in all FireCCI51 burned areas (Figures 8e, f). The fires in croplands start from May and continue until December with two distinctive peaks in June and September (Figures 8e, f). This pattern is associated with the harvesting times in different regions.

The subclasses of burned monthly forest areas were also analyzed with VPD. The results indicated that monthly VPD and burned needle-leaved (Figure 9a) and mosaic tree shrub areas were well correlated (Figure 9c). However, there was no correlation between VPD and burned broadleaved (Figure 9b) and mixed forested areas (Figure 9d).

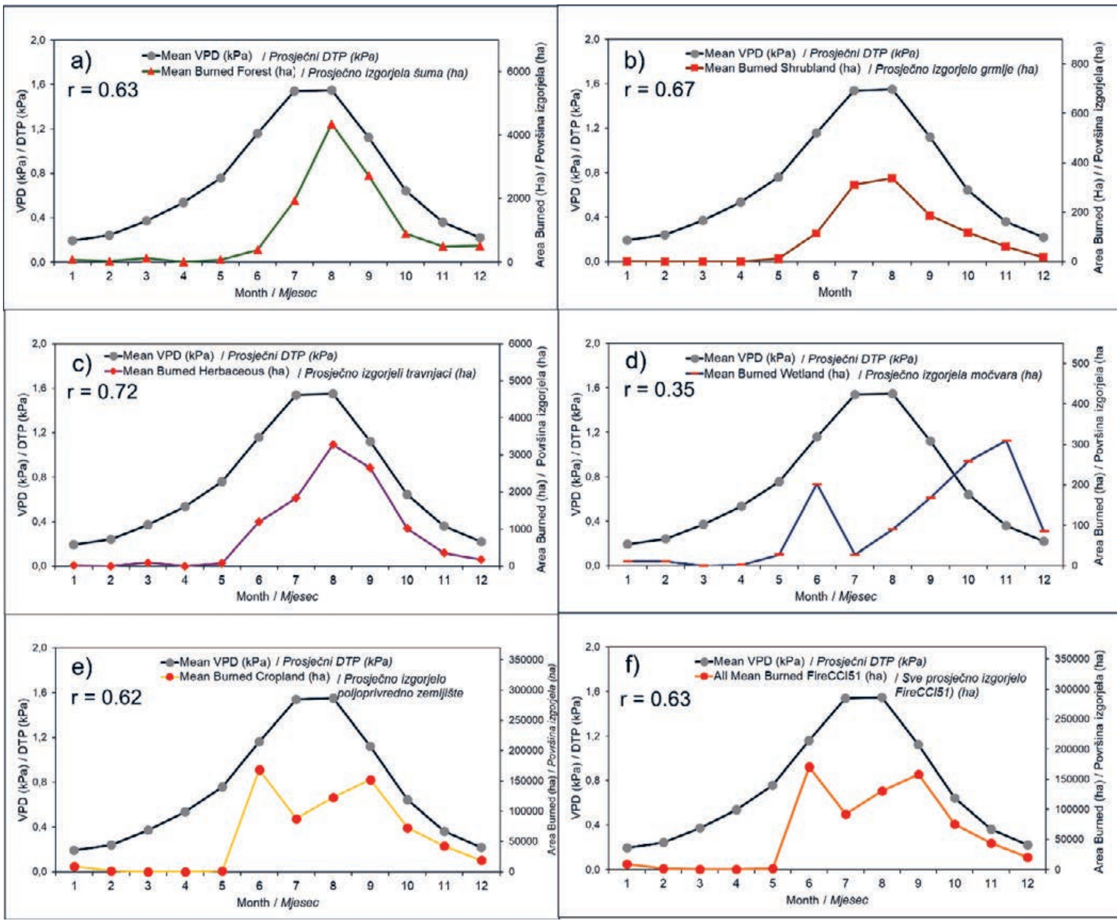

Figure 8. The monthly distribution of mean VPD and burned areas in forest (a), shrubland (b), herbaceous (c), wetland (d), cropland (e) and all burned area in FireCCI51 in Türkiye for the study period (r = correlation coefficient).

Slika 8. Mjesečna raspodjela srednjeg VPD-a i opožerenih površina u šumi (a), grmolikom (b), travnatom (c), močvarnom području (d), poljoprivrednoj površini (e) i ukupnoj opožarenoj površini prema FireCCI51 u Turskoj za razdoblje istraživanja (r = koeficijent korelacije).

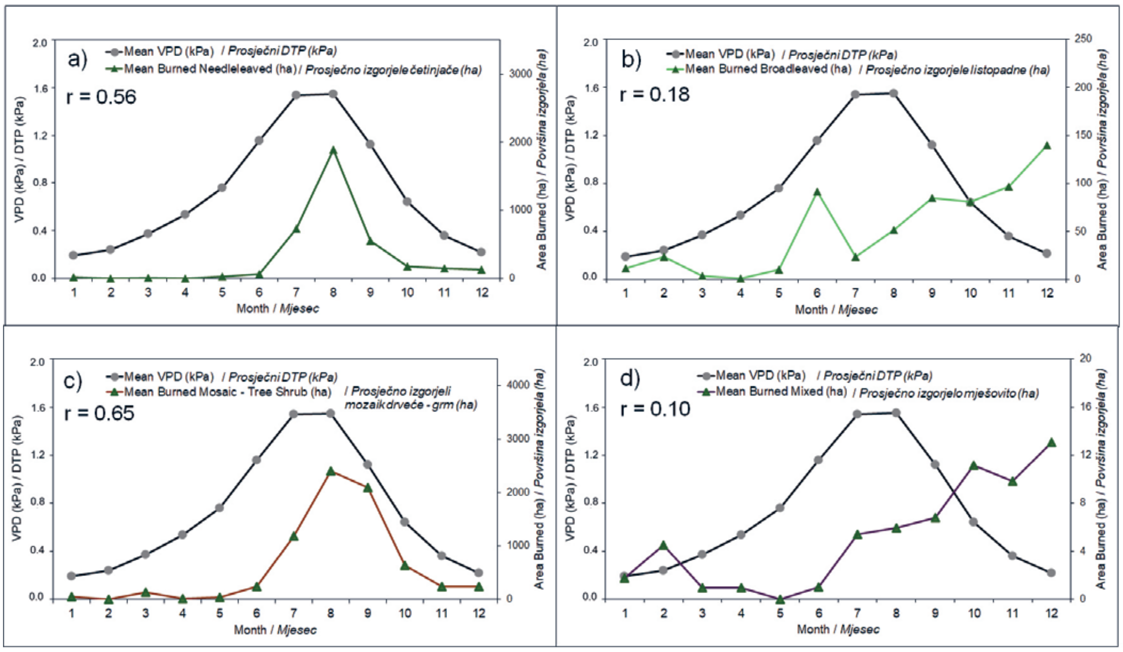

Figure 9. The monthly distribution of mean VPD and subclasses of burned forest areas as needle-leaved (a), broadleaved (b), mosaic tree-shrub (c) and mixed forested lands (d) in FireCCI51 for the study area.

Slika 9. Mjesečna raspodjela srednjeg VPD-a i podklasa opožarenih šumskih površina kao što su crnogorične (a), bjelogorične (b), mozaično drvenasto-grmolike (c) i mješovite šumske površine (d) prema FireCCI51 za područje istraživanja.

DISCUSSION
RASPRAVA

The performance of FireCCI51 in the analysis of long-term fire dynamics – *Učinkovitost FireCCI51 u analizi dugoročnih dinamika požara*

Satellite-based remote sensing products for monitoring burned areas provide consistent and systematic data collection for large areas over time at low cost, and enable the assessment of long-term trends in wildfires (Giglio et al. 2018; Lizundia-Loiola et al. 2020; Otón et al. 2021). The comparison between FireCCI51 satellite data and ground-based GDF fire data provides insights into the accuracy of remote sensing methods in detecting and estimating burned areas. The results indicated that FireCCI51burned area product is a useful tool for analyzing long-term fire dynamics across land cover classes in Türkiye. A similar trend was observed in FireCCI51 burned forest areas and ground-based GDF fire statistics (Figure 3a). However, overestimation of the burned areas up to around ten thousand hectares (e.g., in 2015) was observed in FireCCI51 burned forest area particularly in some years (Figure 3a). This can be attributed mainly to the overestimation issue in FireCCI51 burned area. The results of a different study from Greece with comparable vegetation and climate to Türkiye showed that FireCCI51 overestimates the burned areas in general (Katagis and Gitas 2022).

Moreover, it is known that any burn smaller than the spatial resolution of the input sensor (for FireCCI51 product approximately 6 hectares) is unlikely to be detected (Pettinari et al. 2021) by FireCCI51. The long-term fire statistics (1990-2022) showed that the average burned area per fire is 6.1 ha in Türkiye (GDF 2022; San-Miguel-Ayanz et al. 2023), indicating that a great portion of relatively small-sized burned areas will not be detected by FireCCI51. Therefore, when analyzing fire regimes (i.e., the number of fires, fire size, fire season etc.) the data derived from burned area products like FireCCI51 should be cautiously used. They should be complemented by ground-based fire information. FireCCI51 and other burned area products may prove useful (Katagis and Gitas 2022) to analyze long-term trends of wildfire activity and understanding their interactions with climate.

Long-term wildfire occurrence and land cover types – *Dugoročna pojava požara i tipovi zemljišnog pokrova*

The spatial distribution of fires in FireCCI51 illustrated distinct patterns of wildfire occurrence (Figure 5) across diverse landscapes of the study area (Figure 1). Fires in needle-leaved and shrubland areas were predominantly concentrated in the western and southern regions, characterized by Anatolian red pine and Mediterranean maquis vegetation cover (Figures 5a, b) (Coskuner 2022a). Conversely, broad-leaved burned areas (Figure 5c) were mainly located in the northern part, while herbaceous (Figure 5d) and agricultural fires (Figure 5f) occurred more in the central and southeastern regions where croplands extend throughout the landscape (Figure 1). Although stubble burning is strictly banned in Türkiye, farmers traditionally burn the stubble after harvest (Bilgili 2005; Coskuner 2022a; Yakupoglu et al. 2022) during dry and hot periods. These fires can sometimes be the cause of ignition in the adjacent forested areas (GDF 2022).

Monthly distribution of fires in different land covers showed that needle-leaved (Figure 9a), mosaic tree-shrub (Figure 9c), shrubland (Figure 8b) and herbaceous (Figure 8c) fires occurred in summer months (June-October) and were correlated with vapor pressure deficit (VPD). During the summer season, the moisture content of the surface fuel decreases under low VPD conditions (Bilgili et al. 2019), making vegetation become susceptible to fires. However, monthly distributions of fires in broadleaved and mixed forest were not correlated with VPD. Fires in these land covers mostly occur in autumn and winter. These vegetation types are mostly found in the northern part of the country (Figures 5c, e).

During the summer months, due to the presence of green herbaceous and woody plants in the understory and sub-canopy layers of forests, the amount of dry combustible material is low and the relative humidity is high, leading to high fuel moisture content in the combustible materials. However, as the autumn approaches, the leaves of deciduous trees dry up and fall off, and the herbaceous plants on the forest floor also dry out, resulting in an increase in the amount of dead combustible material on the forest floor. Especially during the autumn and winter months, the effect of southerly winds (foehn) occasionally observed in the region (Yetmen and Aytaç 2017) leads to an increase in air temperature, a decrease in relative humidity, rapid drying of combustible materials on the forest floor, and an increase in the risk of fire (Coskuner 2021). Due to the short durations of foehn winds, fires occur in a very short period time (3 to 5 days). Given that the values used in analyses are monthly averages, the discrepancy seen in the graphs (Figures 9b, d) is understandable. To get a better explanation of the situation, weekly average values of weather conditions are necessary.

Relationship between long-term climate variables, the Angström index and wildfire dynamics – *Odnos između dugoročnih klimatskih varijabli, Angströmovog indeksa i dinamike požara*

The results indicate that long-term climate trends are important for wildfire dynamics in eastern Mediterranean landscapes. The increasing trend of VPD and decreasing trend of rainfall (Figure 3a) from 2001 to 2000 in the study area, as well as the correlation between VPD, rainfall and burned areas highlight the influence of climatic conditions on wildfires. The lowest rainfall was recorded in 2008 (Figure

4a) with an average 493 mm and the highest burned area was seen in that year (Figure 3a). Drought leads to a decrease in the drying out of the vegetation, making landscapes more susceptible to ignition and fire spread. This creates an environment where wildfires can ignite more easily, spread rapidly, and burn larger areas. Additionally, droughts can extend the fire season, further increasing the total burned area (Cardil et al. 2019).

Higher VPD is associated with increased fire activity (Rao et al. 2022; Rodrigues et al. 2022; Mueller et al. 2020). The results also indicated that the burned areas in natural ecosystems such as forest, shrubland and herbaceous lands were correlated with VPD (Figures 7a, b, c). High VPD values lead to increased evaporation of moisture from fuels (Bilgili et al. 2019), making them more susceptible to ignition and promoting fire spread.

The Angström index is calculated by combining air temperature and humidity, and can provide valuable information for long-term fire analysis through its association with climatic conditions and atmospheric dynamics (Wastl et al. 2012; Holsten et al. 2013). The results indicated that the trend of Angström index from 2001 to 2020 was decreasing (Figure 4b). This decrease in the Angström index was highly correlated with the number of fires in the GDF dataset (Figure 4b) and for the most of land covers in FireCCI51 monthly burned area (Table 2). There was no significant correlation between the annual burned area in FireCCI51 - GDF dataset and the Angström index (Table 1). Similar findings were reported in the literature (Coskuner 2021) and the possible reason for this could be the availability of high variation in burned areas and index values in different months. However, the decreasing trend of the Angström index emphasizes that the landscape will be more susceptible to wildfires in Türkiye in the future and underscore the possible influence of climate change on wildfire activities.

CONCLUSIONS
ZAKLJUČCI

Türkiye is one of the largest countries in the Mediterranean region. The analysis of long-term fire dynamics in this country has revealed valuable insights into the interplay between wildfire occurrence, land cover types, climate variables, and atmospheric dynamics in the Eastern Mediterranean Region. Satellite-based remote sensing products like FireCCI51 offer a consistent and cost-effective tool for monitoring burned areas over large regions, facilitating the assessment of wildfire trends. Despite some limitations such as overestimation of burned forest areas, FireCCI51 proves to be a useful tool for understanding long-term fire dynamics.

Long-term climate trends indicate an increasing vapor pressure deficit (VPD). Wildfire dynamics with higher VPD are associated with increased fire activity. The Angström index provides valuable insights into climatic conditions and their potential influence on wildfire occurrence. The decreasing trend of the Angström index underscores the heightened susceptibility of Mediterranean landscapes to wildfires in the future, highlighting the potential ramifications of climate change.

Future studies should focus on analyzing long-term fire regime characteristics including the number of fires, fire size and fire season in different land covers using both ground-based and remote sensing data. This can include projecting future climate scenarios and assessing their potential influence on fire regimes, taking into account factors such as changes in atmospheric dynamics, rainfall patterns, and vegetation dynamics. Thus, studies can provide valuable insights into the spatial and temporal patterns of wildfire activity in the Mediterranean region and help decision makers develop effective firefighting and mitigation strategies in the face of changing environmental conditions.

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Author contributions – *Autorski doprinosi*

KAC conceived the study and lead the writing. KAC, IH and SZ conducted data gathering. KAC and EB made statistical analyses. All authors contributed in the discussion of the literature reviewed.

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Competing interests – *Sukobi interesa*

The authors declare that they have no conflict of interest.

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SUMMARY

Mediteranska regija odlikuje se raznolikim krajobrazima i jedinstvenim klimatskim uvjetima, što ovu regiju čini izuzetno važnom u kontekstu požara. Turska je jedna od najvećih zemalja na Mediteranu s izvanrednim prirodnim bogatstvom, karakteriziranim raznovrsnim biljnim pokrovima koji obuhvaćaju različite ekosustave i staništa. Požari igraju ključnu ulogu u oblikovanju ekosustava u područjima sklonim požarima u Turskoj. Razumijevanje odnosa između sastava vegetacije, klimatskih faktora i povijesnih obrazaca požara stoga je ključno za učinkovito upravljanje požarima u očuvanju okoliša u istočnom Mediteranu i svijetu uopće. Ovo istraživanje izvještava i raspravlja o dinamici požara u Turskoj u razdoblju od 2001. do 2020. godine u različitim klasama pokrova zemljišta, koristeći

ESA FireCCI51 za opožarene površine i podatke o požarima na terenu. Cilj ovog istraživanja je pružiti uvid u složen odnos između aktivnosti požara ispitivanjem interakcija i dugoročnih klimatskih varijabli, deficita tlaka pare (VPD) i Angströmovog indeksa. Analiza podataka FireCCI51 otkrila je različite prostorne obrasce pojave požara u raznolikim krajobrazima na području istraživanja. Požari su pretežno koncentrirani u područjima prekrivenim igličastim vrstama i grmljem na zapadu i jugu, dok su požari u širokolisnim, travnatim i poljoprivrednim područjima češći u ostalim dijelovima Turske. Unatoč zakonskim ograničenjima, spaljivanje ostaje uobičajena praksa, što doprinosi pojavama požara, osobito tijekom suhih i vrućih razdoblja nakon žetve. Dugoročni klimatski trendovi, osobito povećanje VPD-a i smanjenje količine oborina, značajno utječu na dinamiku požara na istraživanom području. Visoki VPD dobro korelira s povećanom aktivnošću požara, što ukazuje na njegovu ulogu u vlažnosti goriva i spaljenoj površini. Povećanje trenda VPD-a i smanjenje Angströmovog indeksa naglašava sve veću osjetljivost krajobraza na požare, što sugerira potencijalni utjecaj klimatskih promjena na spaljenu površinu.

KLJUČNE RIJEČI: šumski požari, FireCCI51, zemljišni pokrov, deficit tlaka pare, Angströmov indeks