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Rethinking lightning-induced fires: Spatial variability and implications for management policies

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ABSTRACT

Lightning is the primary natural ignition source for wildfires. However, in certain ecosystems, anthropogenic fires predominate and account for the majority of fire incidents. In many countries, the prevailing perception holds that wildfires are overwhelmingly human-caused. While statistically accurate when pooling data from across the country, this perspective leads to a misconception that wildfires are not a natural component of ecosystems. This generalization requires a critical examination of regional variability in lightning-induced wildfires (LIWs). As a case study, we examined the spatial distribution of LIWs in Türkiye using national wildfire data between 2002 and 2022. We considered three main wildfire causes: human-caused, lightning-induced, and unknown-origin. We investigated the distribution of fire occurrences and burned areas to demonstrate the spatial variability of LIWs and human-caused fires (HCFs) across Türkiye at the regional and local forest management unit levels. We found considerable regional and local disparities in the incidence of LIWs across Türkiye. We also observed a higher incidence of LIWs in areas with higher lightning densities, especially in the mountainous regions of western and northern Anatolia, including southwestern and northwestern Anatolia. In certain years, the proportion of LIWs exceeds 45 % in some regional units and 75 % in many local units. However, LIWs burned significantly smaller areas than HCFs. The most populated regions primarily experienced HCFs, while in several other regions, including less-populated or forest-rich ones, lightning was a major source of wildfires. Seasonal trends also emerged, showing an increased prevalence of LIWs, with a peak during the fire season and a relatively higher percentage during seasonal transitions. Despite the increasing human activity, LIWs have remained a significant cause of wildfires in several regions in the country. Our results on the significant spatial variability in LIWs challenge the traditional belief that human activities are the primary ignition sources for wildfires across Türkiye and downplay lightning as an ignition source. Our findings suggest that a one-size-fits-all fire management strategy which has led to wildfire suppression policies for the past century is suboptimal for countries where lightning is a significant source of wildfires. Therefore, an ecologically sound and economically efficient wildfire management policy must account for regional variability in the causes of wildfires. Accordingly, we recommend a reassessment of blanket fire suppression strategy in several countries such as Türkiye, advocating for more selective suppression practices that consider the role of naturally occurring wildfires.

1. Introduction

Wildfire serves as a major disturbance factor in ecosystems around the world, manifesting in different patterns and degrees of importance (Bond et al., 2005; Pausas, 2022). The underlying causes of fires exhibit significant variation among ecosystems. Among natural causes, lightning is the primary ignition source for wildfires worldwide (Larjavaara et al., 2005a; Müller et al., 2013; Veraverbeke et al., 2017; Janssen et al., 2023). In particular, ecosystems such as boreal forests experience wildfires primarily induced by lightning, in contrast to Mediterranean-type ecosystems where human-caused fires (HCFs) are prevalent (Stocks et al., 2002; Veraverbeke et al., 2017; Hanes et al., 2019). Lightning-induced fires (LIWs) in boreal regions often burn larger areas than HCFs due to access difficulties and being in remote areas that may not require fire suppression (Stocks et al., 2002). Compared to HCFs, LIWs occur within a more limited seasonal time frame

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(Ganteaume et al., 2013). Such factors cause LIWs to exhibit very different patterns in various ecosystems (Larjavaara et al., 2005b; Attiwill and Adams, 2013; Müller et al., 2013; Abatzoglou et al., 2016; Keeley and Syphard, 2018; Hanes et al., 2019; Coogan et al., 2022). In Mediterranean Europe, which accounts for 90 % of Europe's fires (Seidl et al., 2011), LIWs are substantially lower at around 5 % compared to boreal ecosystems where they can account for up to 50 % of fires (Ganteaume et al., 2013; Hanes et al., 2019). The variability observed in the patterns and impacts of LIWs highlights the complexity of the underlying factors and dynamics, such as historical and anthropogenic fire regimes, meteorological conditions, and human activities. Therefore, comprehensive research is imperative to understand the drivers of LIWs.

Climate change is projected to increase meteorological conditions conducive to lightning in various regions globally, despite uncertainties stemming from divergent modeling approaches (Romps et al., 2014; Finney et al., 2018; Romps, 2019). This rise in lightning activity is expected to increase LIWs (Pérez-Invernón et al., 2023). Moreover, climate change drives larger and more frequent anthropogenic and natural fires in several regions of the world (Cattau et al., 2020). As a result, ecosystems that are currently considered to be marginally affected by lightning fires may become more exposed to such fires in the future. In the Mediterranean basin, where the majority of fires are human-caused, it may initially seem justifiable to overlook LIWs. However, focusing solely on the broader picture without considering regional variability may lead to erroneous conclusions and ineffective or even detrimental fire management plans (Fernandes et al., 2021), posing risks to biodiversity and resulting in substantial ecological and economic consequences. Therefore, it is crucial to thoroughly understand the patterns and dynamics of LIWs not only in regions where lightning fire activity is currently high but also in areas where such incidents are not yet prevalent but may become so in the future.

The global overlook of LIWs can profoundly alter our perception of wildfires, often leading the public to associate fires solely with human causes (Fernandes et al., 2021). This misconception can also subsequently misguide fire management policies and post-fire restoration efforts. For example, fire suppression throughout the 20th century is one of the reasons for the contemporary devastating large fires and fire regime changes in many parts of the world (Moreira et al., 2020; Kreider et al., 2024). Moreover, unnecessary post-fire afforestation or artificial restoration practices that do not align with the natural recovery processes of ecosystems (Tavsanoglu and Pausas, 2022) may have been driven by the idea that fires are not natural but disasters in many fire-prone ecosystems (Pausas et al., 2008). Türkiye serves as a prime example of this issue. In Türkiye, the importance of lightning as a source of fire tends to be underestimated by both the media and the scientific community (e.g., Gültekin and Gültekin, 2024). This perspective is largely based on the fact that, on a national scale, the total number of LIWs is lower than HCFs. Prior studies have indeed discussed the causes of wildfires in Türkiye (e.g., Küçükosmanoğlu, 1993; Avcı and Korkmaz, 2020; Kavgacı and Başaran, 2023), yet they do not thoroughly examine the spatial variability of LIWs. There is only one regional study documenting that 29 % of wildfires are due to lightning in southwestern Anatolia (Sari, 2023). According to the latest published studies, LIWs account for 11.8 % of wildfires between 2001 and 2020 (Avcı and Korkmaz, 2020) and 12.6 % of wildfires between 2004 and 2022 in Türkiye (Kavgacı and Başaran, 2023). The prevailing attitude on underestimating the role of lightning in wildfires, neglects the geographical expanse and climatic, topographic, and ecological diversity of Türkiye (Şekercioğlu et al., 2011), thus potentially skewing fire management strategies towards the exclusive consideration of human-caused origins. Therefore, an in-depth investigation of LIWs in Türkiye considering their potential geographic variability, is needed.

In this study, we aimed to investigate the spatial variability of lightning-induced wildfires across Türkiye. Considering the diversity of climate, topography, and vegetation types throughout Türkiye, we hypothesized that LIWs would exhibit a large amount of spatial variability across different regions of the country. To test this hypothesis, we used wildfire and lightning occurrence data from national databases and performed exploratory spatial analyses to elucidate the distribution of LIWs in Türkiye.

2. Methods

2.1. Study area

The study area covers the entire land area of Türkiye, approximately 780,000 km^2, located between 26° to 45° eastern longitude and 36° to 42° northern latitude. The country exhibits notable topographic diversity, ranging from sea level to several mountain peaks > 3000 m a.s.l. with a maximum of 5137 m elevation. Türkiye's location at the crossroads of Europe, Asia, and Africa within the temperate zone results in a rich diversity of climate and vegetation (Şekercioğlu et al., 2011). The climate exhibits substantial variability, ranging from a Mediterranean climate with mild, wet winters and hot, dry summers on the western and southern coasts to a drier continental climate in the central regions and a humid oceanic climate along the northern coasts (Erinç, 1969). This climatic diversity results in a wide range of vegetation types, including steppic grasslands, shrublands, and a variety of forest ecosystems (Şekercioğlu et al., 2011). Wildfires have played a crucial role in the ecosystems of Türkiye for thousands of years, especially due to its location in the Mediterranean belt and characterized by the hot, dry Mediterranean climate that characterizes a substantial part of the country (Turner et al., 2008; Bekar and Tavşanoğlu, 2017; Şahan et al., 2022).

2.2. Data

We used three datasets in the study: wildfire occurrences, lightning occurrences, and forest administrative boundaries of Türkiye. Wildfire occurrence data was obtained from the General Directorate of Forestry, and cover the period from 2002 to 2022. The dataset includes information regarding the location (before 2013: forest management units; after 2013: forest management units plus XY coordinates), cause, and start date of fires, among other information. We categorized the detailed ignition causes of wildfires into three groups: human-caused, lightning-induced, and unknown-origin. We grouped negligence, power lines, arson, and several others as HCFs. Our dataset contained a total of 47,264 records, with an average of 2251 wildfire occurrences per year.

Lightning occurrence data was gathered from the Turkish State Meteorological Service, covering the period from 2016 to 2022. The dataset included a total of 12,056,013 observations (cloud-to-ground stroke counts) from 41 stations, with an annual average of 1,722,288 lightning incidents (median is 1,456,957 and range is from 1,279,120 to 2,922,705) per year.

The third dataset was the forest administrative boundaries dataset. The forest management framework in Türkiye is composed of three hierarchical levels: forest regional directorates, forest district directorates, and forest sub-district directorates. Each level is subordinate to the preceding one, with the forest regional directorate being the largest and the forest sub-district directorates being the smallest authorized units (Supplement Table 1; Supplement Fig. 1). In total, there were 47 forest regional directorates, 278 forest district directorates, and 1435 forest sub-district directorates in the dataset. We conducted our analyses on the forest regional directorate (hereafter referred to as the regional unit) and forest sub-district directorate (hereafter, the local unit).

2.3. Analysis

We investigated the spatial distribution of human-caused, lightning-induced, and unknown-origin wildfires across regional and local forest management units. Although our analyses were primarily exploratory, they are complemented by Moran's *I* and regression analyses to provide further evidence and support.

We created 1 × 1 km grids within Türkiye's borders to determine the spatial distribution of lightning strokes in Türkiye. Then, we calculated the average number of lightning stroke counts per grid for the 2016–2022 period by aggregating the stroke counts that fall in each grid cell. We calculated the rate of LIWs for each local unit by intersecting the centroid of each fire observation with the corresponding local unit boundaries, aiming to investigate the variability of LIWs at the local unit level. Fire data were summarized based on the cause and month of occurrence to determine the distribution of human-caused, lightning-induced, and unknown-origin fires in Türkiye by month. This approach provided a temporal perspective on the prevalence of different wildfire causes throughout the year.

We used Moran's I statistic to test for global spatial autocorrelation, providing insight into the spatial distribution of LIWs. The Moran's I ranges between −1 and 1, is a widely used method for assessing spatial autocorrelation, and it measures the correlation among observations that are geographically close to each other (Moran, 1948, 1950). Values greater than 0 indicate positive spatial autocorrelation, while values less than 0 indicate negative spatial autocorrelation (Moraga, 2023). We calculated Moran's I based on the percentages of LIWs for local units (with data for 2002–2022). We further used Local Moran's I (LISA - Local Indicator of Spatial Association) to identify and assess statistically significant clusters of LIWs across Türkiye (Anselin, 1995). We calculated Local Moran's I based on the percentages of LIWs for local units. This approach allowed for the detection of local spatial autocorrelation and assessment of areas with particularly high or low LIWs.

We also performed logistic and linear regression to explore the associations between lightning and LIWs occurrences in Türkiye and certain regional units that representative of areas with different wildfire origin trends. Since LIW data included an excess number of zeros for local units, we used a two-staged modeling approach to address this issue by using both presence-absence data of LIW for a logistic regression and LIW per km^2 data obtained by removing zero values for a linear regression analysis (Soyumert et al., 2019).

We used the R programming language (version 4.3.3) for all data processing, analysis, and visualization in the study (R Core Team, 2024). For these purposes, we utilized several packages including tidyverse (2.0.0), data.table (1.14.10), sf (1.0.14), geos (0.2.4), stars (0.6.4), terra (1.7.55) and spdep (1.3.1) (Pebesma, 2018; Wickham et al., 2019; Barrett et al., 2023; Dunnington and Pebesma, 2023; Hijmans, 2023; Pebesma and Bivand, 2023).

3. Results

Our analysis of wildfire data in Türkiye over the past two decades reveals substantial regional and seasonal patterns in wildfire incidence and size. Between 2002 and 2022, Türkiye experienced 47,264 wildfires, which burned 311,270 ha. Most fires occurred in Mediterranean Türkiye, such as the Muğla, İzmir, and Antalya regional units. At the same time, the northern and northeastern regions, characterized by their higher summer precipitation and humidity, experienced the fewest fires (Fig. 1c). The average size of wildfires was 6.6 ha, while the median size was notably smaller at 0.2 ha. The majority of these fires (79.9 %) were less than 1 ha in size, and 99.4 % were less than 100 ha in size, with only 0.6 % exceeding this size, representing the more extensive incidents (Supplement Table 2). The number of LIWs was 5820 during the same period, which burned significantly smaller areas than HCFs, with an average size of 0.8 ha and a median size of 0.1 ha (Table 1; Supplement Table 2). Most LIWs (93.4 %) were under 1 ha in size and 99.4 % of those burned less than 10 ha (Table 1; Supplement Table 2).

Examining the wildfire causes in Türkiye within the study period highlights the distinct contributions of human activity and lightning strokes, as well as regional variations. Between 2002 and 2022, human-caused ignitions were responsible for 50 % of the wildfires in Türkiye, while lightning-induced ignitions accounted for 12 % and the origin of 38 % was recorded as unknown. When considering only fires with known causes, the proportion of HCFs was 80 %, while the proportion of LIWs increased to 20 %. The total number of wildfires and relative proportion of human-caused, lightning-induced, and unknown-origin fires showed variability across regional and local units (Fig. 1b, Fig. 2, Fig. 3, Supplement Table 3). These patterns were consistent across years, as the fire causes remained similar between 2002 and 2022 (Fig. 4), with an exception in Muğla Forest Directorate where a gradual increase of fires with unknown origin through time is observed. A similar trend (low variability in LIW among years and gradual increase of unknowns over time) also existed at the country level (Fig. 5).

In general, we observed three major patterns in the relative proportions of lightning-induced, human-caused, and unknown-origin fires in forest management units: (1) most fires are of human origin, (2) LIWs have a relatively higher or comparable percentage to human-caused fires, and (3) fires of unknown origin have a considerable proportion (Fig. 3). Notably, some regional units, such as İzmir, İstanbul, and Kahramanmaraş, had a high total number of wildfires and a low rate of LIWs (Fig. 2, Supplement Table 3). In contrast, regional units such as Muğla, Isparta, and Denizli not only faced a high total number of wildfires but also a significant proportion of LIWs (Fig. 2, Supplement Table 3). Bolu, Eskişehir, and Kütahya, on the other hand, had a high proportion of LIWs and a lower total number of wildfires (Fig. 2, Supplement Table 3).

Our regression analyses confirmed these disparities between LIWs and lightning occurrences at regional unit level. For example, in the Muğla regional unit, lightning number per km^2 and LIW number per km^2 exhibited a significant positive relationship ($R^2 = 0.38$, $P < 0.0001$; Fig. 6), while in İzmir and Bolu regional units, this relationship was not significant ($R^2 = 0.01$ and $R^2 = 0.02$ respectively, both $P > 0.05$; Fig. 6). On the other hand, the probability of the occurrence of LIW was not explained by lightning number per km^2 in the Muğla and İzmir regional units (explained deviance = 1.5 % and 0.03 %, respectively, both $P > 0.05$) according to logistic regression analysis based on presence-absence data, but a similar analysis pointed out a significant positive relationship for the Bolu regional unit (explained deviance = 14.0 %, $P = 0.0007$; Fig. 6). These difference among regional units result in a weak positive relationship between lightning number per km^2 and LIW number per km^2 for Türkiye (explained deviance = 4.2 % for logistic regression and $R^2 = 0.11$ for linear regression, both $P < 0.0001$; Fig. 6), suggesting that LIW-lightning relationships may differ depending on the scale.

In many forest management units, LIWs reached considerable percentages, and in some units and years, they even exceeded the HCFs. In the Muğla regional unit, which has the highest incidence of wildfires in Türkiye, LIWs account for 30 % of all fires (Fig. 2, Supplement Table 3). When focusing solely on fires with known causes, the proportion of lightning-induced forest fires in the Muğla regional unit was 42 %, while HCFs remained at 58 %. In certain years, the proportion of LIWs to all fires exceeds 45 % in some regional units and 75 % in many local units. For instance, in 2018, lightning was responsible for 48 % of all of the wildfires in the Muğla regional unit, while in more than 19 local units, the proportion of LIWs was more than 70 % in the same year (reached 100 % in 12 local units). At the local unit level, the variability of the proportion of LIWs was more pronounced (Fig. 1b), ranging from 0 % to 100 %. Specifically, in cases where the total number of fires is 10 or more, fires induced by lightning accounted for more than 75 % of the total in 10 local units, all located in southwestern Anatolia (Supplement Table 4).

Seasonal trends also emerged, showing an increased prevalence of LIWs, with a peak during the fire season and a relatively higher percentage during seasonal transitions (i.e.; periods of transition from spring to summer and summer to fall; Fig. 5). Considering HCF:LIW ratios, June, September and October had the highest ratios, not July and August, when most fires occurred. LIWs were distributed throughout the year from March to December, even though the occurrence of LIWs

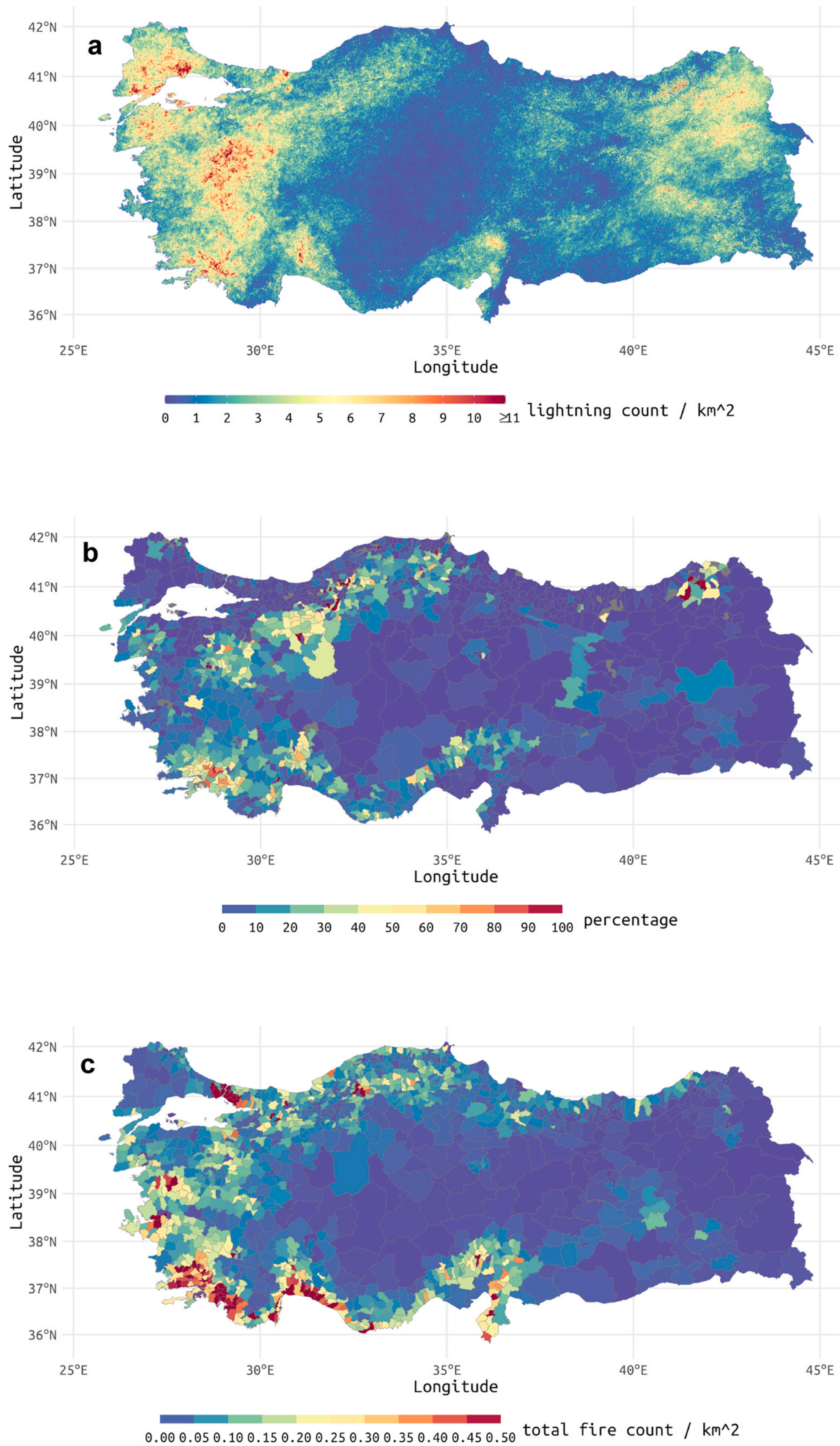

Fig. 1. Spatial variability of (a) lightning strokes, (b) lightning-induced fires, and (c) distribution of the total number of fires in Türkiye. Colors are proportional to the number of average annual lightning stroke counts at each 1×1 km grid (a), represent percentages of lightning-induced fires (b), and the total number of fires per km^2 (c) in each forest management unit.

Table 1
Percentage of the number of fire incidents and burned area in three selected regions and the whole Türkiye (rows) based on various fire size classes (columns). The extended version of the table is presented in Supplement Table 2.

			Fire size (ha)					
Region	**Origin**		$0\text{-}10^0$	$10^0\text{–}10^1$	$10^1\text{-}10^2$	$10^2\text{-}10^3$	$10^3\text{-}10^4$	$10^4\text{-}10^5$
Türkiye	**Human**	occurrence (%)	39.17	8.96	1.57	0.28	0.04	0.01
		area (%)	1.62	4.44	6.95	13.41	25.55	16.05
	Lightning	occurrence (%)	11.50	0.74	0.07	0.01	-	-
		area (%)	0.26	0.35	0.30	0.61	-	-
Muğla	**Human**	occurrence (%)	35.85	4.41	1.11	0.22	0.05	0.02
		area (%)	0.78	1.28	2.84	5.32	17.49	17.85
	Lightning	occurrence (%)	29.12	0.76	0.06	0.03	-	-
		area (%)	0.33	0.20	0.19	0.33	-	-
Bolu	**Human**	occurrence (%)	27.63	9.70	1.35	0.13	-	-
		area (%)	3.88	9.84	20.33	13.70	-	-
	Lightning	occurrence (%)	21.16	2.96	0.40	-	-	-
		area (%)	1.63	3.61	3.27	-	-	-
İzmir	**Human**	occurrence (%)	74.91	13.78	2.55	0.58	0.06	-
		area (%)	3.62	8.41	15.65	42.74	28.08	-
	Lightning	occurrence (%)	5.70	0.52	0.02	-	-	-
		area (%)	0.12	0.28	0.06	-	-	-

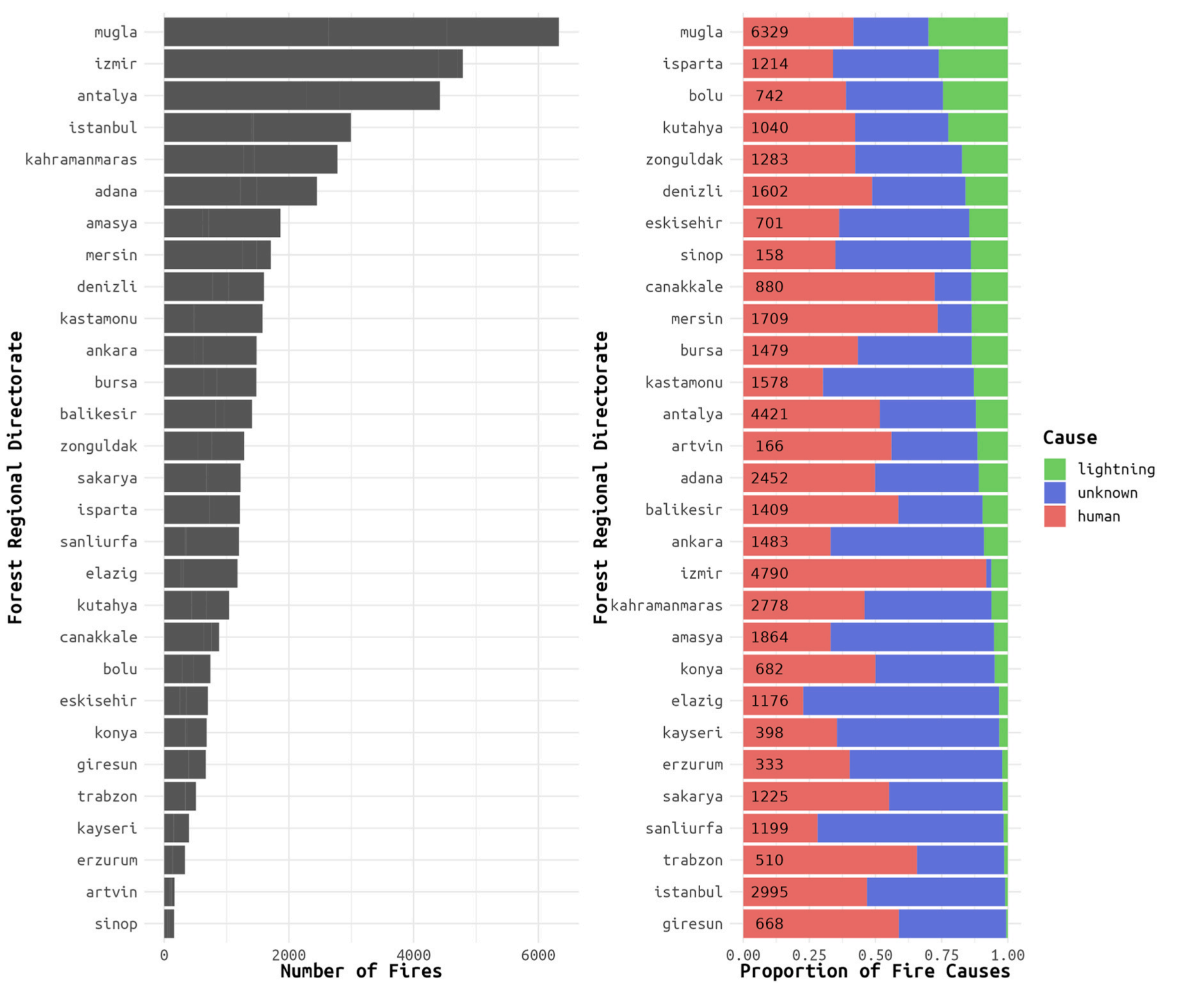

Fig. 2. The total number of recorded fires (left panel) and the relative proportion of human-caused, lightning-induced, and unknown origin fires (right panel) across regional units in Türkiye. Numbers within bars are the total number of recorded fires in each directorate. The raw data for this graph is provided in the Supplement Table 3.

varied considerable among months (Fig. 5).

We found considerable spatial variability in lightning strokes (Fig. 1a) and LIWs (Fig. 1b). We observed a higher incidence of LIWs in regions with higher lightning densities, especially in the mountainous areas of western and northern Anatolia, including southwestern and northwestern Anatolia (Fig. 1b). In contrast, central Anatolia, coastal areas of northern Anatolia, and the southeastern Anatolian plains had significantly lower incidences of both lightning and LIWs (Fig. 1a,b). However, there were exceptions, such as northwestern (Thrace region) and part of northeastern Türkiye, where the rate of LIWs remains low

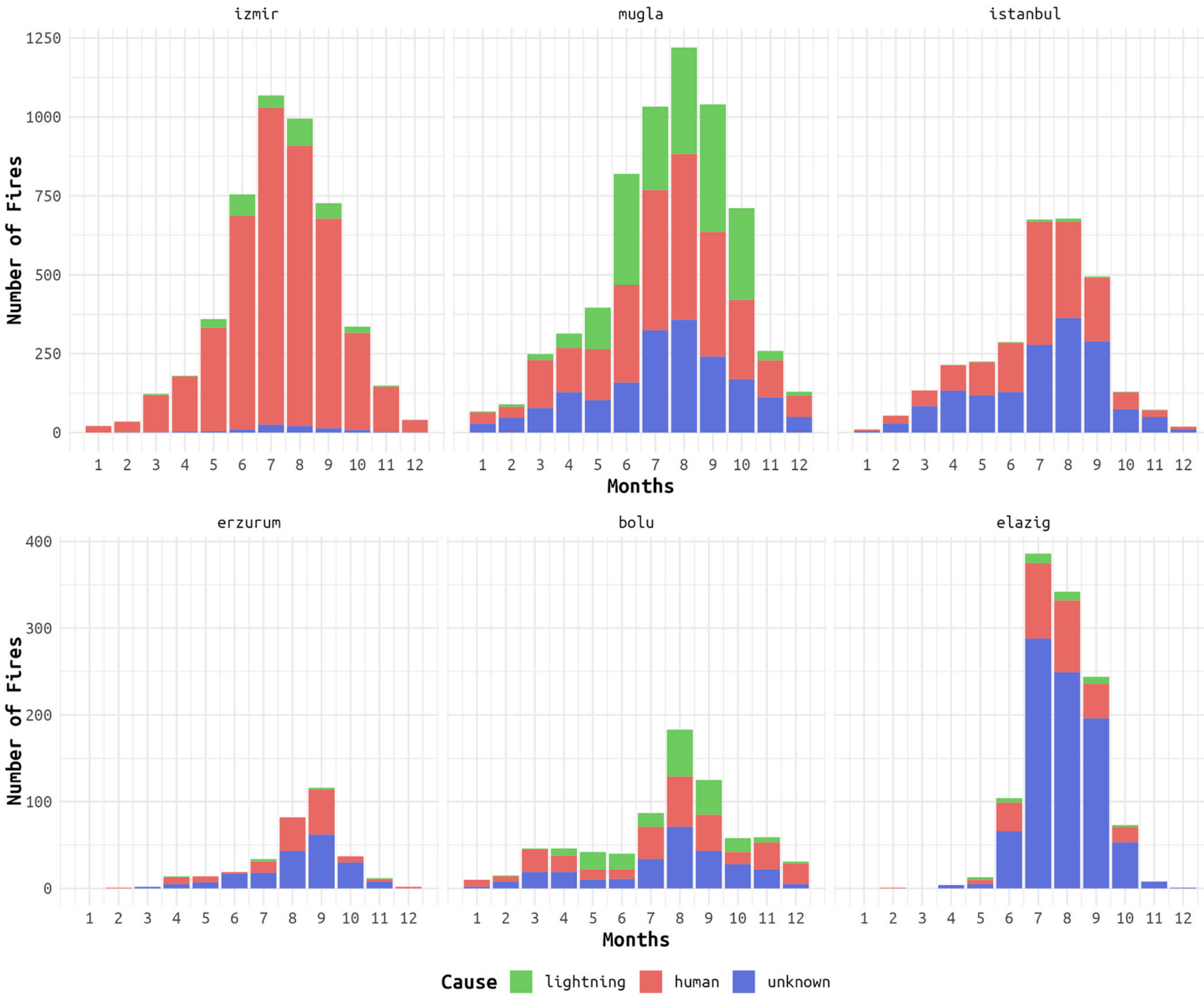

Fig. 3. Representative examples for three major trends/patterns in the relative proportion of lightning-induced, human-caused, and unknown-origin fires in regional units. The upper and lower panels indicate regional units with larger or smaller numbers of wildfires, respectively. Left panels: regional units that most fires are of human origin, center panels: those with at least one-fourth of fires are due to lightning, and right panels: those with unknown origin have a considerable proportion.

despite high lightning intensity (Fig. 1a,b). Density of human population might have shaped the dominant wildfire cause in some regional units, as the proportion of LIWs was just 1 %, 9 %, and 6 % in İstanbul, Ankara, and İzmir regional units, which include the most populated three cities in Türkiye, respectively. More detailed analysis exploring the associations between LIWs and several climatic, geographic, and anthropogenic factors is required to elucidate the drivers of LIWs in Türkiye.

Local units exhibited positive spatial autocorrelation in the percentages of LIWs, indicating a geographic clustering (Moran's $I = 0.45$; P < 0.0001). Local Moran's I analysis reveals clusters with high percentages (high-high) in the mountainous regions of northwestern, western, southwestern, southern, and northeastern Türkiye, and clusters with low percentages (low-low) along the northern coastal areas and the interior regions of central, eastern, and southeastern Türkiye (Fig. 7). The terms "high-high" refer to areas with high values surrounded by neighbors also with high values, whereas "low-low" denotes areas with low values surrounded by neighbors with low values.

4. Discussion

Wildfires exhibit considerable spatial variability, regardless of their origin—whether natural or anthropogenic. In this study, we focused on LIWs and revealed their geographical patterns across Türkiye. Our findings reveal significant regional and local variability of LIWs, often overlooked in broader assessments that fail to account for regional differences. In this regard, our results support our initial hypothesis that, in certain regions, LIWs constitute a substantial portion of wildfire incidents in Türkiye. This is in sharp contrast to areas where human activities are the predominant ignition source such as regions that include the three most-populated cities in this country. Such spatial disparities align with global observations highlighting the influence of topography, climate variability, and ecosystem diversity on fire regimes (Bond et al., 2005; Liu and Wimberly, 2015; Pausas, 2022). Indeed, the climatic and topographic diversity of Anatolia creates a mosaic of ecosystems (Şekercioğlu et al., 2011), each characterized by distinct fire regimes (Bekar, 2016; Tavşanoğlu, 2017; Pausas, 2022). Coupled with the complex structure of convective instability that allows thunderstorms to form (Williams, 2005), this diversity of ecosystems and fire regimes reflects the complex dynamics between meteorological conditions, ignition sources, and wildfire occurrences.

An association between lightning activity and LIWs is to be expected (Coogan et al., 2022). In our study, we observed the clustering of LIWs in

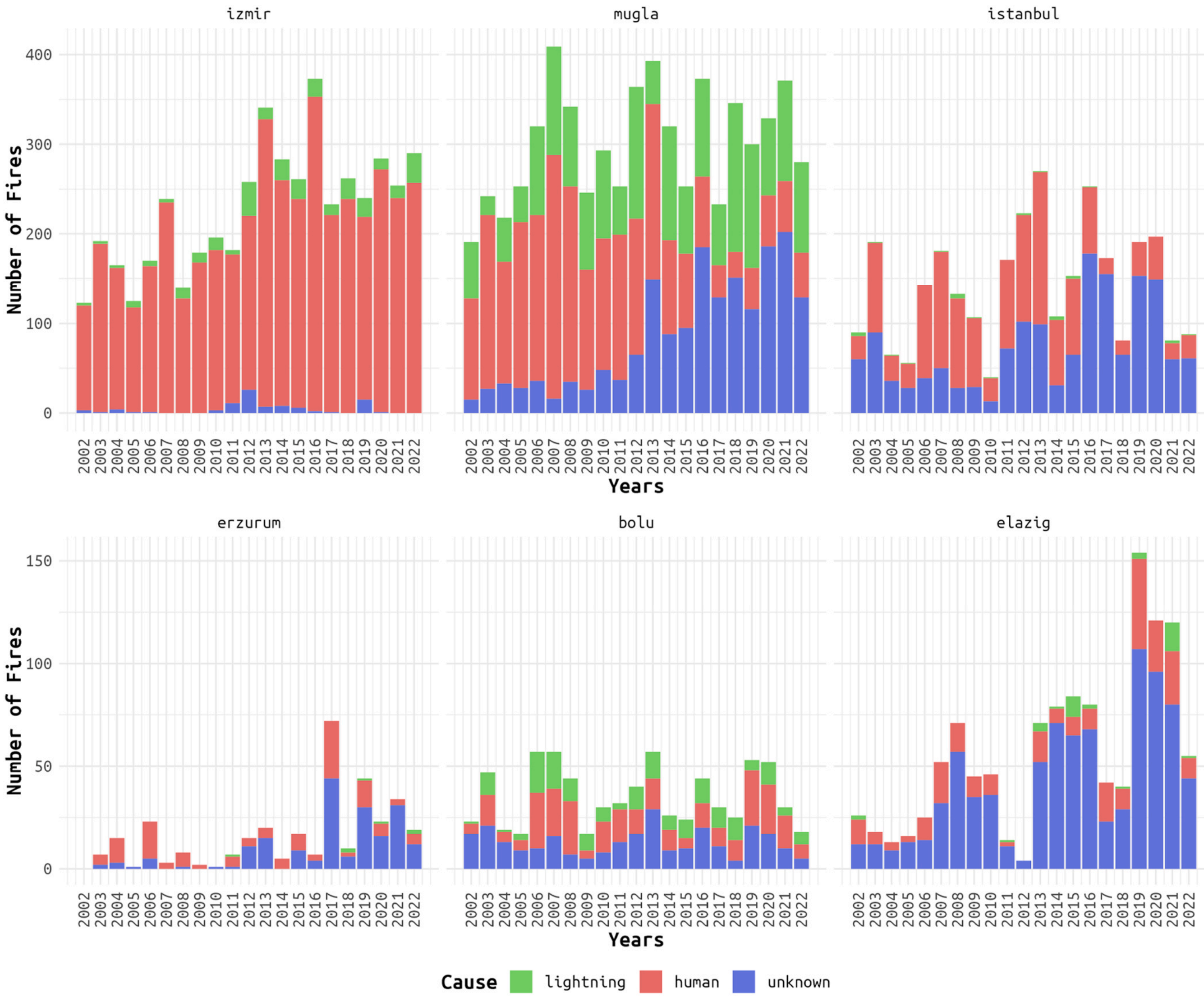

Fig. 4. Yearly distributions of fire causes between 2002 and 2022 for the regional units that are presented in Fig. 3.

certain regions, occurring alongside high rates of lightning activity, emphasizing this pattern. However, while lightning is a prerequisite for the initiation of LIWs, the presence of lightning does not invariably lead to the occurrence of such fires. Regions such as northeastern Anatolia and Thrace present a contrasting scenario where high lightning activity is coupled with a low occurrence of LIWs. This contrast highlights the complex interplay between lightning activity and wildfire occurrence, which involves factors such as fuel conditions, weather and climate, topography, and human presence. The high prevalence of LIWs in certain regions of Türkiye, particularly those with the highest fire activity, such as Muğla, is further supported by observations that fire regimes are primarily influenced by climatic factors related to temperature and precipitation (Bekar and Tavşanoğlu, 2017), and vary geographically across Türkiye (Pausas, 2022). Moreover, our analysis showed that LIW is associated with the number of lightning stroke counts in Muğla regional unit. These findings highlight the substantial role of LIWs in various regions of Türkiye, particularly in Muğla, the most fire-prone region in the country. However, due to disparities in the relationship between LIW and the number of lightning stroke counts at the regional unit scale, only a weak positive relationship existed at the Türkiye scale. These results suggest that the spatial scale under investigation is crucial in evaluating spatial distribution of LIWs. Therefore, our results suggest that reassessing the role of LIWs at local or regional scales in regions characterized by diverse ecosystems and fire regimes, similar to those found throughout Türkiye, can be critical to fully understanding the patterns of fires with natural origins.

LIWs occur in more restricted time periods because they depend on the specific conditions necessary for lightning formation in addition to other factors that may influence fire occurrence. Our results indicated a seasonal pattern in the distribution of LIWs throughout the year. The higher proportions of LIWs in June, September and October compared to July and August, when most fires occur in Türkiye, are possibly due to increased HCFs resulting from increased human activity (tourism, travel, etc.) besides fire weather conditions during these two months across the country, especially in the Mediterranean region. Indeed, the Muğla region, which is located in the Mediterranean-climate zone, exhibited a pattern similar to the country-level data. Moreover, the diversity of climates and topography in Türkiye may also make several other months suitable for LIWs. For example, it is not uncommon to observe LIWs in November or December in the northwestern part of Anatolia. All of these factors indicate that seasonal patterns in meteorological conditions and human activity shape the observed seasonal distribution of LIW in Türkiye.

The traditional belief holds that human activities are the major ignition sources for wildfires across Türkiye, downplaying the role of lightning as an ignition source (e.g., Küçükosmanoğlu, 1993; Avci and

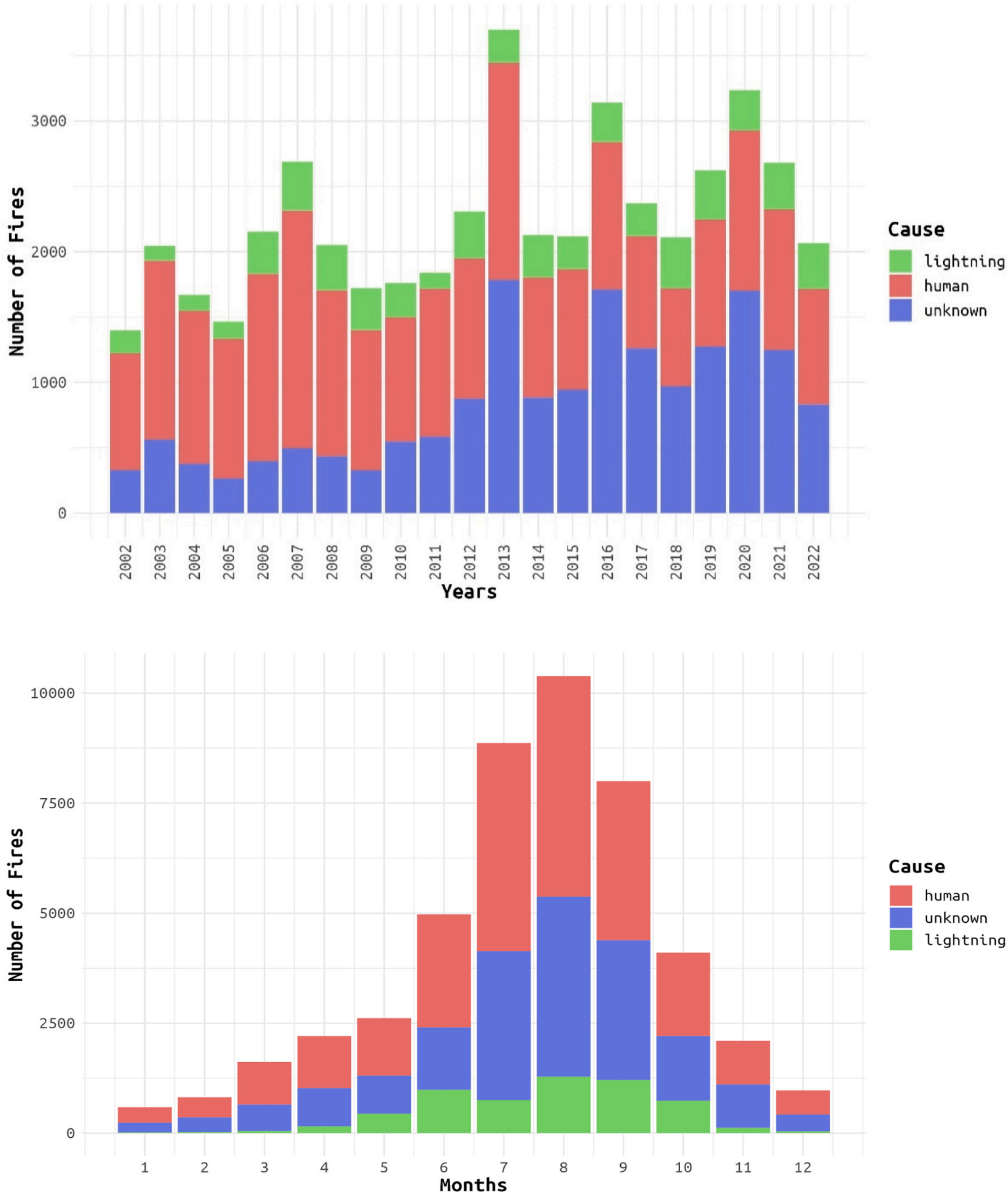

Fig. 5. Yearly and monthly distribution of wildfires with different origins in Türkiye.

Korkmaz, 2020; Kavgacı and Başaran, 2023; Gültekin and Gültekin, 2024). However, our findings on the significant spatial variability in LIWs, especially in areas predominantly impacted by lightning strokes, challenge this belief. This oversight, not exclusive to Türkiye but prevalent globally (e.g., Ganteaume et al., 2013), fosters misconceptions about the inherent role of fire within ecosystems and affects management decisions (Ramos-Neto and Pivello, 2000; Vecín-Arias et al., 2016; Fernandes et al., 2021; Menezes et al., 2022). It reinforces the view that wildfires are solely anthropogenic, overshadowing their natural occurrence. This skewed perception leads to fire management policies that may not fully consider the ecological significance of natural fire regimes, including aggressive fire suppression policies that inhibit natural fire regimes (Chavardès et al., 2018; Şahan et al., 2022). Furthermore, neglecting to recognize wildfires as a natural phenomenon can also result in ineffective post-fire restoration efforts in ecosystems adapted to fire (Tavsanoglu and Pausas, 2022), and restrict our understanding of the ecology, evolution, and biogeography of species (Pausas and Lamont, 2018). Since Komarek (1968) proposed the importance of LIWs for sustaining natural fire regimes more than half a century ago, many researchers have acknowledged their ecological role (Taylor, 1974; Ramos-Neto and Pivello, 2000; Hantson et al., 2022). In today's human-managed ecosystems, the use of low-intensity LIWs as a management tool has also been proposed to restore historical fire regimes and reduce forest fuels accumulated over a century of fire suppression policies (Ramos-Neto and Pivello, 2000; Pineda et al., 2022). Our results on the considerable spatial variability in LIWs at local and regional scales suggest that blanket fire suppression policies in areas dominated by LIWs must be reconsidered. In that sense, a mixed fire management

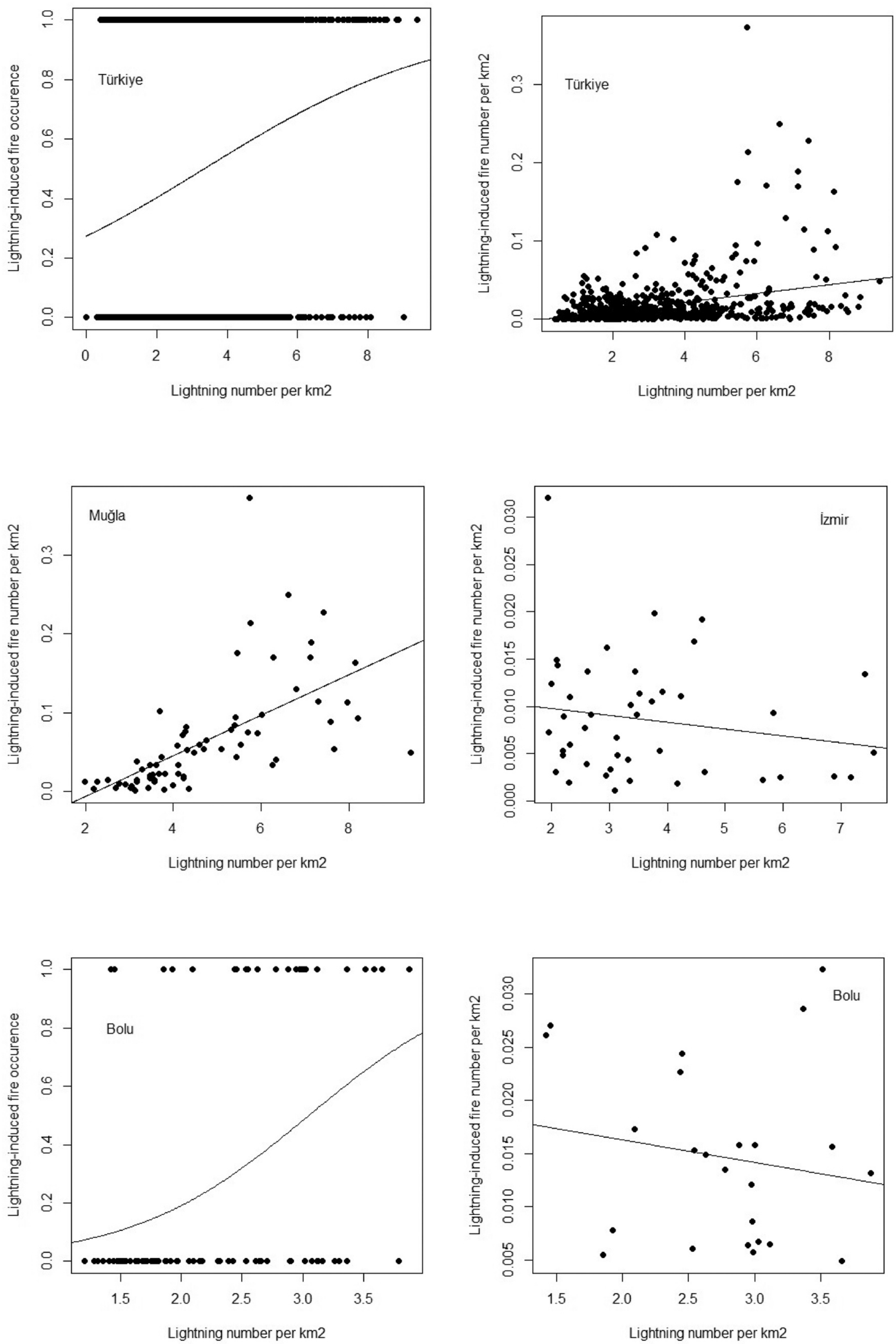

Fig. 6. The association between lightning number per km^2 and LIW number per km^2 at Türkiye scale and in certain regional units.

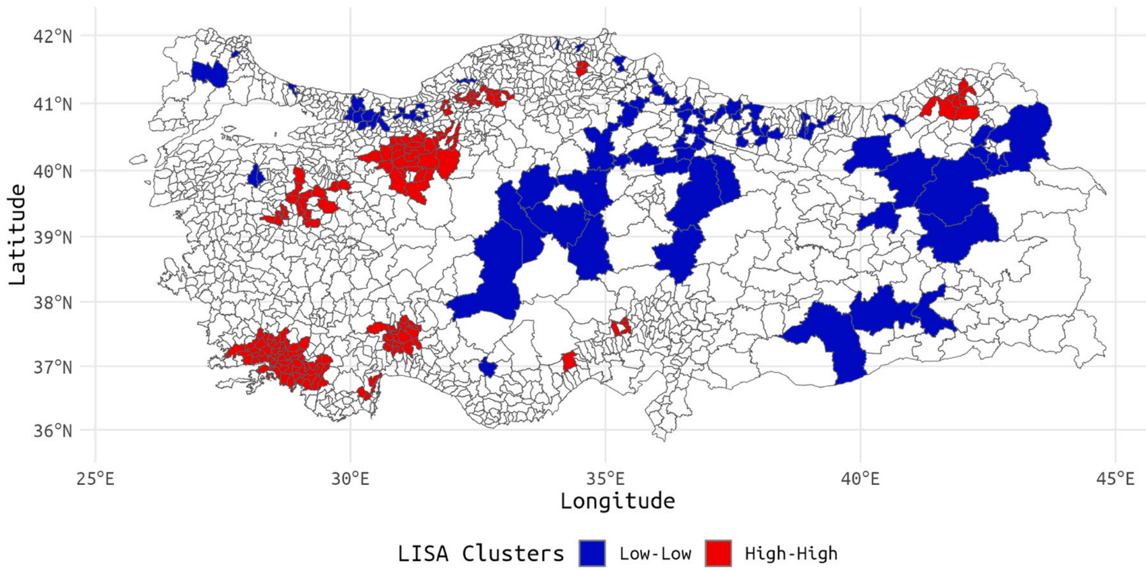

Fig. 7. Distribution of LISA clusters for LIWs across Türkiye.

strategy can be incorporated, including both a let-it-burn approach and fire suppression activities limited to locations related to human socio-economy or fire-sensitive habitats. More selective suppression practices, considering the role of naturally occurring wildfires in areas with a high frequency of LIWs, would allow the restoration of natural fire regimes in long-term fire-suppressed areas. For example, in the United States, a policy of not suppressing some LIWs has been implemented in remote areas away from human settlements (Van Wagtendonk, 2007; Houtman et al., 2013; Pietruszka et al., 2023). Longstanding fire suppression policies, accompanied by socio-economic changes (e.g. rural abandonment) and intensive afforestation activities, have led to fuel accumulation in natural ecosystems, resulting in large fires under the changing climate (Moreira et al., 2020; Pausas and Keeley, 2021). Therefore, novel approaches and protocols for forest and fire management plans that consider the spatial and temporal distribution of LIWs and implement let-it-burn strategies are necessary. However, it should be noted that effectively managing some LIWs requires accurately identifying them and adjusting management practices based on landscape configuration, location (e.g., topography or proximity to human settlements), and the weather conditions under which they ignite and spread.

As our results clearly showed, LIWs burn significantly smaller areas than HCFs in Türkiye, creating a better opportunity to implement such a policy compared to many other Mediterranean countries where lightning fires can burn large areas (Vázquez and Moreno, 1998; Fernandes et al., 2021). Therefore, we recommend a reassessment of blanket fire suppression strategies in several countries, such as Türkiye, advocating for more selective suppression practices that consider the role of naturally occurring wildfires. We believe, however, that this policy change in Türkiye still requires wider discussion among scientists, policymakers, and other stakeholders. Consensus is particularly needed in regions with relatively higher fire activity, such as the Mediterranean and Aegean regions of Türkiye, where the management of LIWs must be carefully implemented. In these regions, the public may not be fully prepared to understand natural fire regimes in anthropogenic landscapes. To implement a let-it-burn policy for LIWs, it is essential to gather more information from local communities in areas more prone to such fires. Additionally, strong integration and communication between foresters (who possess local knowledge of where and when LIWs occur within their management units), meteorological institutions (that can provide precise information on the formation and passage of thunderstorms), and firefighters should be established.

In summary, lightning is an important cause of fire occurrences in certain regions in Türkiye, contrary to the popular belief that HCFs are dominated the entire country. Recognizing the spatial variability of LIWs would enhance our understanding of the natural role of wildfires in ecosystems (e.g., in post-fire restoration), improve forest fire management practices (e.g., adopting a partial let-it-burn strategy), and address logistical challenges in firefighting (e.g., mitigating economic losses during wildfires in remote, mountainous areas).

CRediT authorship contribution statement

Mehmet Göktuğ Öztürk: Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Çağatay Tavşanoğlu:** Writing – review & editing, Supervision, Methodology, Conceptualization. **İsmail Bekar:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The code used in this paper for the data wrangling, analyses, and figures is available via the following GitHub link: https://github.com/mehmetgoktug/Rethinking-lightning-induced-fires. Since we are unable to publicly share the datasets we used in the study due to legal restrictions, researchers interested in accessing these data are encouraged to contact the respective agencies directly for potential data access opportunities. The lightning occurrence data used in this study can be obtained from the Turkish State Meteorological Service, while fire occurrence data and forest administrative boundary data can be obtained from the General Directorate of Forestry.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122262.

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