In-Between Landscape Transformations and Tourism Development: Investigating Latent Trends in Long-term Wildfires' Patterns, Greece (1955–2024)

Ioannis Konaxis

Department of Tourism Studies, University of Piraeus, 80 Karaoli & Dimitriou, EL-18534 Piraeus, Greece
E-mail: ikonaxis@unipi.gr

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Abstract

Global environmental change has increasingly reshaped wildfire dynamics resulting in heightened ecological and socioeconomic risks worldwide. While fire suppression and technical prevention remain central to wildfire and landscape management, broader land-use and governance frameworks are recognized as influential determinants of fire impacts at landscape scales. The present study investigates a long-time series (1955–2024) of wildfire basic indicators (burnt area, fire density, average fire size) with the final aim at deriving latent information clarifying change processes associated with climatic stressors, land-use change, and rapidly evolving socioeconomic conditions in Greece, a Mediterranean country with specific land-use trajectories, social dynamics, economic performances, and governance-related factors. Using an empirical approach based on multivariate statistics, this study evaluates the relative contribution of temporal variability in wildfire pattern as an indirect reflection of anthropogenic pressure. In this perspective,

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insights from existing literature and field-based observations are integrated to support interpretation of the quantitative results based on official statistics and landscape analysis. Wildfire risk seems to grow in the recent decades, both for fire size and frequency. These results underscore the relevance of integrated landscape management policies safeguarding agroforestry systems, and cross-sectoral measures fostering resilient and functional Mediterranean landscapes.

Keywords: Fire size, time pattern, land-use, correlation coefficients, Mediterranean.

Introduction

Wildfires constitute a complex phenomenon emerging from the interactions among ecological, physical, and human-driven factors (Moritz et al., 2005). While regional climatic conditions provide a broad framework for fire occurrence, local weather variability and the intrinsic flammability of landscapes play critical roles in shaping fire behavior, intensity, and spatial distribution (Fernandes et al., 2016; Turco et al., 2019; Pereira et al., 2020). Beyond environmental determinants, human activity modulates frequency and magnitude of wildfires (Mantero et al., 2020). Among these anthropogenic drivers, urban development – have emerged as key factors affecting fire dynamics (Moreira et al., 2011). In addition, rural socioeconomic practices, such as grazing, cultivation, and timber extraction, contribute to spatial and temporal variability in fire risk (Garcia-Ruiz et al., 2020), while governance frameworks and wildfire management policies further regulate landscape susceptibility to fire disturbances (Humphrey et al., 2021).

Although a considerable body of research has explored the localized effects of direct fuel management interventions – including prescribed burning and operational treatments – on fire behavior (Espinosa et al., 2019; Cansler et al., 2021; Stritih et al., 2021), understanding their indirect and landscape-scale consequences remains methodologically and conceptually challenging (Dale, 1997), particularly when aiming to identify general patterns from long-term fire indicator series. In Southern European contexts, empirical studies evaluating fire impacts remain relatively scarce, and most have relied on modeling or simulation approaches to examine hypothetical management strategies (Regos et al., 2016; Sil et al., 2019; Campos et al., 2022).

This study focuses on Greece, providing a robust context for assessing how landscape properties and temporal changes influence wildfire outcomes across complex fire-prone systems (Ferrara et al., 2019; Ascoli et al., 2021; Elia et al., 2022; Malandra et al., 2022). However, these studies have typically relied on relatively short time series and have focused on isolated subsets of potential drivers – for instance, socioeconomic conditions (Mancini et al., 2018), climatic variability (Cilli et al., 2022), or land-use dynamics (Ascoli et al., 2021) – without integrating them into a framework capable of capturing their interactive effects. Furthermore, empirical evidence quantifying the influence of indirect land governance interventions, whether planned or spontaneous, on the structuring of wildfire regimes is still extremely limited (Colonico et al., 2022).

To address these gaps, we implemented a multivariate analytical approach designed to quantify temporal variability in wildfire impacts across Greece, explicitly incorporating a comprehensive suite of environmental and anthropogenic covariates (Moreira et al., 2020). This framework indirectly accounts for natural drivers – including climate, fire weather indices, and landscape flammability – alongside human-related factors, such as socioeconomic context and land abandonment patterns. Importantly, the study emphasizes fire impact metrics directly or indirectly relevant to policy and management objectives, including fire severity, rather than relying solely on traditional descriptive indicators.

Methodology

Study Area

The spatial scope of this study encompasses the entire Greek territory, which covers approximately 131,982 km^2 and displays pronounced geographical and socio-economic contrasts. The national settlement system is constituted with a relatively small amount of large metropolitan agglomerations, most notably Athens, but also Thessaloniki and Heraklion, which function as major demographic and economic hubs. Beyond these urban cores, extensive coastal zones and insular regions in both the Ionian and Aegean Seas have experienced sustained development driven by tourism and permanent habitation. Conversely, much of the interior of the country consists of sparsely populated rural landscapes increasingly affected by long-term population decline and structural economic weakness. A striking feature of Greece's demographic organization is the persistent primacy of the capital region,

Table 1 Per cent share of selected land-use classes by year in Greece. Source: author's elaboration of Eurostat official statistics

Class	1960	1990	2022
Urban	5.8	6.0	6.5
Cropland	29.5	29.9	19.8
Pastures	41.3	39.6	32.9
Forests	21.4	22.3	38.8
Water	2.0	2.3	1.9
Total	100	100	100

which has accommodated more than 30% of the national population since the early 1950s.

Such a pattern of territorial imbalance is not unique, but rather aligns Greece with broader trends documented across Mediterranean contexts and several major European states, including France, Spain, and Italy. In the last sixty years, landscape composition changed rapidly in the country following a continuous economic evolution and social dynamics (Table 1). More specifically, built-up areas accounted for less than 6% of total landscape after World War II (1960) and grew to 6.5% of the whole territory in recent times (2022). Following intense anthropogenic pressures, cropland and pastures decreased more evidently in the study period, while forests expanded moderately possibly as a result of land abandonment and economic decline of inland districts.

Data Sources and Elementary Variables

Secondary data producing landscape and wildfire indicators have been considered in this research. Data sources basically include official statistics from national providers (namely, Hellenic Statistical Authority, ELSTAT, or National Greek Fire Service, and Eurostat). We developed a statistical analysis of two basic indicators of wildfires' regime, namely total burnt area and number of individual events, made available each investigation year (1955–2024) for the whole of Greece. We augmented the database with other two variables, namely the per cent share of (i) high forests and (ii) other natural (wooded-shrub) landscapes burned up each year; this last variable includes the Mediterranean maquis and garigue. Descriptive statistics were implemented to illustrate the basic patterns of change characteristics in long-term wildfires' regime of Greece.

Statistical Analysis

On the premise that intrinsic temporal variability in wildfire regimes is influenced by local heterogeneity (Salvati and Serra, 2016), temporal relationships among fire-related indicators were first examined through a pairwise correlation framework. Both parametric statistics based on the Pearson product–moment coefficient and non-parametric measures relying on Spearman's rank correlation were calculated to evaluate the strength and functional form of inter-variable associations, and to distinguish linear from non-linear linkages. Correlation values were interpreted along the conventional range from $+1$ to -1, with zero indicating the absence of association, and statistical significance was assessed at the 0.05 level after applying Bonferroni's correction for multiple comparisons (Ciommi et al., 2019). The absolute annual ratio between Spearman and Pearson coefficients at the country scale was additionally computed to characterize the dominant type of relationship. High ratios, particularly when Spearman exceeded Pearson values, were considered indicative of non-linear dynamics, as reported in earlier demographic applications (Duvernoy et al., 2018). Where appropriate, original variables were log-transformed and subsequently standardized prior to analysis.

A Principal Component Analysis (PCA) was run on the correlation matrix derived from the four descriptive variables introduced above, with the aim of synthesizing wildfire regimes and decomposing both the magnitude and direction of change according to the temporal framework adopted in this study. Components associated with eigenvalues greater than one were retained, and their interpretation relied on calculating loadings, representing the contribution of each indicator, and scores, capturing temporal positioning. Outcomes were displayed through a biplot that simultaneously represented loadings and scores within a common factorial space (Colantoni et al., 2016). To further investigate long-term temporal configurations in Greece, a hierarchical clustering procedure was applied to the annual data matrix – comprising four columns corresponding to the same variables used in the PCA and seventy rows spanning 1955–2024 – and producing dendrograms as graphical illustration (Di Feliciantonio et al., 2018).

Results

Descriptive Statistics

The apparent and latent characteristics of wildfires' regime in Greece were investigated aggregating the available data into seven decades from 1955

Table 2 Selected characteristics of Greek wildfires (decadal average of the number of fires, area (km^2) and the percent share of forests and other woodland types in total burnt area), 1955–2024. Source: author's elaboration of Elstat (Hellenic Statistical Authority) official statistics

Decade	Fires	Area	Forest (%)	Woodland (%)
1955–1964	649	105.425	43	37
1965–1974	655	144.587	33	34
1975–1984	1018	319.314	37	39
1985–1994	1555	569.614	40	43
1995–2004	8429	462.063	20	33
2005–2014	9746	517.567	14	32
2015–2024	9545	527.077	19	36

to 2024 (i.e. 1955–1964, 1965–1974, 1975–1984, 1985–1994, 1995–2004, 2005–2014, 2015–2024) as reported in Table 2, considering together the number of events, the aggregated burnt area and the percentage of high forests and other woodland in total burnt area. The number of fires increased substantially over time, moving from nearly 650 events per year, on average, to 9,500 events. The first two decades and the last two decades resulted to be rather homogeneous and reflect two extremes in the available time series. The burnt area per year increased, on average, in a continuous fashion moving from 105 km^2 in the initial observation decade to 527 km^2 in the last observation decade. However, an extremely high surface area exposed to fires was also observed between 1985 and 1994 and represents a clear outlier in the available time series. The percentage of high forests in total burnt area slowly decreased over time, approximately passing from 40% to 20%, on average. Conversely, the percentage of woodland was rather stable around 35% over time.

Correlation Analysis

Table 3 illustrates the results of a (parametric and non-parametric) correlation analysis using both moment-product linear Pearson coefficient and co-graduation Spearman rank coefficient estimating intensity and significance of the pair-wise relationship among the four relevant variables describing widlfires' regime (see Table 2) over 70 years (1955–2024) in Greece. Significant correlations were indicated in bold ($p < 0.05$) after Bonferroni's correction for multiple comparisons. The number of events was correlated positively and linearly with fire size (similar value and same sign of both Pearson and Spearman coefficients). The number of fire events resulted to be

Table 3 Results of parametric and non-parametric correlation analysis estimating intensity and significance of the pair-wise relationship among relevant variables over 70 years (1955–2024) in Greece (see Table 2 for descriptive statistics of the elementary variables); significant correlations ($p < 0.05$) corrected for Bonferroni's multiple comparisons in bold. Source: author's statistical elaboration of Elstat (Hellenic Statistical Authority) official data

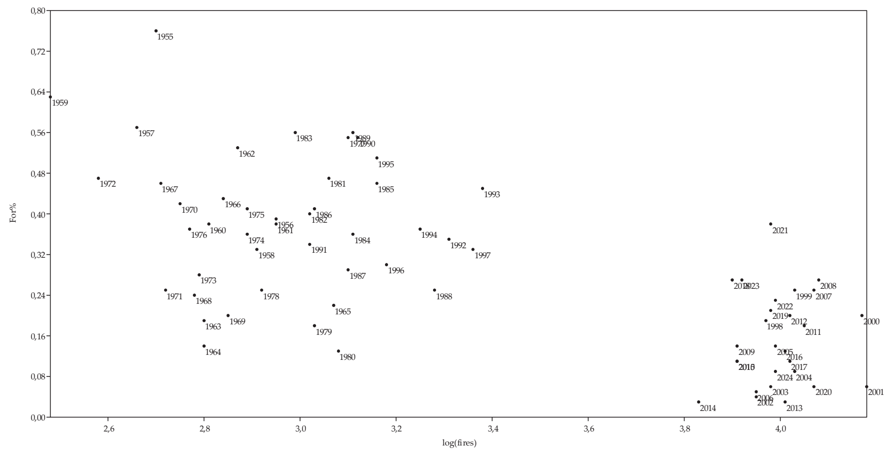
Variable	Log(fires)	Log(area)	Forests (%)
Pearson			
Log(area)	**0.45**		
Forests (%)	−**0.67**	−0.14	
Woodland (%)	−0.16	**0.27**	−0.02
Spearman			
Log(area)	**0.54**		
Forests (%)	−**0.60**	−0.05	
Woodland (%)	−0.03	**0.31**	0.03

negatively correlated with the percentage of high forests in total burnt area. The relationship is linear also in this case. Finally, the percentages of high forests and of other woodland in total burnt area were weakly and positively correlated. All in all, these elaborations indicate that a higher number of events is associated with non-forest fires, i.e. events involving cropland and other non-wooded vegetation (pastures, meadows, fallow land, unproductive soils or, eventually, wetlands).

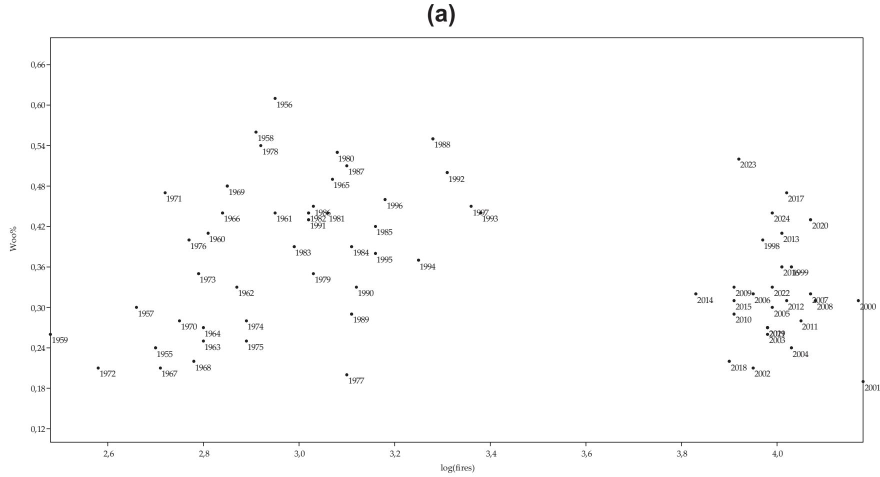
The relationship between the number of fire events (log-transformed) and the per cent share of high forests in total burnt area (Figure 1(a)) illustrates an evident clustering of recent years (approximately ranging between 1998 and 2024) and previous years (from 1955 to 1997). Based on the scatterplot, the discriminant variable was the occurrence of fire events. A similar pattern was observed when considering the per cent share of woodland in total burnt area (Figure 1(b)).

The relationship between fire size (log-transformed) and the per cent share of high forests in total burnt area (Figure 2(a)) illustrates a more mixed situation compared with the previous analysis. Recent years were clustered in the lower part of the scatterplot, although with no clear spatial pattern (fire size). A similar condition was observed when considering the per cent share of woodland in total burnt area (Figure 2(b)).

The relationship between the per cent share of high forests and other woodland types in total burnt area (Figure 3) illustrates a more mixed situation compared with previous elaborations. Recent years were clustered in the left side of the scatterplot, and the reverse trend was observed for



(a)



(b)

Figure 1 The relationship between the number of fire events (log-transformed, ‘log(fires)’) and the per cent share of high forests (‘For%’, panel (a) and woodlands (‘Woo%’, panel (b) in total burnt area. Source: author’s statistical elaboration of Elstat (Hellenic Statistical Authority) official data.

past years. As in earlier cases, the most relevant variable discriminating among the temporal axis was the per cent share of high forests in total burnt area. Taken together, more recent fires seem to be bigger in size than in the past but are also threatening a lower proportion of high forests than in the past, possibly involving more cropland or other (non-wooded) land-use classes.

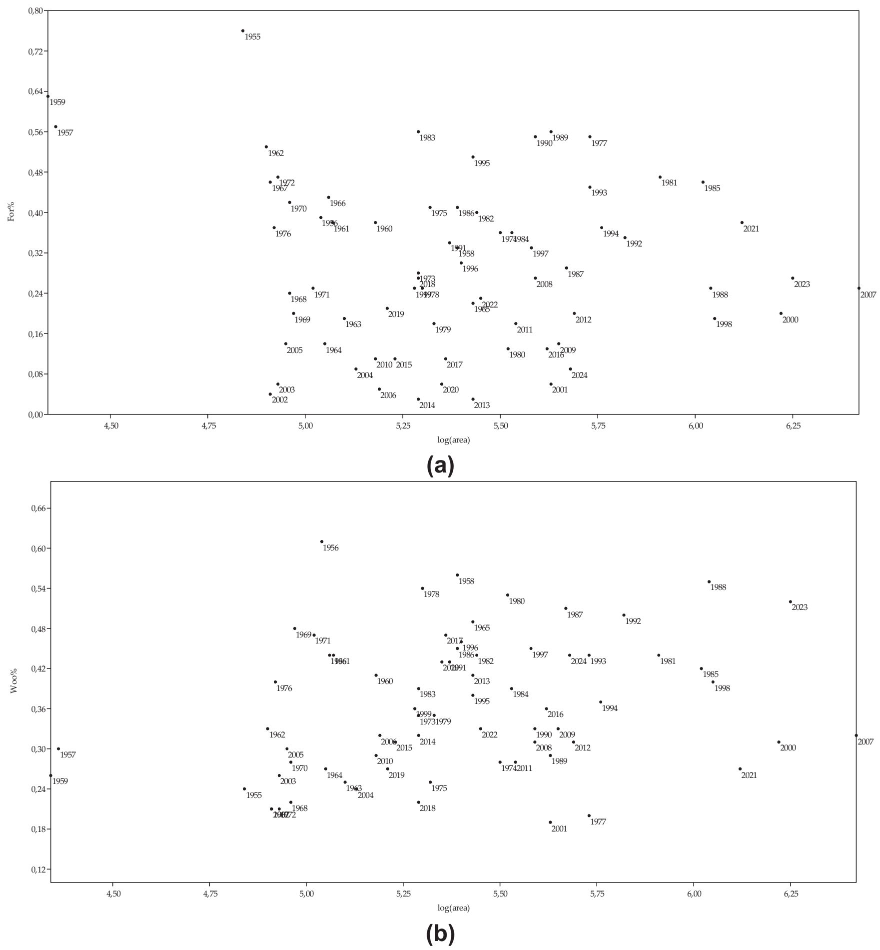


Figure 2 The relationship between fire size (log-transformed, 'log(area)') and the per cent share of high forests ('For%', panel (a) and woodlands ('Woo%', panel (b) in total burnt area. Source: author's statistical elaboration of Elstat (Hellenic Statistical Authority) official data.

Multivariate Analysis

An exploratory data analysis was run on the input matrix consisting of four variables (see Table 2) relevant in the investigation of wildfires' regime made available every year during the period 1955–2024. More specifically, a Principal Component Analysis extracting two main dimensions (PC1: 46.9% and PC2: 30.1%) was adopted here, accounting 77% of the total variance overall. Figure 4 illustrated the results of the analysis based on a traditional

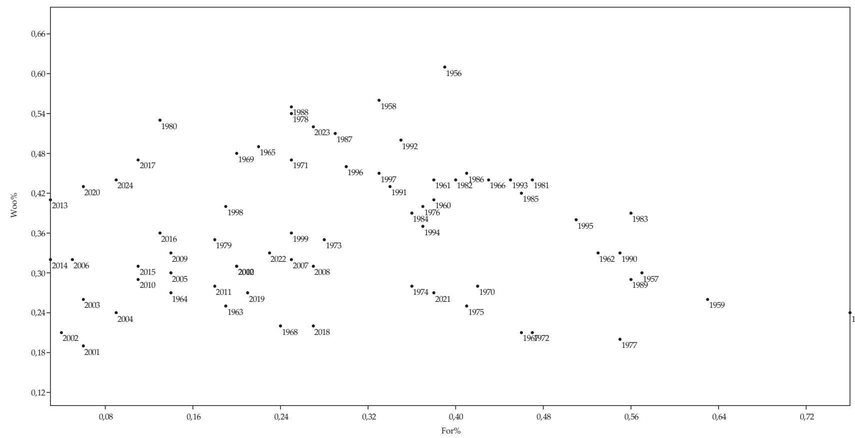


Figure 3 The relationship between the per cent share of high forests ('For%') and woodlands ('Woo%') in total burnt area. Source: author's statistical elaboration of Elstat (Hellenic Statistical Authority) official data.

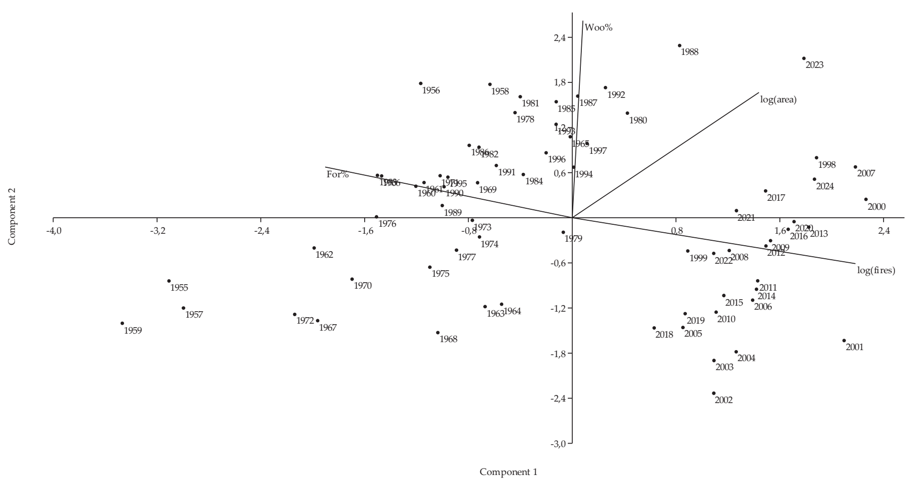


Figure 4 Results of a Principal Component Analysis summarizing the latent complexity of relevant wildfires' characteristics over time (see Figures 1–2 and text for relevant variables' acronyms). Source: author's statistical elaboration of Elstat (Hellenic Statistical Authority) official data.

biplot graphical representation. Component 1 (horizontal) illustrates a clear temporal gradient moving from past years (left) to recent years (right) and based on the overall frequency of fire events (positively associated with the axis, and thus higher over recent times) and the per cent share of forests in

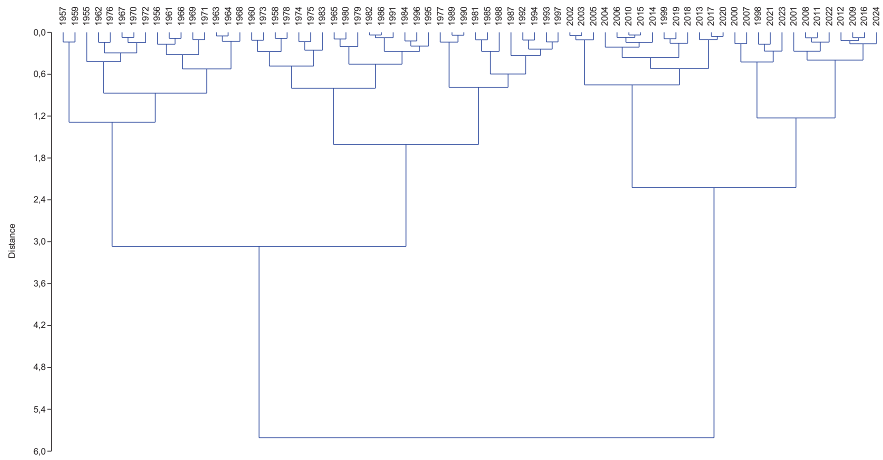


Figure 5 A dendrogram illustrating the results of a hierarchical clustering (Euclidean distances, Ward's agglomeration rule) classifying years based on the dominant wildfires' regime as quantified using four relevant variables ('log(fires)', 'log(area)', 'For%' and 'Woo%'); see Table 2 for descriptive statistics. Source: author's statistical elaboration of Elstat (Hellenic Statistical Authority) official data.

total burnt area (negatively associated with the axis, and thus higher over past times). Being constructed as geometrically independent from Component 1, Component 2 was clearly associated with the per cent share of woodlands in total burnt area, in turn associated with specific years especially in the 1970s, the 1980s and the 1990s. Fire size ('log(area)') was basically unrelated with the other analysis' dimensions and mostly associated with 2023, reaching the highest amount of burnt areas in the country all over the investigated time series.

Figure 5 summarizes the outcome of a hierarchical clustering with Euclidean distances and Ward's agglomeration rule for input amalgamation. A dendrogram was used to illustrate the results of the analysis and classified years based on the dominant wildfires' regime quantified considering four relevant variables ('log(fires)', 'log(area)', 'For%' and 'Woo%'). In line with the outcomes of previous analysis, hierarchical clustering confirmed a clear differentiation in two main groups of years (from 1998 to 2024, right-side, and from 1955 to 1997, left-side). However, a more subtle time division was highlighted, evidencing three sub-groups in the left-side cluster (the initial years in the time series from 1958 to 1968, left, the intermediate years from 1960 to 1995, middle, and the more recent years from 1977 to 1997, right), documenting a progressive shift in the wildfires' regime toward bigger and more frequent fires in Greece moving from left to right. At the same time, two sub-groups were also observed in the right-side main cluster, distinguishing years from 2002 to 2020 (left side) and from 2000 to 2024 (right side). These two sub-groups indicate homogeneous years with different (overall) conditions of fire danger (lower in the left cluster, higher in the right cluster). Taken together, hierarchical clustering document a continuous worsening of wildfires' characteristics over time when moving from left to right in the dendrogram.

Discussion

In Mediterranean Europe, anthropogenic influences have historically exerted a disproportionate effect on fire regimes compared with other geographic regions (e.g. De Rosa and Salvati, 2016; Cuadrado-Ciuraneta et al., 2017; Zambon et al., 2019, often amplifying wildfire incidence and severity due to the density of human settlements and intensive land management practices (Fernandes et al., 2020). This regional context has prompted sustained scientific and policy debates regarding the potential of land governance strategies, grounded in bio-economy principles and nature-based solutions, to mitigate wildfire impacts under ongoing and projected climate change scenarios (Moreira and Pe'er, 2018; Verkerk et al., 2018; Ascoli et al., 2022). Financial mechanisms such as the European Rural Development Program and other (research or professional) initiatives have been instrumental in promoting these strategies, enabling the creation of resilient ecosystems (European Commission, 2018). By investigating seven decades of the recent fire history in Greece, this study estimates (apparent and more latent) changes in widfires' regimes over time, and contributes to more effective and efficient policy implementation strategies.

Across the last seven decades, wildfires in Greece have shown a clear long-term intensification. While some periods were marked by exceptionally large burned surfaces, the overall trend points to more frequent and, in recent years, generally larger fires. At the same time, the share of high forests affected by fires has progressively declined, whereas the proportion of other wooded areas has remained broadly stable, suggesting a growing involvement of agricultural and open landscapes. Latent relationships among the main indicators indicate that years with many fires tend to coincide with larger burned areas and a lower proportion of high forests. More recent decades stand out from earlier ones, being characterized by a higher fire occurrence and a shift in the types of land most affected, reflecting – at least partly – the main landscape changes illustrated briefly in the descriptive analysis whose results are reported in Table 1. Multivariate analyses consistently separate earlier from recent years and highlight a gradual transition toward more severe wildfire regimes over time, with the most recent period representing the highest overall level of fire danger observed in the record.

Based on such results, a diverse suite of measures can be mentioned here aimed at fostering landscapes capable of withstanding wildfire exposure while maintaining essential ecosystem functions (e.g. Fernandes, 2013; Tedim et al., 2016; Bacciu et al., 2022). Indirect prevention approaches seem to be particularly appropriate in the recent context studied in this paper, as they are conceptually embedded within the framework of integrated fire management, which advocates for coordinated, cross-sectoral landscape governance to optimize fire prevention, mitigation, and resilience outcomes (Rego et al., 2010).

By incorporating fire risk reduction objectives into broader land-use (and socio-ecological) management strategies, these integrated measures support the creation of multifunctional landscapes that simultaneously deliver ecological, social, and economic benefits (European Commission, 2018). Moreover, the economic self-sufficiency of many indirect interventions allows them to overcome the spatial and financial constraints that often limit direct, operational fire prevention measures (Wunder et al., 2021), providing scalable and long-term solutions for enhancing landscape resilience under increasingly challenging climatic conditions (Ascoli et al., 2022). Fire prevention strategies have to deal with evolving environmental and socioeconomic scenarios mainly based on landscape transformations (e.g. Zambon et al., 2017). The combination of a warming climate, fuel patterns and socioeconomic conditions are responsible for increasing large fires occurrence throughout Europe. In the latter countries, fires result in more severe and long lasting effects due to the lower fire resistance and resilience of forests.

Conclusions

In order to cope with a changing world, transfer of fire management strategies is highly recommended due to the modified spatial pattern and amount of fuels that allow wildfire to spin out of control. Future research should clarify promptly how fire prevention can make large fire suppression more cost-effective and propose prevention actions based on broader sustainable landscape (forest/non-forest) management to increase wildfires response preparedness. These objectives could be reached more effectively by sharing national, regional and local good practices among countries with different operational experiences and skills, underlying different levels of wildfires response preparedness.

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