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Landscape-Based Fire Resilience: Identifying Interaction Between Landscape Dynamics and Fire Regimes in the Mediterranean Region

Jinlai Song, Daniele Cannatella(✉), and Nikos Katsikis

Delft University of Technology, 2628 CD Delft, The Netherlands
J.SONG-6@student.tudelft.nl, {D.Cannatella, N.Katsikis}@tudelft.nl

Abstract. Wildfires are widely viewed as key evolving inputs of Mediterranean ecosystem. But anthropogenic climate changes and other socioecological recessions have transformed normal wildfire into megafire. The paradigm shift is needed since the suppression capacity has been increasingly overcome from the fire department. This research is aiming to integrate diverse landscape dynamics and fire regimes, to interpret the interactions between them and identify a series of heterogeneous fire typologies in the Mediterranean region in order to support the application of landscape-based approaches. By classifying the land system dynamics into meteorologic, physiographic, biological and anthropogenic indicators (in relation with wildfire ignition and propagation), geographic information system based approaches and statistic analysis are applied to create diagnostic mappings. The results establish 10 types of landscape-based fire typologies which can be used as the decision support tool to prioritize risk mechanism and then lead to mitigate wildfire risk by changing contextual territorial elements in landscape system in order to create an integral long time territorial design.

Keywords: Mediterranean land system · wildfire regimes · landscape dynamics · land cover · fire management

1 Introduction

The Mediterranean ecosystem is a unique and diverse environment that has been formed by natural and anthropic processes. Wildfires are an important input to this ecosystem, as they play a critical role in maintaining biodiversity and reshaping the landscape (Pausas et al. 2008). In recent years, normal fires have become increasingly destructive since the growing climate activism and social movements, leading to severe natural and socioeconomic damages. Although such catastrophic events have been apparent and partly-solved for some time, contemporary wildfire management policies in Mediterranean climate regions have continued to focus almost entirely on short-sighted fire suppression-led reaction (Curt and Frejaville 2018). They are seeking to minimize burned area in the short-term during the crisis-happening phase and react to public opinion with ever-expanding investment in firefighting capacity, while failing to adequately and proactively

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address the underlying causes of the problem. This can result in extensive damage with loss of life, property damage, and environmental degradation. The paradigm shift and pragmatist approach are urgently needed (Moreira et al. 2020) when confronted with the demand to coexist with wildfire in Mediterranean Basin. It is also the privileged area for a broad scale with geo-information and geo-modelling based study.

The high urbanization rate of most bordering countries in Mediterranean Basin (Aggestam and Pülzl 2018), coupled with a widely known sensitivity to natural hazard, the persistence of old agricultural practices, and the diversity of ecosystems form a high and local complex heterogeneity landmark ensemble (Egidi et al. 2020). Events such as political instability also have significant impacts on the region's human-environment balances. Large-scale spatial implications can result from changes in land use patterns, displacement of people, and disruption of traditional practices. In this context, the landscape-based fire typologies are defined as the unique but homogeneous combination of natural or artificial factors interacts with wildfire regimes that makes landscape distinctive. Then the ignition and propagation of wildfires change within these diverse amalgamations on spatial and temporal scales.

Recent work has begun to investigate the comprehension of historical wildfire and spread patterns change in non-linear processions (Sequeira et al. 2020). New prevention landscape approaches aiming for predicting fire behaviours and providing basic information for management are called landscape-based fire scenarios which refer to multiscale land-type planning units for a fire generation model with different applications at national (Montiel Molina and Galiana-Martín 2016), regional (Molina et al. 2019) and local (Sequeira et al. 2020) scale in Spain. The Mediterranean Basin as a fire-prone area is all the more fantasized, as it is almost never studied as a whole (Darques 2015).

In this paper we work on a broader Mediterranean scale among complex landscape and atmospheric heterology, and create an integrated method of accumulating all the landscape reality in a vertical direction spatially (from subsoil to climatic factors). By exploring the relationship between landscape dynamics and fire regimes through meteorological, physiographic, biological and anthropogenic perspectives, we can identify landscape typologies in relation with fire behaviors, determine their spatial distributions and even represent the Mediterranean land system with the context of wildfire risk. The result of typology definition creates manageable units that can be used for policy making and decision support tool, monitor changes in dynamic values in order to develop the potential approaches in reducing territorial vulnerability and facilitating adaptation and resilience of wildfire in a holistic and proactive way.Subsequent paragraphs, however, are indented.

2 Theoretical Basis

The theoretical underpinning expounded in this paper serves to contextualize the classification of indicators for fire-landscape interaction and to establish the foundation for the methodology. The terminology of pyrogeography as an emerging discipline provides the intellectual framework of this research to understand and classify the complexity of fire and landscape index on in a global context. It enables currently isolated scholars studying varied aspects of fire to add value to each other's work. (Krawchuk et al. 2009; Roos et al. 2014). Such a synergy of perspectives is crucial given the increasing evidence that current fire management paradigms are unable to cope with the manifold challenges associated with wildland-urban interface, and the rural exodus leaving behind abandoned and increasingly flammable land-use systems, increasingly severe fire weather under the global climate change, and finally the increasing tension between biodiversity conservation and fire management objectives (Kruger 2014; O'Connor et al. 2011). What's more, the field of landscape character assessment establish certain assumptions and evaluate the landscape accordingly (Meeus 1995). While risk management cycle including preparedness, mitigation, prevention, response and recovery provide continuous perspective for evaluating landscape typologies and the direction to build upon the upcoming strategies. Finally, socio-economic-spatial structure reinterprets the movement and state policy differentiation on wildfire management, which becomes a crucial anthropic variable characterizing landscape features.

3 Material and Methods

3.1 Study Area

The study area is defined within a spatial extent in the European part of Mediterranean Climate Regions by focusing on areas surrounding the Mediterranean Sea in north side that share similar atmospheric and biophysical characteristics (see Fig. 1), as it describes the approximate extent of representative Mediterranean natural and political communities (Olson et al. 2001). Peninsulas of Iberian, Apennine, Balkan and Anatolia are included in this extent. The average density of the Mediterranean countries exceeds

Fig. 1. Study area (partially France, Portugal, Italy, Spain, Croatia, Bosnia & Herzegovina, Montenegro, Albania, Turkey; completely Monaco, Greece, Malta, Cyprus)

100 inhabitants/km^2, making it among the regions with highest human influence. The ecoregion is characterized by the Mediterranean specific regional features: a climate of hot dry summers and humid, cool winters. The surprising hilly landscape contains high mountains and rocky shores, thick scrub and semi-arid steppes, coastal wetlands and sandy beaches as well as a myriad of islands dotted across the sea.

3.2 Landscape Classification

The landscape dynamic in relation with fire regimes are classified into four main groups incorporating in 14 sub-variables. The first group of meteorological perspectives includes air temperature, humidity and wind speed. Then the physiographic indicators changes in slope, south aspect and elevation. The biological group covers fuel cover intensity, soil moisture and river density. The last group of anthropogeny are comprised by WUI(wildland and urban interface), population vulnerability (population exposed in WUI), road density, land use change and forest management intensity.

The spatial vehicle of variables are operated on a 10*10 km grid within the extent of study area in order to meet the average resolution of raster data. Thus, the goal of identifying fire patterns on a resolution able to capture the spatial variability of fire-environment interactions in heterogeneous landscape mosaics.

3.3 Spatial Analysis of Territorial Dynamics

Meteorological Change. Mediterranean climate is characterized by high temperatures and low relative humidity during the summer months which can create conditions conducive to the ignition and rapid spread of wildfires (Syphard et al. 2009). The presence of dry fuels, such as dead vegetation, can further increase the risk of fire. The timing and distribution of precipitation occurs during the winter season, leading to a build-up of vegetation and fuel for fires during the dry summer months. This creates a situation in which wildfires can quickly spread and become difficult to control. Wind speed and direction can also have a significant impact on wildfire behavior. High-pressure systems can create dry and windy conditions while during the winter months, low-pressure systems can bring wet and windy conditions that can make fire suppression efforts more difficult.

Physiographic Conditions. Specific mountain areas in the Mediterranean region of the European part where topography influences wildfire behaviors include the Pyrenees, the Alps, and the Apennines (Pérez-Sanz et al. 2013; Tinner et al. 2000). These mountain ranges have a range of elevations, slopes, and aspects. For example, steep slopes and south-facing aspects in the Pyrenees and Alps can create conditions conducive to wildfire ignition and spread, while higher elevations in the Apennines can provide cooler and moister conditions that reduce the risk of fire. In addition to these larger mountain ranges, there are also smaller, isolated mountainous areas in the Mediterranean region, such as the mountains of Corsica and Sardinia. These steep canyons or ridgelines that can create chimney-like conditions that accelerate fire spread (Clarke et al., 1994).

Biological Diversity. The study area is characterized by a high degree of biological diversity, with a range of plant and animal species that have adapted to the unique climatic conditions of the region (Pausas and Vallejo 1999). Wildfires shapes these ecosystems with many species having evolved to thrive in fire-prone environments. Mediterranean pine trees and eucalyptus have developed thick bark and serotinous cones that allow them to survive and regenerate after fire. High-intensity wildfires can lead to significant tree mortality, reducing tree cover density and altering the structure and composition of forest ecosystems. In addition, fires can cause changes in hydrological conditions, increasing the risk of soil erosion and altering water quality (Bodí et al. 2014). Specific river valleys and soil types can be particularly vulnerable to the impacts of wildfire, with erosion and sedimentation leading to decreased biological diversity and degraded ecosystem services.

Anthropogenic Uncertainties. HumSans and fuel are important parts of the system and that reciprocal effects exist between many components of the system (Riley et al. 2019). Firstly, the wildland-urban interface (WUI) in Mediterranean countries is characterized by a mix of land uses, challenging topography, and limited infrastructure and resources, which pose significant challenges for managing wildfire risk (Mitsopoulos et al. 2015). In southern Spain, the WUI is characterized by the extensive development of tourist resorts and urban areas along the coast, which are located in close proximity to natural areas. Additionally, the abandonment of agricultural production has led to a proliferation of wildland areas that are more susceptible to wildfire. Since the beginning of the 20th century, economic development has lead to a massive abandonment of agricultural land in Mediterranean regions (Nainggolan et al. 2012). In Spain and Portugal this evolution has been quite dramatic resulting in the abandonment of many marginal lands due to both heavy stocking reduction and crop abandonment. The selective abandonment of marginal agriculture land in more mountainous areas and the concentration of crop fields in valley bottoms near urban centres can lead to an increased homogeneity of (semi-)natural land use/cover types, such as shrublands and forests.

3.4 Data Description

More data and data with higher thematic and spatial resolution were available for the European part of the region (Table 1). The following criteria were used when choosing the data: 1). Highest spatial resolution; 2). Data were as recent as possible and kept almost in the same temporal scale; 3). Data underwent validation. This way we could ensure independence of the data and later analyze how the occurrence of land systems relates to population distributions. All input maps were resampled to 10*10 km grid in an Lambert equal area projection.

Table 1. Data used in indicators categories.

Categories	Factors	Units	Format	Resolution	Source
Meteorological	wind speed	m s-1	raster	3 km	New European Wind Atlas
	humidity	kg kg-1	raster	0.5° × 0.5°	Copernicus Climate Change Service
	annual temperature	K	raster	0.5° × 0.5°	Copernicus Climate Change Service
Physiographic	slope	degree	raster	30 km	Copernicus
	aspect	N-NE-E-SE-S-SW-W-NW, Flat	raster	30 km	Copernicus
	elevation	m	raster	30 km	Copernicus
Biological	fuel density	% proportion of total forest from land area	raster	1 km	European Forest Institute
	soil moisture	Soil Moisture Index (SMI) 0–1	raster	5 km	EEA geospatial data catalogue
	river density	m	polyline	/	HydroSHEDS
Anthropogenic	WUI proportion	Percentage of cell area (%)	raster	1 km	EFFIS
	population vulnerability	Percentile (%)	raster	1 km	EFFIS
	road density	m	polyline	/	European Environment Agency
	land-use change	/	polygon	/	CORINE Land Cover
	forest management intensity	/	raster	1 km	BBN session

3.5 Methods and Techniques

Considering fire typologies as landscape units which are defined through the analysis and interpretation of quite diverse territorial factors, geographic information system based methods perform a spatial analysis of the area attributes of homogeneity (Galiana-Martín and Montiel-Molina 2011). The landscape indicator groups in the extent of Mediterranean are resampled in the spatial vehicle of 10 km*10 km grid, which allows the normalization of fire-prone data intervals. Clustering analysis are used for the aggregation of feature similarity which is based on the set of attributes in order to find the spatially correlated landscape patterns (Wu 2004) (see Fig. 2).

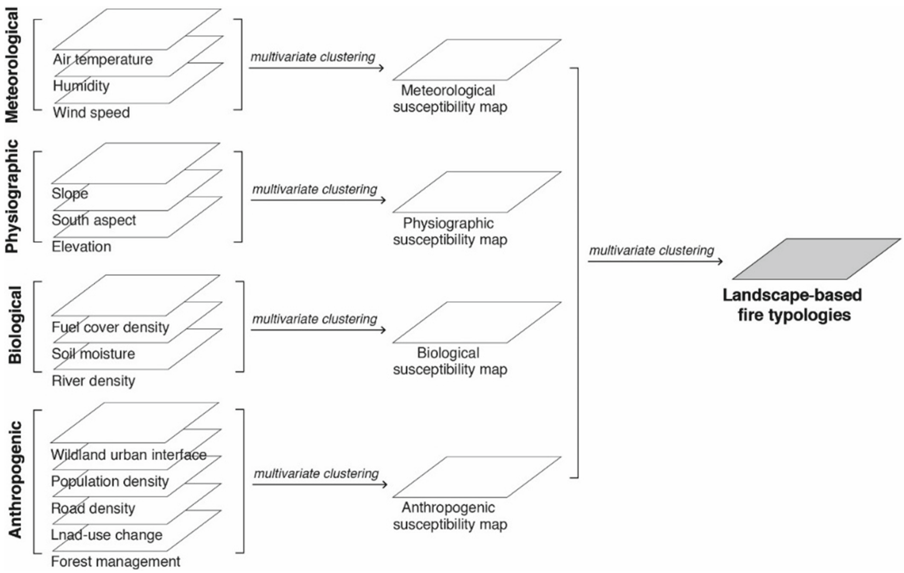

Fig. 2. GIS-base methodology

4 Results and Discussion

4.1 Landscape-Based Fire Typologies

The diagnostic map of landscape-based fire typologies in terms of both composition and configuration is one of the main outputs of this research that is shown in Fig. 3 and 4. Figure 5 illustrates the proportion of each typology in the extent of whole study area and their dominant features, which is also the basis for naming and grouping. Wildfires are produced and interact with identified ground realities among each of the landscape typologies, corresponding to part of Mediterranean land system features simultaneously (Blondel 2006).

Settlement Distribution. The typology of urban interface mixed with unmanaged wildland is characterized by the peri-urban areas have expanded into previously successive uninhabited wildland. Socio-economic trends in Europe towards more urban land use in rural regions and shrub encroachment are resulting to spatial change of interface (Modugno et al. 2016). The human properties are placed at high risk of woodlands and shrubs as the source of fuel for wildfires. Most of this type of landscape is often found at the foothills of south Alps and Apennine and middle Portugal. The second typology in this group is characterized by a combination of densely populated coastal areas and vegetation that is highly flammable under several transitional climate types and subtypes. The vegetation has a high concentration of oils and resins, making them highly combustible. For instance, Holm oak (Quercus ilex L.) is a climazonal species along the western Mediterranean, mostly in Croatian coast. Aleppo pine (Pinus halepensis Mill.) is a typical Mediterranean species that accounts for about 10% of all forests in the Mediterranean (Rosavec et al. 2022). The fragmented villages with multiple rainfed agricultural

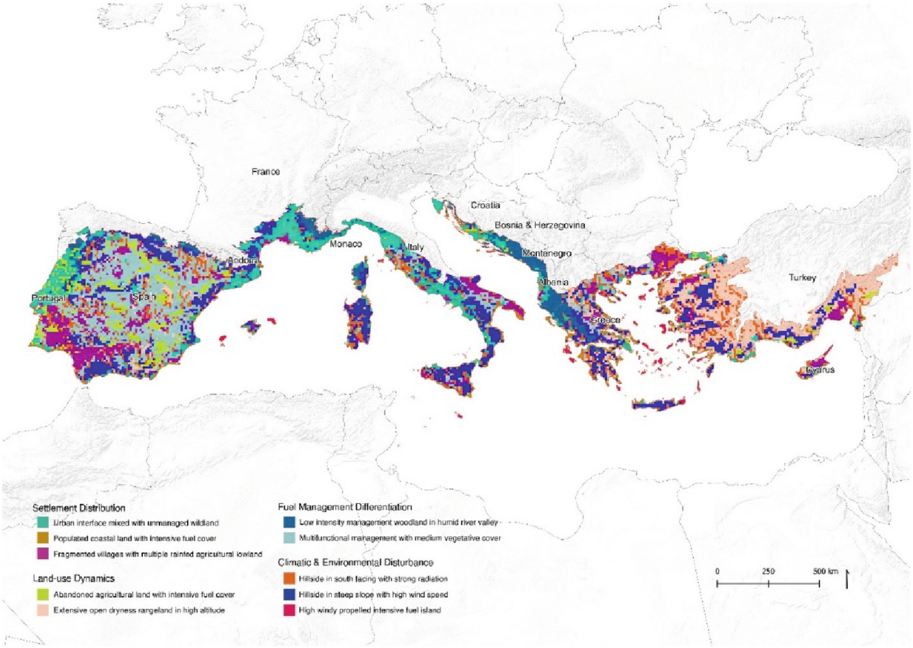

Fig. 3. Mediterranean landscape-based fire typologies

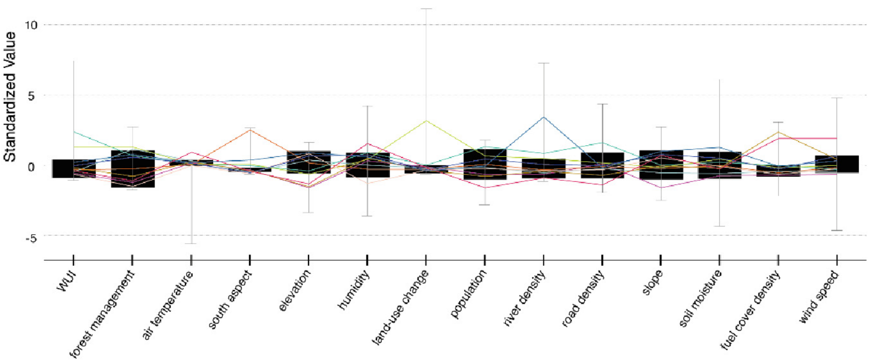

Fig. 4. Plot-box statistic of each variables

lowland type is basically distributed in the river basin of Guadiana and southern Tagus. The clustered villages among intensively used croplands, rangelands and seminatural lands parallel with altered fire regimes tend towards ecosystem process.

Land Use Dynamics. The typical Mediterranean region often shows human pressure affects the landscape characteristics through littoralisation, intensive agricultural practices, land abandonment, urban sprawl, and tourism concentration which leads soil deterioration and Land Use/Land Cover Changes (LULCCs) (Bajocco et al. 2012). This

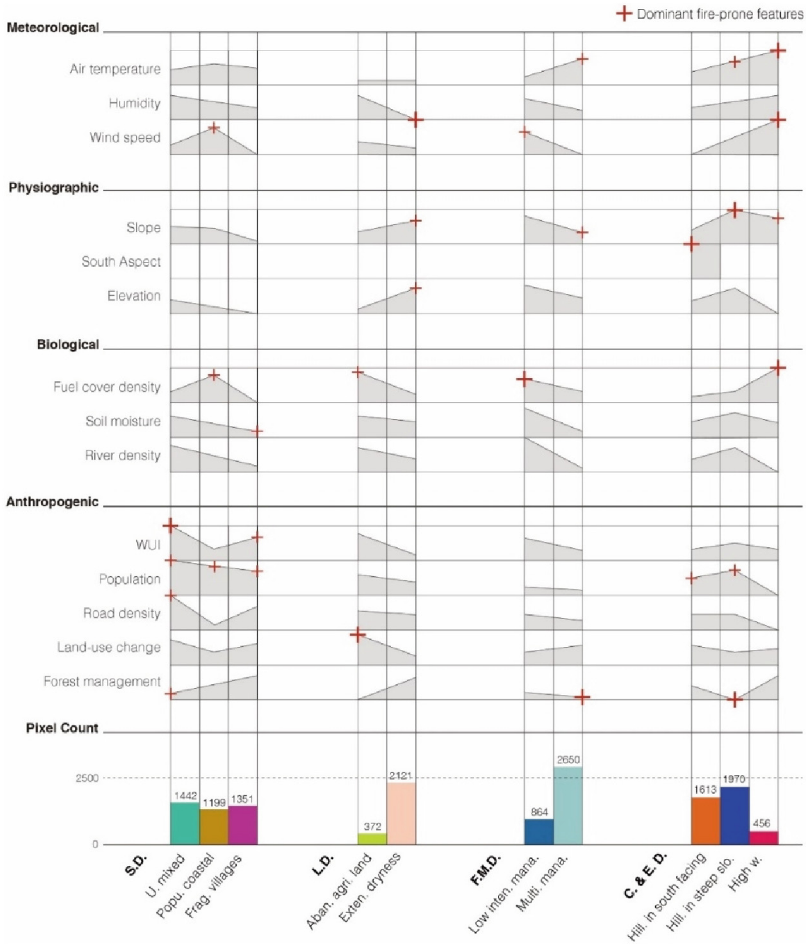

Fig. 5. Dominant features of each landscape-based fire typologies

trend can be reflected in the fire typology of abandoned agricultural land with intensive fuel cover in the inland depopulation area in Spain and Portugal. This land abandonment results in unmanaged vegetation prone to fire and then, leading the soil erosion, deforestation and habitat fragmentation. In the Anatolia peninsula and Balkan regions, the next fire typology is identified as the extensive open rangelands with dry, arid conditions in remote areas with a lower population density. These areas are typically used for grazing livestock and are often located at high altitudes, where temperatures are cooler with lower potential evapotranspiration and vegetation is sparse. Wildfires in these areas tend to spread quickly due to the lack of vegetation and can be difficult to control.

Fuel Management Differentiation. Sustainability and multifunctionality have been the guiding European forest policy models (Aggestam and Pülzl 2018) within which forest management with local conditions has been embedded in fire typologies definition. In this case, the river valleys of Durance in France, the Pindus Mountain ridge in Greece, and the Montenegro mountains areas are characterized as the next fire type. This close-to-nature management covers across large, interconnected areas may lead some natural wildfire ignitions. But at the same time, they are often located in a high river density context, where humid basin can help to prevent fires from spreading. The type of multifunctional management with medium vegetative cover is mainly distributed in the inland of Spain and northern Greece. The vegetation there exhibits fragmented patterns mixed with multifunctional and intensively managed forests which are aiming to more than one objective occurring e.g. timber, water production, erosion protection, biodiversity, climate mitigation and adaptation and recreation (Nabuurs et al. 2019).

Climatic and Environment Distribution. The last group of fire typologies characterization shows their specialities in hillside and archipelagos. One of the hillside types with particularly obvious landscape feature that is under the south facing hillside with strong radiation which promotes fire ignition and propagation. The pattern in dark blue represents the fire type of hillside in steep slope and canyons with high wind speed which illustrates some similarities with Mediterranean mountain system and often consistent with dense fuel configuration e.g. the Sistema Central in Spain and Portugal, the Apennines, and the Pindus Mountain in Greece. The devastating fires are associated with short episodes of severe fire weather generated by hot and dry winds (Moritz et al. 2010). Noteworthy, hillside should not be considered as the isolated landscape feature in fire typologies. The smallest proportion typology of high windy propelled intensive fuel island shows its speciality in the Aegean archipelago and Malta. Of the various types of vegetation that make up the forests and woodlands on the islands, fire statistics indicate that most of the blazes occur in the Turkish pine (Pinus brutia) forests and, to a somewhat lesser extent, in shrub lands (Ne'eman and Trabaud 2000). Prevention of fires on the islands, including the use of prescribed burning, is relatively inadequate, and public participation in fire prevention remains limited.

4.2 Representation of Land System

Contemporary landscapes are contingent outcomes of past and present patterns, processes and decisions (Rounsevell et al. 2012). Thus, the land system is central to understand the relationship between human and environment. Some researches have previously combined territorial indicators to classify land use systems, touching less with natural crisis. The biomass in Anthropocene on global scale has been mapped by Erle C. Ellis (Ellis 2011), which framed a systematic classification of the hybrid socio-ecological fabric associated with the long and continuous human use of the earth's surface. The result from Tomáš Václavík (Václavík et al. 2013) reveals diversity across the global land system archetypes. European scale characterizations are mapped by Christian Levers etc. (Levers et al. 2018) and reflected as the land-system archetypes and archetypical change trajectories mainly within cropland, grassland or mosaic systems. Our approach moves forward the existing classification systems by accounting for the land system conditions with their specific landscape disturbance for the Mediterranean region. The 10 typologies in the groups of settlement distribution, land-use dynamics, fuel management differentiation, climatic & environmental disturbance reinterpret the Mediterranean landscape at the first time under a novel semantic system of wildfire risk, revealing another way of understanding territorial realities (Fig. 6). Considering the possible degradation of landscape value and the loss of the cultural pattern in the Mediterranean region (Čurović et al. 2019), this identification of fire-landscape system could also put the existing characteristics in a dynamic process of climate change, ecosystem evolution and settlement emigration.

4.3 The Population Susceptibility

In the European Mediterranean regions, there exists a complex interrelationship between fire and population density. Although the effectiveness of higher population densities in keeping fire incidence low decreased in the last decades (Moreira et al. 2023). The phenomenon of high population and housing density has been still found to increase the likelihood of anthropogenic ignition due to the accumulation of fuel resulting from agricultural abandonment or even deliberate field cleaning in some areas (Chergui et al. 2018). Consequently, such regions are more prone to frequent fires that pose significant threats to human lives and infrastructure. Conversely, post-fire changes in the landscape may trigger settlement emigration (Henriques and Khachani 2006).

The population's vulnerability to certain factors is visually represented in Fig. 7 through the juxtaposition of population density data from 2020 with the previous diagnostic map (see Fig. 3), aiming to investigate the distribution of human settlements across various fire-landscape types. The fragmented rural settlements are mostly located in the typology 4, which is abandoned agricultural land with intensive fuel cover, particularly in central Portugal and peri-urban of Madrid in Spain (see Fig. 7,a,b). The changes of productive land ("baldio" and "dehesa") in the Iberian peninsula have been bringing highly mixed of village, cropland and forest which altered the fire regimes (Maranon 1988). The littoralization process of Mediterranean countries shows obviously in Spain and southern France (see Fig. 7, b). Urban clusters in these areas are overlayed with the typology 1,2 and 9 corresponding to the specific contexts. The typology 1 that presents wildland-urban interface appears more in the peripheral metropolis of central Italy (see Fig. 7,c) where changes in the socio-economic context have widely influenced the expansion of high- and medium-density settlements shaping a complex fringe landscape(Salvati et al. 2014). The interface type can also be seen in peri-urban of Athens (see Fig. 7,e), Lisbon and Coimbra (see Fig. 7, a). The densified urban areas along the Dinaric Alps mountain range are reflected in the typology with steer slope where the huge topographic differentiation propels fire into the human settlements (see Fig. 7, d). The inhabitants of the islands located in the Aegean Sea and western Anatolia are susceptible to the hazard under conditions of high wind-propulsion, as classified as typology 10 (see Fig. 7, e).

4.4 Application of Results for Wildfire Risk Management

The results of this research on the interplay between fire regimes and landscape dynamics in Mediterranean Climate Regions of the European part have produced a diagnostic map and typologies catalogue with significant implications for wildfire risk management.

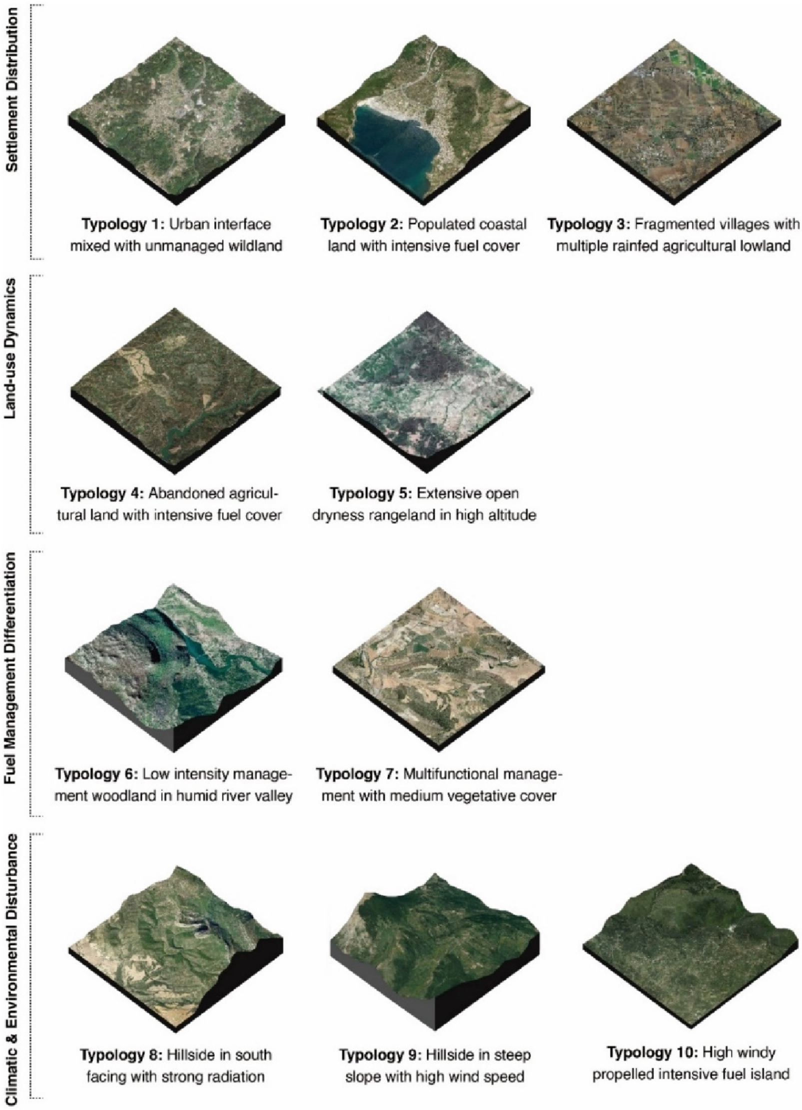

Fig. 6. Representing landscape system in relation with fire in Mediterranean Climate Regions (EU part)

This aggregation of territorial realities offers a novel methodology for characterizing fire hazard and landscape interaction that accurately identify the most risk-prone areas and can inform proactive and effective strategies. The fire-landscape types delineated in the map can be employed as a framework for implementing multiple landscape-based approaches to mitigate fire risk, including fuel reduction treatments (Collins et al. 2010), prescribed burning (Fernandes and Botelho 2003), vegetation management, and other measures tailored to the specific landscape typology. In addition, the visualized and

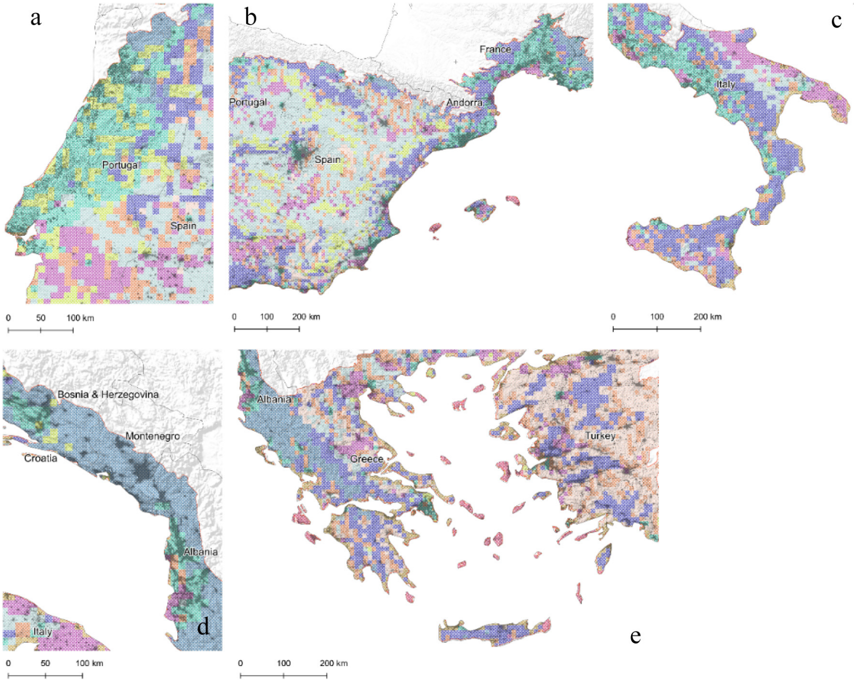

Fig. 7. Population susceptibility in key locations (central Portugal, central Spain, littoral Spain and French, central and southern Italy, the Dinaric Alps, part of Greece and western Anatolia peninsula)

represented typology study and spatial patterns can serve as a decision and negotiation support tool with stakeholders in wildfire risk management, enabling stakeholders to better understand potential risks and prioritize management actions.

Furthermore, the defined typologies are provided with a discrete class assigned to each pixel and thus ignore within-pixel heterogeneity. So that downscaling works are necessary pursuing sub-nations, regional and local investigation in diverse contexts that follows the same method. By developing relatively high-resolution models, for example 1 km*1 km grid, it is able to quantify substantial spatial variation in the key driver of some of the most costly wildfire in some specific locations. Macro-scale fire fisk variables exhibit a wide spectrum of complexity (Williams and Abatzoglou 2016) in global earth system, which also need to embed with necessitate quantitative modelling to better understand future fire responses. Furthermore, to enhance our comprehension of the territorial susceptibility that contribute to the occurrence and disturbance, e.g. flooding, erosion, over-exploitation etc., these models facilitate the identification and assessment of areas at greatest natural hazards to examine scenarios of land-use trajectories and inform targeted management plans.

4.5 Data Uncertainties

The presence of semantic inconsistencies arising from the combination of various remote sensing and modelling products can result in inaccuracies in datasets (Fritz and See 2008). In the present study, the spatial resolution differences across the datasets have been mitigated to a certain extent via resampling and reassignment. However, the primary source of uncertainty in the data is attributed to temporal scale variations. On one hand, it may limit its use in applications where shorter-term biodiversity or ecosystem changes prevail. For instance, fuel cover density data comes from EU forest map, version 2011. But its highly related fuel management intensity data is generated during 2019 (Nabuurs et al. 2019). On others, of the climatic variables under consideration, the precipitation index and annual average temperature are derived from the mean value spanning from 1979 to 2019 but the wind speed index for the same time period is absent.

The outputs of diagnostic map and statistic result provide a new methodology of territorial data assimilation to typify the spatial composition and configuration of fire-landscape in the extent of Mediterranean Climate Regions in European part. The characteristics of each typology cannot be only observed and measured by single sensors since the complexity and heterology of territorial systems. The iterations of data are required in the attributes of upcoming fire-landscape typology research under the same proposed method in order to ensure the accuracy of the clustered result.

5 Conclusion

Wildfires in the Mediterranean bioregion are widely reviewed as the crucial part of its ecosystem for centuries. In fact, the landscape system and the fire regimes have been evolving interactively which needs to be investigated in a comprehensive process. By understanding of Mediterranean pyrogeography, the dataset is developed by the perspective of meteorology, physiography, biology and anthropogeny based on a fire-prone data interval in order to reinterpret the fire-landscape interaction as a system. The output of this reidentification map reveals 10 fire-landscape typologies and their spatial distribution in the Mediterranean, which improves the understanding of land system with natural crisis and is a basis for assessment of future changes under the regional climate, land use and land cover change and changes in management intensity. It also provides a evaluation and decision support tool in some specific locations for fire management, biodiversity protection and conservation of landscape values. Thus, the downscale works of analysis are still needed for bridging the disconnection between Mediterranean research and landscape design practice. The prospective use cases must additionally account for the geopolitical and socio-cultural context of the region in question, as a means of establishing an integrated framework for fire management.

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