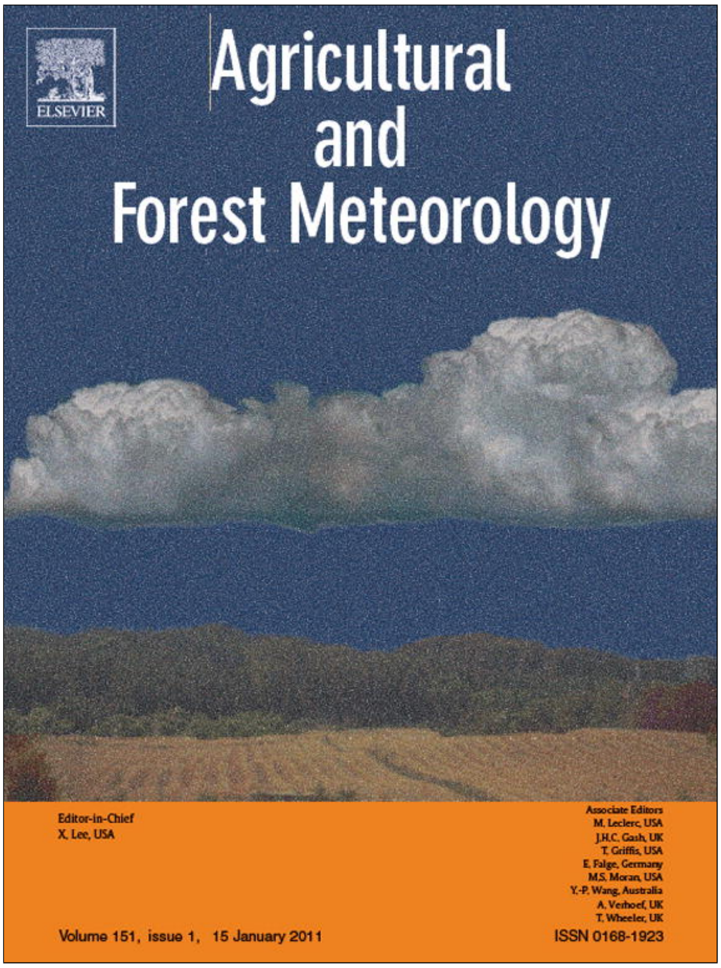

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Where did the fires burn in Peloponnisos, Greece the summer of 2007? Evidence for a synergy of fuel and weather

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ABSTRACT

The aim of this study is to explore the burning pattern of the catastrophic wildfires that occurred in Peloponnisos, southern Greece, in 2007. These fires caused the loss of 67 lives and were recognized as the most extreme natural disaster in the country's recent history. We compare the 2007 fires against fuel availability across the landscape in the light of a null model using Monte-Carlo randomization and against the fire pattern for the preceding period, 2000–2006. Additionally we applied a multi-response permutation-procedure test, a data-driven method free from assumptions about the underlying distribution. The study contributes to the ongoing debate over the relative importance of fuel versus weather in explaining large and intense wildfires. While the majority of the 2007 wildfires burned low-elevation fire-prone ecosystems, a part of them moved to non-fire-prone ecosystems, indicating a departure from the burning pattern of recent history. The CORINE land-cover categories most affected by fire included agricultural lands highly interspersed with large areas of natural vegetation followed by sclerophyllous vegetation, transitional woodland shrubs, complex cultivation patterns and olive groves. These reflect greater fuel accumulation through the encroachment of natural vegetation in abandoned fields as well as changing patterns of land-use. The rising proportions of humid and sub-humid areas burned are clearly related to weather patterns. The synergistic effect between fuel and weather helps explain the unusually large 2007 wildfires in Peloponnisos. This change may imply a climatically driven alteration of the established fire-regime promoted by fuel accumulation that portends major ecological consequences. The ecological disaster foreseen is justified by the lack of specific adaptations to cope with fire in non fire-prone plant communities.

1. Introduction

The landscapes of the Mediterranean Rim have a distinctive character arising from their physiography and the long history of human development. The physical background creates a mosaic of landscapes, which supports a broad array of habitats and high species diversity (Cowling et al., 1996). Mediterranean type ecosystems evolved under the influence of environmental stresses (primarily summer drought and low soil-nutrient availability) and the periodic influence of natural hazards (e.g. fire and tectonic instability). They have also experienced centuries of human impact, since the Mediterranean Basin was settled by humans long ago, and are thus characterized as man-made landscapes (Pérez et al., 2003). Indigenous agriculture and animal husbandry have been practiced here for more than 10,000 years (Le Houerou, 1981; Naveh, 1998; Naveh and Dan, 1973), in combination with deforestation practices and fire management (Trabaud and Galtié, 1996). These patterns existed in dynamic equilibrium at least until the Second World War (Caravello and Giacomin, 1993), but started to change around 1950 following major changes in economy and lifestyles. Initially, there were extensive rural migrations followed by agricultural intensification and mechanization, while the invention of new irrigation techniques expanded the agricultural domain. Yet, these patterns have changed again. Now, the most productive lands are used intensively, while less productive areas are abandoned entirely or subjected to less intensive use and afforestation (Pérez et al., 2003; Vega-García and Chuvieco, 2006). Vegetation succession has led to scrub encroachment and forest development (Carmel and Kadmon, 1999; Pérez et al., 2003; Scozzafava and De Sanctis, 2006; Vega-García and Chuvieco, 2006). Reforestations and extensive

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plantations have been promoted in the Mediterranean region in the last decades, both under the scope of forest policies (Pausas, 2004) or more recently, as a policy-driven management alternative in abandoned agricultural land (MacDonald et al., 2000; Mallinis et al., 2011; Pausas, 2004). As a result of these changes in the traditional landscape mosaic, the landscape is now more susceptible to fuel accumulation and this may lead to increased fire occurrence (Loepfe et al., 2010; Moreira et al., 2001, 2011; Vega-García and Chuvieco, 2006).

Fire is an integral part of many terrestrial biomes including Mediterranean ones, but it is also a major factor of disturbance (Pausas et al., 2008). During the last decades an increase in the number and size of fires has been observed in European Mediterranean areas (Moreno et al., 1998; Piñol et al., 1998) and elsewhere (Flannigan et al., 2009) revealing a change in fire regime. The major driving forces behind this change in the Mediterranean include land abandonment and afforestation of former agricultural land leading to increased fuel accumulation (Moreira et al., 2001, 2009; Pérez et al., 2003), although the influence of climatic changes cannot be ignored (Pausas et al., 2008; Pausas, 2004; Piñol et al., 1998). Moreira et al. (2011) reported that the effects of fire on ecosystems and landscapes may vary from region to region as a result of local fire history, regeneration patterns and topographic constraints (Viedma, 2008). Additionally, fire incidence depends not only on structural factors but also on spatial factors considered as causal processes that reflect the degree of influence due to neighborhood effects (Chou, 1990; Vázquez and Moreno, 2001), setting thus the role of space as an important factor.

Climatic extremes observed recently (Founda and Giannakopoulos, 2009; Tolika et al., 2009), raise the question originally framed by Agee (1997), about the relative importance of weather versus fuel in controlling fire behavior (Cumming, 2001). The weather hypothesis proposes that large, severe fires that burn intensively through the landscape are driven primarily by extreme weather events, irrespective of fuel type or condition (Agee, 1997; Cumming, 2001; Nunes et al., 2005). On the other hand, the fuel hypothesis proposes that spatial variation in fuels is the most important factor influencing fire spread and severity (Cumming, 2001; Nunes et al., 2005). These contrasting hypotheses have been examined in Mediterranean climate ecosystems of North America (Keeley and Fotheringham, 2001; Minnich, 2001) especially in the context of fire suppression and fuel management (Meyn et al., 2010). On one hand, Keeley and Fotheringham (2001) make the case that catastrophic fires are less dependent on fuel and more dependent on the coincidence with severe weather. On the other hand, Minnich (2001) argues that fire occurrence is spatially and temporally constraint by the rate of fuel accumulation and previous fire history. The debate still continues. Westerling et al. (2006) showed that, in the western USA since 1970, large wildfire activity increased in frequency and duration in areas, where land-use histories have relatively little effect on fire risks and this increased activity is strongly associated with increased spring and summer temperatures and an earlier spring snowmelt. Meyn et al. (2007) argued that it is the characteristics of the ecosystem that determine the relative importance of the two mechanisms; in biomass-rich, rarely-dry ecosystems large, infrequent fires are limited by climate, while in biomass-poor, at least seasonally dry ecosystems large fires are limited by fuels. On the contrary, Vázquez et al. (2002) discussed the role of humans and showed that when a region is under strong human pressure (such as peninsular Spain) the role of man may alter the prevailing relationship between fire regimes and potential natural vegetation. Indeed, the pattern they found revealed that areas with higher primary productivity burned more frequently and extensively, even if climatic conditions were not as favorable for fire occurrence.

Apart from the human component, specific traits of vegetation, topography and meteorology are considered critical variables in fire ignition, spread and behavior in the Mediterranean Basin. Mediterranean vegetation characteristics, mostly formed through mechanisms of adaptation towards summer drought (i.e. flammable vegetation types and fire-prone ecosystems), and other peculiarities of the Mediterranean-type climate (i.e. strong winds), favor fire occurrence and spread. Additionally, the recent expansion of wildland–urban interface is very typical in Mediterranean countries. Forest fires in the wildland–urban interface have become very common in Europe, as population and human infrastructure facilities are disseminated throughout the forested zones, especially in the vicinity of large cities and tourist resorts (Viegas et al., 2003), and also due to afforestation of abandoned agricultural lands located close to settlements (Galiana-Martin et al., 2011). Agrarian activities, land abandonment and development processes are important underlying factors of fire occurrence in the Mediterranean (Martínez et al., 2009) while their relationships might vary in space (Koutsias et al., 2010).

The aim of this study is to investigate the spatial pattern and environmental drivers of the large and extensive wildfires that occurred in Peloponnisos, Greece, in 2007. These wildfires, according to Fire Brigade statistics, burned thousands of hectares (189,952 ha) of forests (56,928 ha), forested areas (60,260 ha), grasslands (17,777 ha), agricultural land (42,596 ha) and other land cover types (12,391 ha). More importantly they caused the loss of 67 human lives, and they are recognized as the most extreme natural disaster in the recent history of Greece. This study contributes to the ongoing debate on the relative role of fuel versus weather in explaining large, intensive wildfires. Changes observed in the spatial pattern of wildfires might indicate changes of the underlying causal factors, especially concerning fuel and weather.

2. Study area

Peloponnisos is situated in the southern part of Greece (Fig. 1) covering an area of 21,549 km^2 with a population of 638,942 inhabitants mostly employed in agricultural activities. The area is characterized by a variety of geological substrata (conglomerates, limestone, flysch) and soil types. Various climatic and vegetation zones are found in the area as a result of the diverse terrain, the altitude of which ranges from sea level to 2407 m. West Peloponnisos experiences higher annual precipitation than its eastern part. Extended mountain ridges stretch through the central part of the region creating a more temperate climate with oro-Mediterranean (above the timberline vegetation types) conditions at higher elevations. Vegetation is diverse, being the typical Mediterranean Aleppo pine (*Pinus halepensis* Mill.) forests and the phryganic and evergreen sclerophyllous shrublands in the lowlands. Above 800 m, these vegetation types are replaced by Black pine (*Pinus nigra* Arnold subsp. *pallasiana* (Lamb.) Holmboe) and Greek fir (*Abies cephalonica* Loudon) forests, forming well structured and dense forest stands up to the timberline; above the timberline oro-Mediterranean grasslands, rocks and screes are the predominant vegetation types. Umbrella pine (*Pinus pinea* L.) forms localized stands along the west coast, while several thickets of deciduous oaks (*Quercus ithaburensis* Decne subsp. *macrolepis* (Kotschy) Hedge & Yalt., *Quercus frainetto* Tenand *Quercus pubescens* Willd.) are also found in the interior.

3. Data and methods

3.1. Data

Annually resolved fire perimeters for the period 2000–2007 were provided by the European Forest Fire Information System

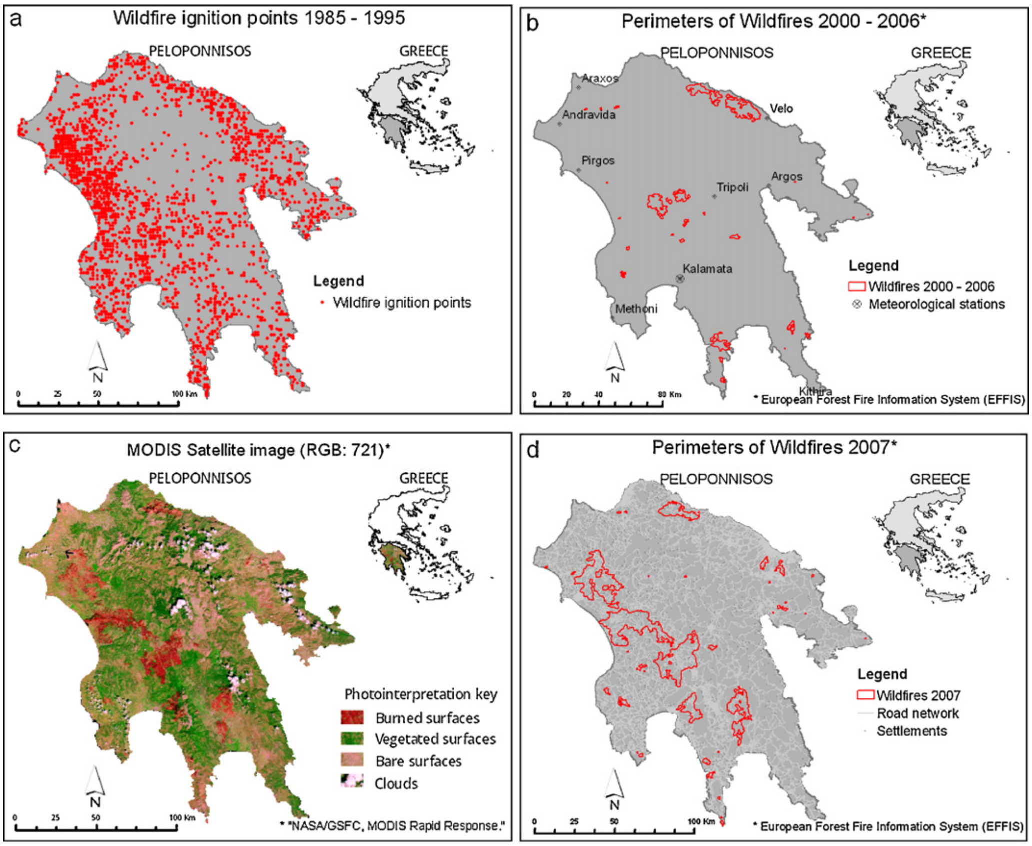


Fig. 1. Location of the study area. (a) Wildfire ignition points 1985–1995 used to define fire occurrence zones, (b) fire perimeters 2000–2006 used to characterize the recent fire history, (c) MODIS satellite image just after the 2007 wildfires, and (d) fire perimeters of the 2007 wildfires in Peloponnisos.

(EFFIS) of the European Commission Joint Research Centre (Fig. 1). Fire perimeters are derived from MODIS satellite imagery at spatial resolution of 250 m processing in JRC. According to EFFIS, fires larger than 40 ha in size are mapped, although smaller burned areas may also be captured. Additionally, fire observations for the period 2000–2007 have been provided by Hellenic Fire Brigade, which are in agreement with the JRC data (Fig. 2) as far as the total burned area is concerned.

Land cover thematic resolution was defined at three levels of detail by using CORINE land cover 2000 classes of level 1 (5 headings), 2 (15 headings), and 3 (44 headings). The working scale of CORINE project is 1:100,000 and the smallest mapping unit is 25 ha (European Environmental Agency, 1994). We separated the CORINE

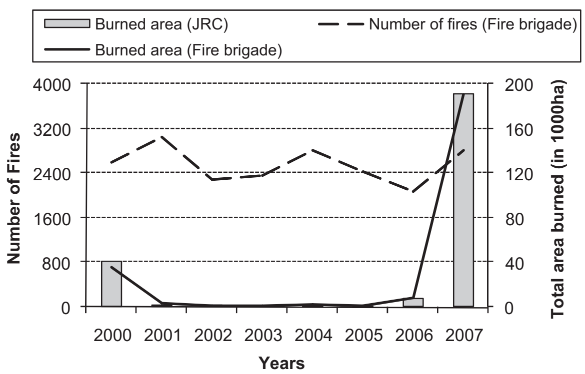


Fig. 2. Number of fires (fire brigade statistics) and total area burned as reported from Hellenic Fire Brigade and as estimated from the annually resolved fire perimeters for the period 2000–2007 provided by the European Forest Fire Information System (EFFIS) of the European Commission Joint Research Centre.

land cover category of Coniferous forests in: (a) lowland coniferous forests for areas with altitude below 800 m corresponding mainly to Aleppo pine (*P. halepensis*) and Umbrella pine (*P. pinea*) forests, and (b) highland coniferous forests for areas with altitude above 800 m, mainly Greek fir (*Abies cephalonica*) and Black pine forests (*Pinus nigra* subsp. *pallasiana*).

Other spatial data considered in our study were bioclimatic maps representing: (a) the bioclimatic belts and their winter variants on the basis of Emberger's pluviothermic quotient and thermic variants, and (b) the designated bioclimatic belts based on the xerothermic period, as derived from Bagnouls–Gaussen's xerothermic index. Monthly weather observations of air temperature and precipitation provided by Hellenic National Meteorological Service were used to characterize fire weather of the studied period. Data were obtained from Kalamata station (Fig. 1) located at sea level and relatively close to the Greek fir (*Abies cephalonica*) and Black pine forests (*Pinus nigra* subsp. *pallasiana*) affected by those fires. Additionally, daily observations of air temperature, precipitation and wind speed from nine meteorological stations spread throughout the study area (Fig. 1) were provided by Hellenic National Meteorological Service and used to show the temporal correspondence between the daily weather conditions and the dates of the main episodes of fire occurrence. Comparison of the daily observations during August 2007 with the corresponding mean daily values of the two preceding (2005, 2006) and two following years (2008, 2009) might reveal critical anomalies during the days of fire episodes.

In correspondence with the bioclimatic belts, five elevation zones covered by different vegetation types were distinguished: (a) sea level to 500 m corresponding mostly to phryganic and dry Mediterranean pine forests mainly of *P. halepensis*, cultivations and grazing land; (b) 500–1000 m corresponding to dry *P. halepensis*

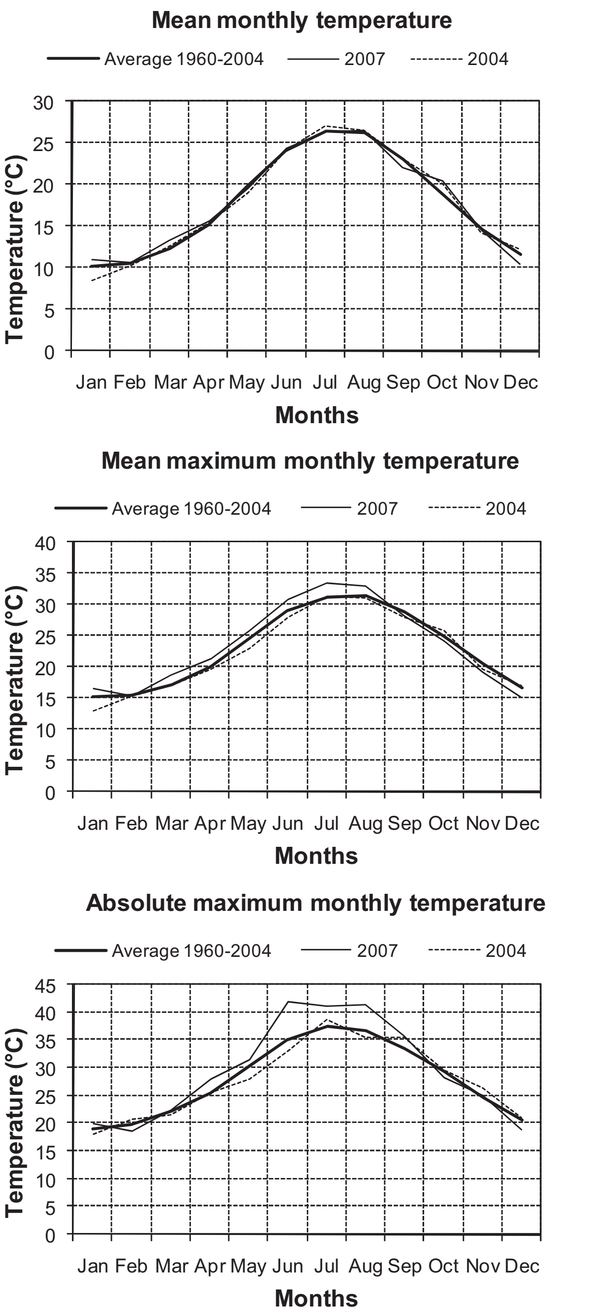


Fig. 3. Mean, mean maximum, and absolute maximum monthly temperatures of the period 1960–2004, the extreme fire year of 2007, and the year 2004 where no large fire events observed.

forests and mountainous conifer forests (800–1000 m) consisting mainly of *P. nigra*; (c) 1000–1500 m covered mainly by *P. nigra* and *A. cephalonica* forests; (d) 1500–2000 m where *P. nigra* and *A. cephalonica* forests are predominant; and (e) above 2000 m where extended Greek fir forests form the timberline, above which oro-Mediterranean grasslands, meadows, rocks and screes are present. Olive groves, orchards and other cultivations are found at the lowlands, while grazing is practiced almost everywhere.

3.2. Weather observations

Fig. 3 presents the mean, mean maximum, and absolute maximum monthly air temperature of the period 1960–2004, the extreme fire year of 2007, and the year of 2004 where no large fire events were observed, while Fig. 4 presents monthly precipitation. Fig. 5 and Table 1 present the same information however averaged at a yearly basis. These figures show that 2007 was an extreme year from a climatic point of view. Although the average mean air temperature is 17.91 °C, just 0.15 °C higher than the mean temperature of the period 1960–2004 (17.76 °C), the mean maximum and the absolute maximum temperature is 0.66 °C and 1.6 °C higher than the 1960–2004 average, and 0.7 °C and 1.24 °C higher than the 2000–2007 average. In August these differences increase reaching 1.43 °C and 4.87 °C. Additionally, the total precipitation in 2007 (665.6 mm) was lower than the average total precipitation

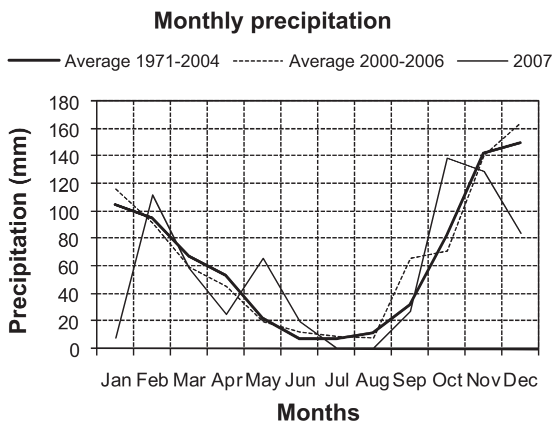


Fig. 4. Monthly precipitation of the year 2007 as compared to the average of the period 1971–2004, and 2000–2006.

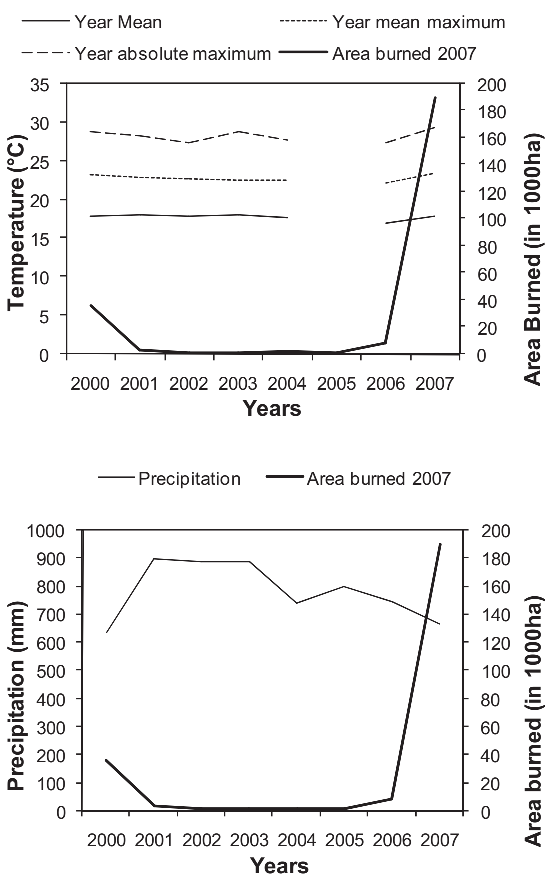


Fig. 5. Mean, mean maximum, and absolute maximum yearly temperatures, and total precipitation of the period 2000–2007 (data for 2005 are not available) collated to the total area burned for the same period.

Table 1
Mean, mean maximum, and absolute maximum yearly temperatures, and total precipitation for the period 2000–2007 (data for 2005 are not available), collated to the average values of the period 1960–2004 and 2000–2007.

Period	Air temperature			Precipitation (mm)
	Mean (°C)	Mean maximum (°C)	Absolute maximum (°C)	
2000	17.89	23.25	28.87	635.1
2001	18.02	22.97	28.23	894
2002	17.88	22.79	27.43	884.2
2003	17.99	22.46	28.89	884.4
2004	17.75	22.47	27.73	739.3
2005	[a]	[a]	[a]	798.8
2006	16.96	22.16	27.45	743.2
2007	17.91	23.50	29.42	665.6
2000–2007	17.90	22.80	28.18	780.6
1960–2004	17.76	23.25	28.87	770.8[b]

[a] Missing data.
[b] Precipitation data cover the period 1971–2004.

of the period 2000–2007 (780.6 mm) and the period 1971–2004 (769.8 mm).

As shown in Fig. 5 and Table 1, the year 2007 presents the highest mean and absolute maximum air temperature and the second lowest total precipitation during the period 2000–2007. The year 2000 also presents similar high values. According to fire statistics, 2000 is the second highest as far the total burned area is concerned (41,366 ha). Additionally, monthly precipitation of the year 2007, as compared to the average of the period 1971–2004 and 2000–2006, is presented in Fig. 4. According to the climatic data from Kalamata station there is one precipitation peak in May that could support fuel built up, while July and August were completely dry indicating dry fuel conditions.

Finally, as shown in Fig. 6 during the days of fire episodes between the 23rd and 29th of August (indicated as gray area in the graphs), a sharp increase of maximum temperature is observed on

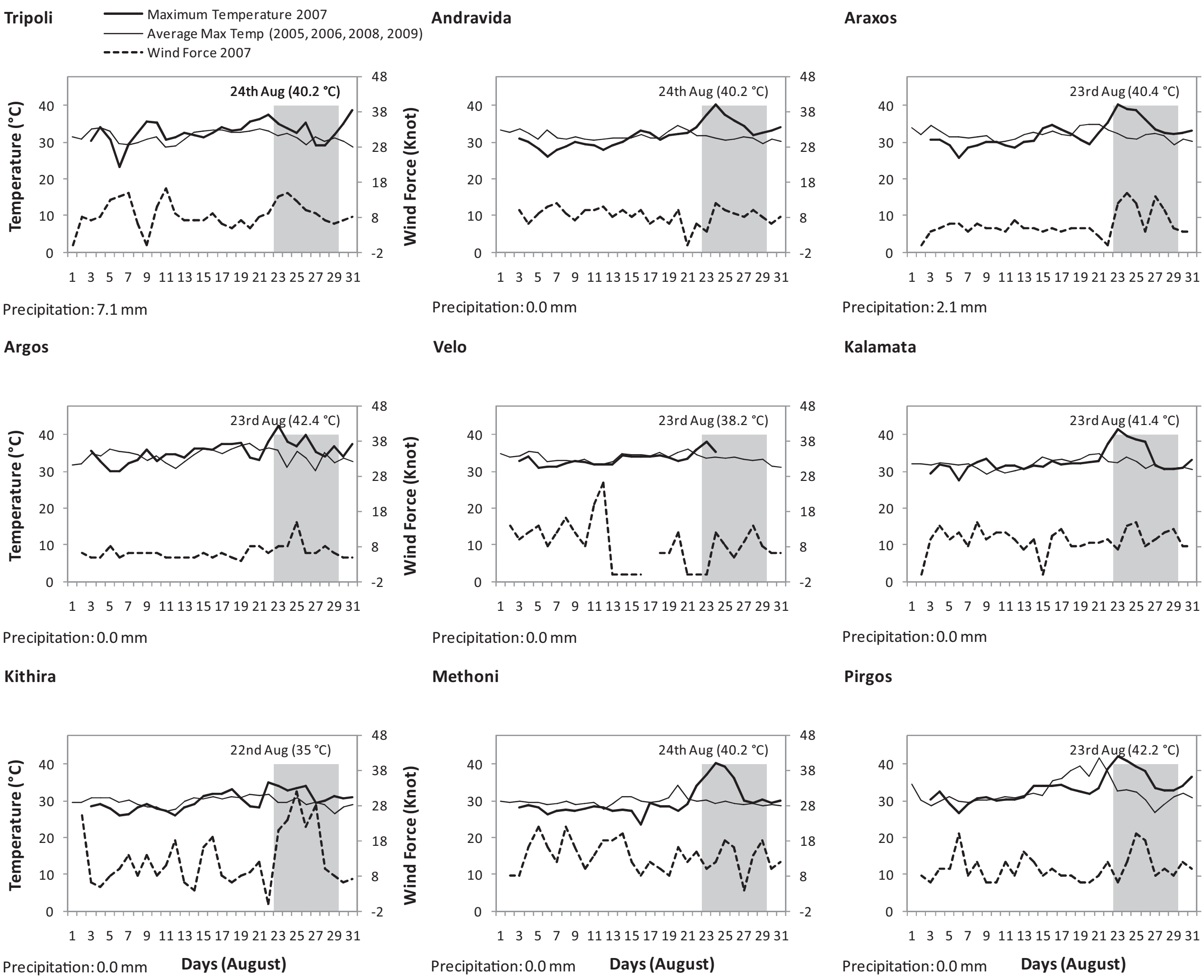


Fig. 6. Daily observations during August 2007 and average daily values (2005, 2006, 2008 and 2009) of maximum temperature and wind speed. Total precipitation is also indicated. The gray area corresponds to the days where the extreme fires were occurring (23–29 August).

the 23rd or 24th of August accompanied with strong winds. Additionally, in almost all stations total precipitation in August was zero (with two exceptions where only a minimal amount of rainfall was encountered) indicating very dry conditions. These weather conditions can be characterized as extreme for the study area and as favorable for large fires.

3.3. The 2007 fires

According to the EFFIS dataset, the total burned area for the period 2000–2006 was 53,950 ha, of which 41,366 ha (76.67%) were burned in the year of 2000 which also presents a peak in total burned area (Fig. 2). Out of this area only 1294 ha (2.4%) were burned twice during this period, while the rest was burned only once. The total burned area in 2007 was 190,836 ha which is almost 3.5 times more than the total area burned during the previous 7 years (2000–2006). There is an overlap of 10,183 ha between the 2007 wildfires and the wildfires of 2000–2006, which means that only 5.3% of the 2007 burned areas had been burned at least once more in the recent history (2000–2006). Of the 10,183 ha overlapping burned area, 9992 ha (98.13%) had experienced fire only once while only 191 ha (1.87%) had been burned twice during the period of 2000–2006.

These values are in accordance with the data provided by the Hellenic Fire Brigade for the same period (Fig. 2). The fire size pattern in Peloponnisos is characterized by many small and few large fires. However, in 2007 more large fires are observed compared to 2000–2006 (Fig. 7). According to the official statistics of the Hellenic Fire Brigade 2812 fires have been recorded in 2007 which burned 189,952 ha in total. The 28 largest fires (1% of the recorded events) were responsible for 98.48% (187,038 ha) of the total burned area. In the period 2000–2006, 15,151 fires which burned 51,848 ha have been recorded. During this period, the 1% of the largest fires (152 events) were responsible for the 90.41% (46,876 ha) of the total burned area. Out of the total burned area, 87.96% (167,087 ha) was consumed during the days of the extreme fires (23–29 August).

Finally, according to the Hellenic Forest Service from 1985 to 2004 4480 fires (with a total burned area of 210,198 ha) occurred in Peloponnisos. Out of these, 880 fires (19.64%) occurred within the 2007 fire perimeters that burned 42,791 ha (22.43%). This gives evidence of fuel accumulation since at least the 77.57% of the 2007 burned areas did not experience a fire since 1984.

3.4. Fire occurrence zones

To define fire occurrence zones we used the kernel density interpolation approach using historical fire observations recorded between 1985 and 1995 by the Hellenic Forest Service. This approach had been originally introduced in wildfire occurrence mapping by Koutsias et al. (2004), to address the inherent positional inaccuracies of historical wildland fire ignition observations. We used the fixed mode instead of the adaptive one while the bandwidth size of the kernel was set to 4000 m following Koutsias et al. (2004). Additionally, kernel density estimation was applied also to control points that correspond to “no-fire” points established after a random sampling design and exclusion of points outside a 3000 m buffer zone of around fire ignition points. Finally, the kernel density estimates of both the fire ignition points and the control points were combined into one layer after inverting the kernel densities of the control points to a negative scale by multiplying the original densities times the value −1. The final density surfaces were reclassified to four equal area classes corresponding to four fire occurrence classes. Kernel density interpolation has been implemented using CrimeStat® Ver. 3.1 (Levine, 2007) (Fig. 8).

Table 2
Proportions of land-types in Peloponnisos (column 1), including total cover (column 2), what was burned in wildfires over the period 2000–2006 (column 3), what was burned in the 2007 wildfires (column 4). All units are percentages.

Land cover	Available in the study area (%)	Percentage burned 2000–2006	Percentage burned 2007
CORINE level 1			
Artificial surfaces	1.29	0.38	1.19
Agricultural areas	43.23	34.76	46.69
Forests and semi-natural areas	55.06	64.86	51.86
CORINE level 2			
Arable land	4.65	0.7	1.8
Permanent crops	12.96	13.06	9.59
Heterogeneous agricultural areas	25.16	20.52	35.28
Forests	12.46	16.72	17.2
Shrub and/or herbaceous vegetation associations	41.34	47.73	34.34
CORINE level 3			
Non-irrigated arable land	3.3	0.7	1.8
Olive groves	9.06	4.86	8.29
Complex cultivation patterns	9.17	3.04	9.5
Land principally occupied by agriculture, with significant areas of natural vegetation	15.99	17.48	25.78
Broad-leaved forest	2.22	1.86	4.3
Coniferous forest	7.49	12.42	7.95
Mixed forest	2.75	2.44	4.95
Natural grassland	7.52	12.89	7.54
Sclerophyllous vegetation	24.55	16.72	14.95
Transitional woodland shrub	9.07	18.13	11.85
Coniferous			
Low-land coniferous	27.57	61.36	56.26
High-land coniferous	72.43	38.64	43.74

3.5. Data analysis

For data analysis we converted the original geographical layers provided in vector format to raster format of 250 by 250 m spatial resolution compatible with the original spatial resolution of the satellite data used to derive the fire perimeters. To determine that this spatial resolution does not conflict with CORINE, where the minimum mapping unit is 25 ha and corresponds to an area of less than 1 pixel, we estimated and compared the land cover frequencies for both, the original vector data and the transformed raster data. The frequency numbers of CORINE land cover classes show no significant differences between the two data formats that could affect the results (see Supplementary material, Tables S1–S3).

3.5.1. Monte Carlo randomization test

At first, we compared the 2007 fires against what is available to burn across the landscape considering a random null model. If the different land-cover categories of a given landscape were equally fire-prone, then one would expect fires to burn with a similar proportion as the available to burn (Moreira et al., 2009). We then compared the 2007 wildfires against what was burned during the recent fire history (2000–2006). Additionally, we compared also the recent fire history (2000–2006) against the available to burn considering a random null model. Absolute (hectares) and relative (%) extent of (i) what is available in the study area and considered as expected under the random null model, (ii) what has been burned in 2000–2006 and considered as expected on the basis of recent history, and (iii) what has been burned in 2007 for each geographical layer was extracted from GIS (Tables 2 and 3; see also Supplementary material Tables S4 and S5).

To determine whether the 2007 wildfires burn significantly different than what is available to burn we applied a Monte Carlo randomization test (Bajocco and Ricotta, 2008; Conedera et al.,

Table 3
Proportions of bioclimatic categories, elevation zones, and fire occurrence zones in Peloponnisos (column 1), including total cover (column 2), what was burned in wildfires over the period 2000–2006 (column 3), what was burned in the 2007 wildfires (column 4). All units are percentages.

	Available in the study area (%)	Percentage burned 2000–2006	Percentage burned 2007
Bioclimatic belts based on the xerothermic index			
$x = 0$ axeric	0.25	0.00	0.00
$1 < x < 40$ transitional sub-Mediterranean	1.88	0.00	0.51
$40 < x < 75$ attenuated meso-Mediterranean	22.32	15.01	15.47
$75 < x < 100$ accentuated meso-Mediterranean	47.97	48.60	69.44
$100 < x < 125$ attenuated thermo-Mediterranean	20.49	26.18	13.11
$125 < x < 150$ accentuated thermo-Mediterranean	7.09	10.22	1.46
Bioclimatic belts based on pluviothermic quotient and thermic variants			
Humid/cold	12.86	7.55	4.48
Humid/temperate	25.20	23.46	42.21
Semi-arid/hot	5.11	8.81	2.89
Semi-arid/temperate	8.59	13.99	1.43
Sub-humid/cool	14.17	12.75	15.43
Humid/cool	15.57	19.45	20.59
Semi-arid/cool	9.59	9.36	1.10
Sub-humid/temperate	3.18	4.62	11.35
Sub-humid/hot	5.72	0.00	0.51
Elevation zones			
0–500	52.98	49.03	59.25
501–1000	32.76	38.43	33.71
1001–1500	12.25	12.54	6.55
1501–2000	1.89	0.00	0.49
>2000	0.12	0.00	0.00
Fire occurrence zones			
Low	25.39	1.11	4.89
Medium	24.97	8.19	9.40
High	24.86	27.49	19.51
Very high	24.77	63.22	66.20

2010; Moreira et al., 2001), without considering any criteria other than the complete randomness. The 2007 wildfires were randomly reassigned to each class of the geographical layer considered in such a way that the probability of assignment to each class is equal to the relative extent of that class (Bajocco and Ricotta, 2008), first in the whole area when the random null model is considered, and second in the 2000–2006 fires when the comparison concerns the recent fire history. Similar analysis has been done for the fires of 2000–2006 (Tables 2 and 3; see also Supplementary material Tables S4 and S5).

3.5.2. Multi-response permutation procedure (MRPP)

In principle, the burning pattern of wildfires contains a certain degree of spatial autocorrelation that influences the statistical power of the analysis which the Monte-Carlo randomization test does not consider. Therefore, following Nunes et al. (2005) we applied also the multi-response permutation procedure (MRPP) that is a data dependent method free from underlying distribution model assumptions to analyze grouped data based on Euclidian distances. MRPP, originally introduced by Mielke et al. (1976), tests whether there is a significant difference between a priori classified groups of objects and is often analogous to parametric tests such as the *t*-test or the analysis of variance (Cai, 2006). If two groups are different, then distances within the group tend to be smaller than between groups. When data are in blocks then a slight modification of MRPP model is used for paired comparisons refereed as MRBP (multi-response permutation procedure for blocked data) (Mielke, 1991; Nunes et al., 2005). Finally, the Multivariate Medians and Distance Quantiles (MEDQ) is used to estimate multivariate medians for grouped data and group differences detected by MRPP analyses (Nunes et al., 2005). For further details refer to Mielke and Berry (2001) and to Nunes et al. (2005). The software used to implement all the MRPP analyses is Blossom (Cade and Richards, 2005). The MEDQ results of the differences between medians in burned areas and the available to burn at global and local scale are presented in Table 4.

For the definition of the available-to-burn area that is required from the MRPP test we followed two approaches; the global one and the local one following Nunes et al. (2005). At global scale the available-to-burn area was estimated and expressed in percentages of the entire region. At local scale we used a box surrounding each fire polygon similar to Cumming (2001) while Nunes et al. (2005) used buffer polygons of the same size as the fire polygons.

4. Results

4.1. CORINE land cover

4.1.1. CORINE level 1

During 2000–2006, 34.76% of the burned area in Peloponnisos was agricultural land and 64.86% was forests and semi-natural areas, with 43.23% of the Peloponnisos area covered by agricultural land and 55.06% by forests and semi-natural areas. In 2007, the relative proportions were 46.69% and 51.86% respectively. Therefore, the 2007 fires follow neither the pattern of recent fire history nor what is available to burn when the random null model is applied (Table 2 and Fig. 8). More specifically, in 2007 agricultural areas were burned more compared to recent history and to the area available to burn, while the opposite trend is observed for forests and semi-natural areas. The deviation of the observed patterns from the random null model was significant ($P < 0.0001$) for all categories (Table 2, Fig. 4 and also see Supplementary material Table S4).

According to MEDQ results (Table 4) although the agricultural areas are not characterized as a positive fire-selectivity class, the differences between the recent history and the year 2007 has been considerably increased from −21.896 to −9.967, while the forests and semi-natural areas decreased from +23.591 to +11.607 indicating a departure of the burning pattern of 2007 compared to the recent history.

4.1.2. CORINE level 2

At CORINE level 2, the 2007 wildfires burned a relative higher amount of heterogeneous agricultural areas (35.28%) compared to both the available (25.16%) and the recent fire history (20.52%). The second-in-size burned class is shrubby and/or herbaceous vegetation with 34.34%, however this is much less than both the available (41.34%) and the recent history (47.73%). This is a clear shift in the burning pattern for the year 2007 compared to recent fire history. Finally, forests displayed a similar burning pattern in 2007 (17.20%) as in the recent history (16.72%) (Table 2, Fig. 8 and also see Supplementary material Table S4).

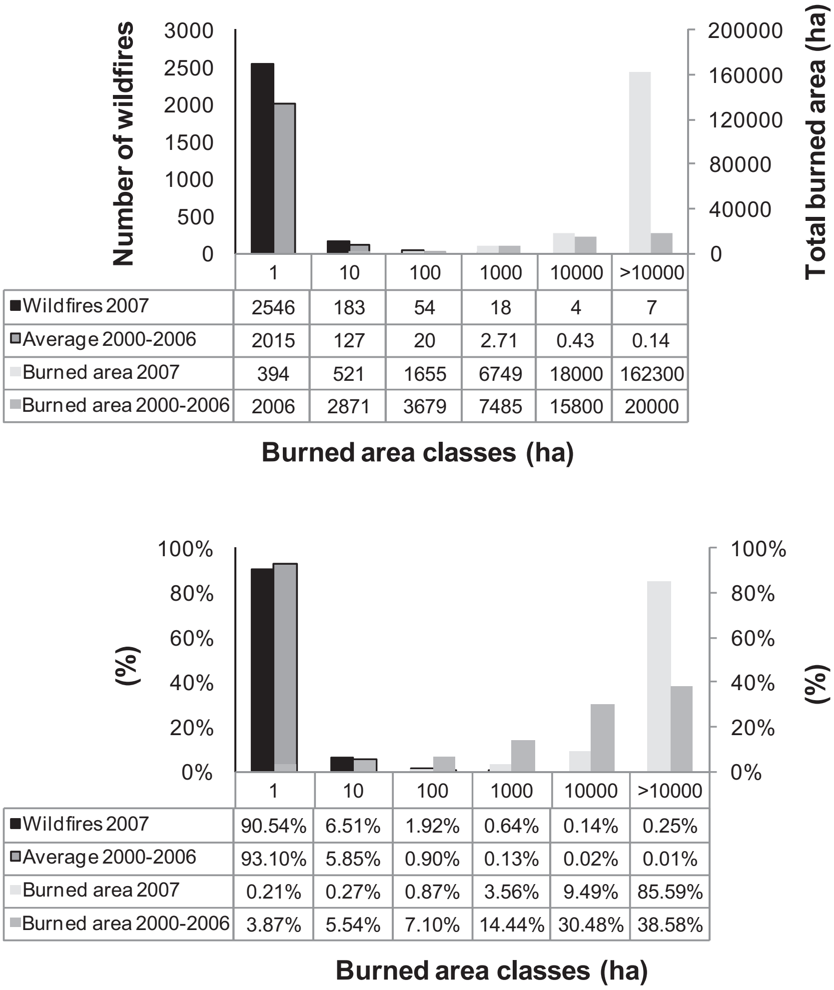
According to MEDQ results (Table 4), although the class “Shrub and/or herbaceous vegetation associations” is a positive fire-selectivity class, in 2007 it has been affected much less than the period 2000–2006, while the exact opposite trend is observed for the class “Permanent crops” that despite its negative fire-selectivity character has been affected much more in 2007 than in 2000–2006.

4.1.3. CORINE level 3

The land cover types that showed remarkable increase in the 2007 wildfires when compared to those of 2000–2006 were the categories “complex cultivation patterns” (9.5%) and “land principally occupied by agriculture, with significant areas of natural vegetation” (25.78%) (Table 2 and also see Supplementary material

Table 4
MEDQ results of the differences between the medians in affected by the fires areas and their available to burn at global and local scale in 2007 and during the recent fire history (2000–2006).

	Global						Local					
	2000–2006			2007			2000–2006			2007		
	Available	Burned	Difference	Available	Burned	Difference	Available	Burned	Difference	Available	Burned	Difference
CORINE level 1												
Artificial surfaces	1.290	0.000	−1.290	1.29	0.053	−1.237	0.000	0.000	0.000	0.479	0.053	−0.426
Agricultural areas	43.258	21.362	−21.896	43.258	33.291	−9.967	29.005	21.362	−7.643	38.442	33.291	−5.151
Forests and semi-natural areas	55.047	78.638	23.591	55.047	66.654	11.607	70.995	78.638	7.643	61.079	66.654	5.575
CORINE level 2												
Arable land	4.652	2.648	−2.004	4.652	0.684	−3.968	3.014	2.648	−0.366	0.756	0.684	−0.072
Permanent crops	12.954	2.182	−10.772	12.954	10.330	−2.624	4.124	2.182	−1.942	15.531	10.330	−5.202
Heterogeneous agricultural areas	25.182	20.053	−5.129	25.182	19.381	−5.801	22.336	20.053	−2.283	20.248	19.381	−0.867
Forests	12.469	8.595	−3.874	12.469	8.397	−4.072	9.212	8.595	−0.617	7.527	8.397	0.870
Shrub and/or herbaceous vegetation associations	41.312	65.596	24.284	41.312	59.865	18.553	60.296	65.596	5.301	54.026	59.865	5.839
CORINE level 3												
Non-irrigated arable land	3.308	4.240	0.932	3.308	0.668	−2.640	4.054	4.240	0.186	0.919	0.668	−0.251
Olive groves	9.065	1.532	−7.533	9.065	12.022	2.957	2.349	1.532	−0.817	14.335	12.022	−2.313
Complex cultivation patterns	9.166	2.193	−6.973	9.166	4.113	−5.053	2.360	2.193	−0.167	4.975	4.113	−0.862
Land principally occupied by agriculture, with significant areas of natural vegetation	16.014	22.977	6.963	16.014	18.414	2.400	22.159	22.977	0.818	17.597	18.414	0.817
Broad-leaved forest	2.230	3.393	1.163	2.230	1.555	−0.675	4.276	3.393	−0.883	2.038	1.555	−0.483
Coniferous forest	7.487	5.010	−2.477	7.487	6.209	−1.278	4.747	5.010	0.263	4.719	6.209	1.489
Mixed forest	2.752	4.544	1.792	2.752	2.226	−0.526	4.093	4.544	0.451	2.016	2.226	0.210
Natural grassland	7.509	14.402	6.893	7.509	11.267	3.758	13.845	14.402	0.557	10.842	11.267	0.425
Sclerophyllous vegetation	24.544	26.860	2.316	24.544	34.389	9.845	26.711	26.860	0.148	31.593	34.389	2.796
Transitional woodland shrub	9.055	11.459	2.404	9.055	6.905	−2.150	11.403	11.459	0.056	6.695	6.905	0.210



	1	10	100	1000	10000	>10000
Wildfires 2007	2546	183	54	18	4	7
Average 2000-2006	2015	127	20	2.71	0.43	0.14
Burned area 2007	394	521	1655	6749	18000	162300
Burned area 2000-2006	2006	2871	3679	7485	15800	20000

	1	10	100	1000	10000	>10000
Wildfires 2007	90.54%	6.51%	1.92%	0.64%	0.14%	0.25%
Average 2000-2006	93.10%	5.85%	0.90%	0.13%	0.02%	0.01%
Burned area 2007	0.21%	0.27%	0.87%	3.56%	9.49%	85.59%
Burned area 2000-2006	3.87%	5.54%	7.10%	14.44%	30.48%	38.58%

Fig. 7. Histogram data plot of fire sizes for the period 2000–2006 and the year of 2007 in absolute and relative numbers.

Table S4). Between these two, complex cultivation patterns did not burn differently than expected under the random null model (9.17%). The burned area corresponding to land principally occupied by agriculture, with significant areas of natural vegetation was 25.78% compared to 15.99% available in Peloponnisos. This constitutes again a shift of the burning pattern in the year of 2007 as concerns land cover. Coniferous forests in total burned significantly less (7.95%) compared to recent history (12.42%), but similar to what is available to burn (7.49%). Sclerophyllous vegetation is the second highest burned land category (14.95%), however this percentage was significantly less than what is available to burn (24.55%) and what was burned in recent history (16.72%). Finally, transitional woodland shrubs, although it was the highest burned category in recent history (18.13%) and was burned twice as much as the available (9.07%), in 2007 its percentage was 11.85% (Table 2 and also see Supplementary material Table S4).

According to MEDQ results from the agricultural categories listed in Table 4 the categories “Olive groves” and “Land principally occupied by agriculture, with significant areas of natural vegetation” show positive fire selectivity. Between the two, however, only in the category “Olive groves” has the difference between the area burned in 2007 and that available been increased compared to 2000–2006. Additionally, from the forests and semi-natural areas categories listed in Table 4 the categories “Natural grasslands” and “Sclerophyllous vegetation” show positive fire selectivity. However, between the two, the difference increased from 2000 to 2006 only for the “Sclerophyllous vegetation” category.

4.2. Lowland versus highland coniferous forests

Fire-prone stands of lowland conifers, present almost double rates of burned area (56.26%), compared to the area expected by a random null model (27.57%). However, the 2007 value was lower than in the recent history (61.36%). On the other hand, the non-fire prone forests of highland conifers (43.74%) were more affected in 2007 compared to that expected by the recent history (38.64%) (Table 2 and also see Supplementary material Table S4). These results indicate a shift in the burning pattern in 2007, where the fires burned mountainous conifer forests of higher altitudes in cooler environments.

4.3. Bioclimatic zones

When we classified the areas according to the number of biologically dry days (x), we found that the relative extent of what the 2000–2006 fires burned was 10.22%, 26.18% and 48.60% for the $125 < x < 150$, $100 < x < 125$ and $75 < x < 100$ categories, respectively (Table 3). For 2007, these numbers were modified to 1.46%, 13.11% and 69.44% while those available for the whole study area were 7.09%, 20.49% and 47.97%, respectively. Therefore, the 2007 wildfires seem to deviate significantly from the burning pattern of recent history since there was a clear movement from areas with a high to low number of biologically dry days. In the recent fire history there was a preferential burning of more biologically dry areas as compared to those available, while the 2007 fires burned

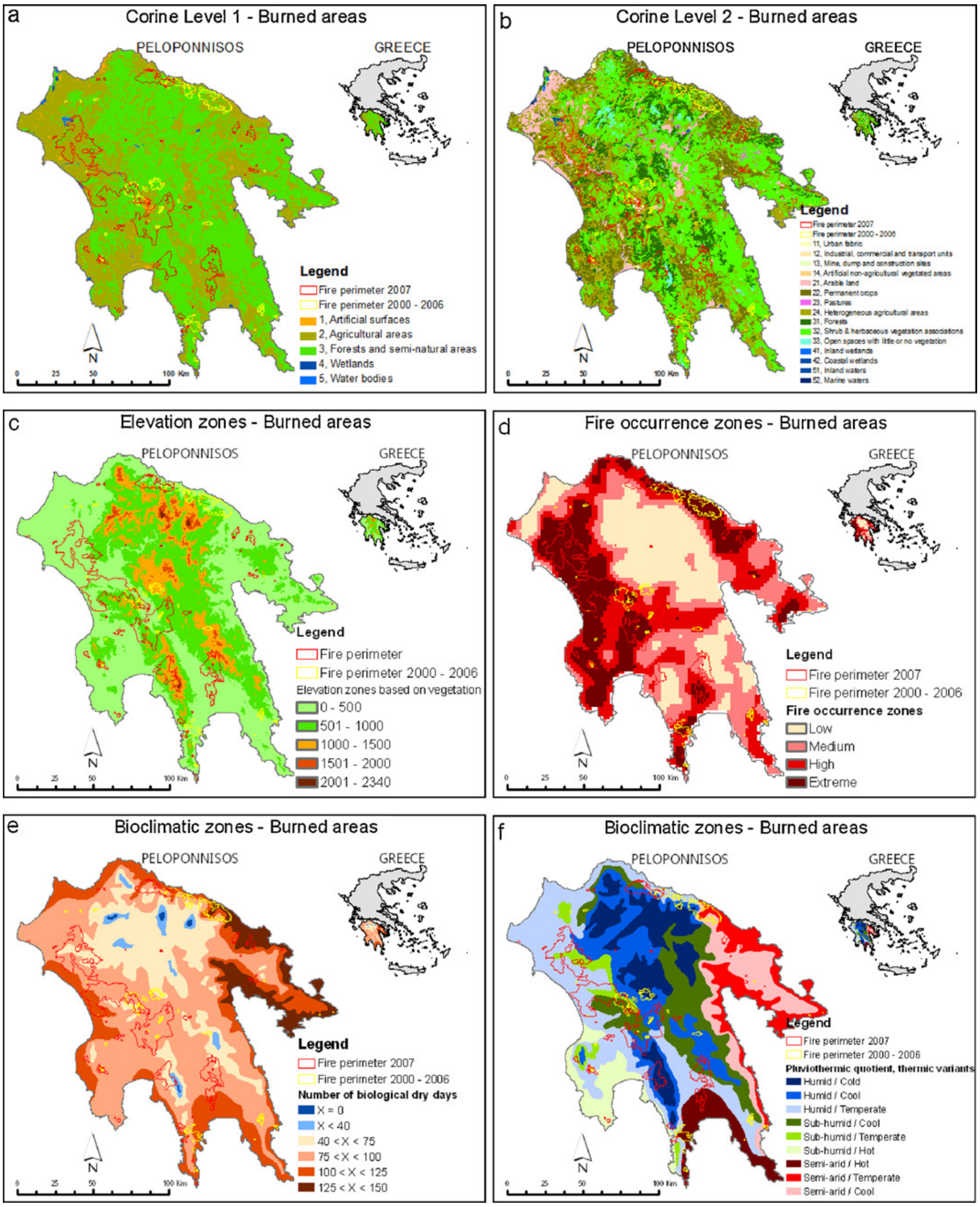


Fig. 8. Spatial overlay of fire perimeters of the 2007 wildfires and those of recent history (2000–2006) with (a) CORINE level 1, (b) CORINE level 2, (c) elevation zones, (d) fire occurrence zones, (e) bioclimatic zones based on the xerothermic index, and (f) bioclimatic zones based on pluviothermic quotient and thermic variants.

selectively less biologically dry areas. For the first time since 2000, burned areas appeared in the attenuated meso-Mediterranean category ($40 < x < 75$) although the percentage burned was very small (0.51%). Similar trends are observed when the comparisons concern the bioclimatic belts defined on the basis of the pluviothermic quotient and its thermic variants. The 2007 fires burned significantly less in all the semi-arid categories, while they burned significantly more in all the humid and sub-humid categories except the cold one. Moreover, in the 2007 wildfires we observed a shift towards cooler areas than in the previous years (Table 3, Fig. 8 and also see Supplementary material Table S5).

4.4. Elevation zones

Concerning the elevation zones, the burning pattern of the 2007 wildfires in Peloponnisos is quite different than expected on the basis of recent fire history. The majority of 2007 wildfires shifted to the lowest elevation zone (0–500 m, 59.25%) compared to 49.03% in recent history, while a small percentage moved to higher altitudes (1501–2000 m, 0.49%) compared to 0% observed in recent history (Table 3, Fig. 8 and also see Supplementary material Table S5). The 0–500 m zone is where agriculture is concentrated and is more affected by the 2007 fires, while the 1001–1500 m zone is where high-land coniferous forests are concentrated and affected more as compared to recent fire history. The absolute and relative distribution of the burned areas in 2007 concerning the elevation zones summarizes the burning pattern revealed so far: the majority of fires burned fire-prone ecosystems found at low altitudes, while a significant part moved to non fire-prone ecosystems found at higher altitudes characterized by cooler and more humid climatic conditions.

4.5. Fire risk zones

Similar burning patterns for the 2007 wildfires were also observed by the distribution of the burned areas within fire occurrence zones created by the wildfire ignition points of 1985–1995. Wildfires of the recent history and wildfires of 2007 justify the value of these fire occurrence zones, since burned areas are mainly distributed within the highest fire risk zones. The absolute and relative distribution of the burned areas in 2007 indicates that the majority of the fires burned fire-prone ecosystems found in high fire occurrence zones, while a small amount of them moved to non-fire prone ecosystems found in low fire occurrence zones, not having experienced frequent fires so far. In recent history, only 1.11% of the burned areas were located in low fire occurrence zone, while in 2007 this percentage increased to 4.89% (Table 3, Fig. 8 and also see Supplementary material Table S5).

5. Discussion

Our study revealed that the category "agricultural land interspersed with significant areas of natural vegetation" were among the CORINE land cover types most affected by the catastrophic fires of 2007 in Peloponnisos followed by "sclerophyllous vegetation", "transitional woodland shrubs", "complex cultivation patterns", "olive groves" and others. This situation may reflect the encroachment of natural vegetation into abandoned fields and hence greater fuel accumulation but it may also reflect the recent evolution of the wildland–rural interface. Major social and economic changes in land use have affected the wildland–rural interface as well as the wildland–urban interface resulting in an increased amount of biomass (fuel), higher exposure to man induced fire, and conflicts (Galiana-Martin et al., 2011; Massada et al., 2009; Moreira et al., 2011; Pérez et al., 2003). The conflicts at the wildland–rural interface are mainly related to rural abandonment, inconsistent policies on land management (fire use and grazing), and the designation of protected areas for nature conservation. While in less developed countries forests are being cleared and converted to agriculture, in developed ones (where agriculture is concentrated in the most productive land) less productive areas are being abandoned or subjected to less intensive use and afforestation (Pérez et al., 2003; Vega-García and Chuvieco, 2006). Agricultural abandonment and afforestation occurring in the last 40–50 years in the Mediterranean region, associated to socio-economic and political changes (Mallinis et al., 2011; Moreira et al., 2001), have considerably changed the Mediterranean landscape especially in mountainous areas (Pérez et al., 2003; Vega-García and Chuvieco, 2006). Urbanization can have a great impact on forest fires, since land abandonment following population movement is associated with fuel accumulation. This enables more favorable conditions for turning fire ignition points into relatively large fires although the ignition risk might be less.

Apart from the agricultural land that was so extensively burned in 2007 fires in Peloponnisos, there were also deviations in the forest types burned. The available to burn category "Forests and semi-natural areas" covers 55.05% at the scale of Peloponnisos, while at local scale this percentage increases to 61.08% in 2007; thus the majority of the fires occurred in areas where the category "Forests and semi-natural areas" locally prevails. Moreira et al. (2010) showed that once an ignition occurs, there is a resulting fire size-dependent spatial pattern with the ones resulting in large fires being more likely in forest or shrublands among others. Although the majority of the forests burned were those of the lower elevation Mediterranean pines (*P. halepensis* and *P. pinea*), fires also burned mountainous conifer forest types of higher altitudes and cooler environments. The areas with the endemic Greek fir and those with Black pine (highland coniferous forests), which in Peloponnisos find their southernmost geographical distribution limit, were burned relatively more in 2007 than in recent history. Historical data show that for the period 1965–1989 only 1304 ha of fir and 9152 ha of Black pine forests were burned throughout Greece. Arianoutsou et al. (2008) have shown that the percentage of fire events in mountainous conifer forests have steadily been increased throughout Greece since the late 1980s, in some cases being 3–4 times higher than those of the previous years. This fact has been linked to the extended drought periods that these ecosystems are facing. Although no specific study has been done, it would be reasonable to link these drought periods to climate warming. Amanatidis et al. (1993) showed significant decreasing trends in the precipitation over an area in Central Greece (Marathon) [33–42% for the rainy period and 29–32% for the dry period] for 1926–1990. Piervitali and Colacino (2003) noted a significant trend in annual precipitation decrease by a rate of 3.2 mm/year for 1951–1995, based on 69 meteorological stations located in different countries of the central-western Mediterranean.

The link between observed shifts in climatic patterns and fire occurrence has recently started to be a focal issue of research. Piñol et al. (1998) studied a climatic series of 50 years from a Mediterranean locality in southern Spain and two relevant fire hazard indices. Both fire hazard indices increased over this period as a consequence of increasing mean daily maximum air temperature and decreasing minimum daily relative humidity. They concluded that an effect of climate warming on wildfire occurrence is supported by this relationship. Pausas (2004) analyzed data from 350 meteorological stations in the eastern Iberian Peninsula covering a time period of 50 years (1950–2000) and fire records for the same area. He concluded that a clear pattern of increasing number of fires and size of area burned is observed during the last century. He suggested that this increase is related partly to changes in the observed climatic pattern. Similar conclusions have been drawn from studies in the western United States (Westerling et al., 2006), particularly in areas where land-use histories have relatively little effect on fire risks and are strongly associated with increased spring and summer temperatures. Additionally, Liu et al. (2010) have shown that worldwide future wildfire potential is increasing significantly, while relative changes are greater in southern Europe. The summer of 2007 was exceptionally hot for southeastern Europe, the Balkan Peninsula and also part of Asia Minor, with significant positive anomalies of the seasonal surface air temperature but also distinct periods of extremely high temperatures. A number of heat waves hit the area in summer 2007 (at the end of June, in July and August), during which the highest temperatures ever recorded have been observed (occasionally reaching 47 °C). Winter minimum temperatures (mainly during January) were also found to be exceptionally high and were reported as more "statistically extreme" than the summer maxima (Tolika et al., 2009). In addition to 2003 summer for Western Europe, the heat waves of summer 2007 in southeastern Europe can be viewed as further evidence of abnormally hot summers nowadays (Founda and Giannakopoulos, 2009). Furthermore when analyzing the daily weather observations from nine meteorological stations in the area, we observed a sharp increase of maximum temperature accompanied by strong winds during the days of the fire episodes (i.e. from 23 to 29 of August 2007). This temporal overlap between the extreme weather conditions and the largest fire episodes further highlight the importance of weather conditions for this large catastrophic event.

The synergistic effect of fuel and weather can explain the large, catastrophic wildfires of 2007 in Peloponnisos. Thompson and Spies (2009) explain the variation observed in crown damage within a large mixed-severity wildfire also by vegetation and weather. Weather and other human or environmental factors can explain fire occurrence or extreme events also in other environments and not only in Mediterranean biomes though a unique pattern is not always the case (Armenteras-Pascual et al., 2010; Beverly and Martell, 2005; Zumbrunnen et al., 2009, 2011). Pereira et al. (2005) using time series of the total annual burnt area in Portugal reveal two main features, a large inter-annual variability and a positive trend since the early 1980s. They showed that inter-annual variability was partly due to the amount of precipitation in the fire season and in the preceding late spring season and partly to the occurrence of atmospheric circulation patterns that induce extremely hot and dry spells over western Iberia. On the other hand, the observed positive trend of burnt area was mainly related to changes in farming and land use.

The burning pattern of 2007 wildfires displayed a shift from what recent history had led us to expect, since larger proportions of humid and sub-humid areas and a lower proportion of semi-arid areas were burned. Moreover, in the 2007 wildfires we observed a shift in their location towards cooler areas compared to previous years. Finally, the absolute and relative distribution of the burned areas within both the elevation zones and the fire occurrence zones summarizes the burning pattern revealed so far. The majority of the fires burned fire-prone ecosystems found at low altitudes and in high fire occurrence zone areas, while a small number moved to non fire-prone ecosystems found in high-elevated, cooler areas and in low fire occurrence zones that had not previously experienced fires. Arianoutsou (2007) has pointed out the risk of ecological disasters if the scenario of fires shifting over higher altitudes and northern latitudes become reality. These non fire-prone plant communities lack adaptations to cope with fire, and thus an ecological disaster seems possible.

We should point out that there is a certain degree of correlation among land cover, bioclimatic zones, elevation, and fire risk zones analyzed in our study. This imposes a certain degree of difficulty in separating the effect of each specific factor. Also another caveat of our study is that we examined in detail two factors, fuel and weather, and how they relate to the observed shift in burning pattern. However, there is a third factor, namely fire ignitions which set up the classic fire triangle controlling combustion (Schoennagel et al., 2004). We have no data on human pyrogenic behavior so as to categorically rule out the possibility that these processes caused the observed shifts. A final caveat is that our analysis which was based on the extreme wildfires of 2007 does not allow us to conclude whether the observed shift is permanent or whether the burning pattern will revert to normal.

Mediterranean ecosystems, according to Meyn et al. (2007), are biomass poor and rarely dry ecosystems where both fuel amount and fuel moisture limit the occurrence of large, infrequent fires. This seems to be the case in our study, where the synergy of fuel (as denoted by the most affected land cover category and local fire history which gives evidence for fuel accumulation), and weather (as denoted by the extremes in temperature, precipitation and wind) can explain the large and catastrophic fires of 2007. These catastrophic wildfires burned areas that did not experience fire during the recent history (and thus accumulated fuel) and also abandoned fields with natural vegetation encroachment. Also, the extreme weather conditions contributed towards the decreased fuel moisture allowing wildfire to spread to areas that are usually moist and thus non-fire-prone.

6. Conclusions

Our study of the burning pattern of the 2007 wildfires in Peloponnisos reveals a clear differentiation from the burning pattern of recent fire history (2000–2006). As expected, the majority of the 2007 wildfires burned fire-prone ecosystems found at low-elevation and in high fire occurrence zones. However, a number of fires moved to non-fire-prone ecosystems found at high elevation, cooler areas and in low fire occurrence zones that had not previously experienced fires. Agricultural land, highly interspersed with significant areas of natural vegetation, was the CORINE land cover type mostly affected by fire, thus reflecting the encroachment of natural vegetation in abandoned fields and also recent patterns of evolution in the wildland–rural interface where agricultural land is increasingly intermixed with natural vegetation. The larger proportions of humid and sub-humid areas burned along with a lower proportion of burned semi-arid areas compared to recent history, reflects an important shift clearly related to weather conditions.

Probably the most important conclusion is the shift observed in the types of natural vegetation burned and the prevailing weather conditions. The synergistic effect of fuel and weather can explain the large and catastrophic wildfires of 2007 in Peloponnisos. However, the larger proportions of humid and sub-humid areas burned compared to the lower proportion of semiarid areas burned may indicate a shift of burning pattern. These patterns may indicate climatically driven changes to the established fire regime promoted by fuel accumulation, which may have major ecological implications if verified.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2011.12.006.

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