Reg Environ Change (2016) 16:1929–1940
DOI 10.1007/s10113-015-0884-0

ORIGINAL ARTICLE

Mapping fire behaviour under changing climate in a Mediterranean landscape in Greece

Ioannis Mitsopoulos[1] · **Giorgos Mallinis**[2] · **Anna Karali**[3] · **Christos Giannakopoulos**[3] · **Margarita Arianoutsou**[4]

Received: 21 May 2014 / Accepted: 15 October 2015 / Published online: 31 October 2015

Abstract Understanding how future climate periods influence fire behaviour is important for organizing fire suppression strategy and management. The meteorological factors are the most critical parameters affecting fire behaviour in natural landscapes; hence, predicting climate change effects on fire behaviour could be an option for optimizing firefighting resource management. In this study, we assessed climate change impacts on fire behaviour parameters (rate of fire growth, rate of spread and fireline intensity) for a typical Mediterranean landscape of Greece. We applied the minimum travel time fire simulation algorithm by using the FlamMap software to characterize potential response of fire behaviour for three summer periods. The results consisted of simulated spatially explicit fire behaviour parameters of the present climate (2000) and three future summer periods of 2050, 2070 and 2100, under the A1B emissions scenario. Statistical significant differences in simulation outputs among the four examined periods were obtained by using the Tukey's significance test. Statistical significant differences were mainly obtained for 2100 compared to the present climate due to the significant projected increase in the wind speed by the end of the century. The analysis and the conclusions of the study can be important inputs for fire suppression strategy and fire management (deployment of fire suppression resources, firefighter safety and exposure, transportation logistics) quantifying the effect that the expected future climate periods can have on fire suppression difficulty in Mediterranean landscapes.

Keywords Fire behaviour · Climate change projections · Landscape fire modelling · Mediterranean ecosystem

Introduction

Forest fires have always been present in the Mediterranean ecosystems; thus they constitute a major ecological and socioeconomic issue. During the last decades, both the number and the average size of large fires have shown an increasing trend, causing extensive economic and ecological losses and often human casualties (European Commission 2011). Many factors are considered to contribute to this change, including climatic change (Flannigan et al. 2000; Pausas et al. 2008; Hewitson et al. 2014) and human practices leading to increased fuel accumulation (Moreira et al. 2009). Fire statistics show a significant increase in both the number of wildfires and burnt area in Greece. The

---

✉ Ioannis Mitsopoulos
ioanmits@gmail.com

Giorgos Mallinis
gmallin@fmenr.duth.gr

Anna Karali
akarali@noa.gr

Christos Giannakopoulos
cgiannak@meteo.noa.gr

Margarita Arianoutsou
marianou@biol.uoa.gr

[1] The Global Fire Monitoring Center (GFMC) Fire Ecology Research Group, c/o Freiburg University, Georges-Köhler-Allee 75, 79110 Freiburg, Germany

[2] Department of Forestry and Management of the Environment and Natural Resources, Democritus University of Thrace, 68200 Orestiada, Greece

[3] Institute of Environmental Research and Sustainable Development, National Observatory of Athens, 15236 Athens, Greece

[4] Department of Ecology and Systematics, Faculty of Biology, University of Athens, 15784 Athens, Greece

number of fires doubled and the area burned tripled during the years after 1980 (Dimitrakopoulos et al. 2011), and several reasons have been speculated for this augmentation in wildfire activity such as changes in population activities, socioeconomic conditions, land use, fuel accumulation, drought frequency and duration (Dimitrakopoulos and Mitsopoulos 2006). Increase in area burned demonstrates that wildland fires occur in a more severe mode in terms of fire behaviour parameters, such as fire size, fire rate of spread and fireline intensity, thus creating major difficulties in fire suppression efficiency (Andrews et al. 2011). Furthermore, increased wildland fire activity over the last 30 years has had profound effects on budgets and operational priorities of the Forest Service, Civil Protection agencies, Fire Service and local entities with wildland fire responsibilities. Fire suppression tactics during wildland fires is a very complex issue. Firefighter officers have to consider a priori the wildfire threats and need to have the ability to identify in real time the expected fire propagation, intensity and the potential of a wildfire to affect natural resources and valuable assets. Furthermore, they need to decide what type of fire suppression mode is required to protect efficiently the high valuable artificial and natural resources (Yoder 2004). The deployment of fire suppression forces and resources requires accurate estimates of variety of factors such as potential fire behaviour, topography, weather and personnel safety and exposure (Haight and Fried 2007).

Although it has not yet been clarified as to whether the meteorological conditions or the landscape pattern fundamentally determines fire risk and spread (Moreira et al. 2011), it seems that the climatic and weather conditions in the Mediterranean have a profound effect on fire occurrence (Koutsias et al. 2013; Bedia et al. 2013). Fire behaviour and risk are linked directly to weather, as temperature, atmospheric moisture, drought conditions and winds affect ignition potential, fire spread and intensity, and increase suppression difficulty and increased fire effects. Greece, being part of Eastern Mediterranean, is considered a “hot spot” for fire studies, not only because of its high sensitivity to changes in recent decades in those socioeconomic processes recognized to be driver of fire regime changes, such as processes of rural depopulation, land abandonment and reduction in traditional forest use (Moreira et al. 2011), but also for the reason that according to the majority of climate models, the most likely evolution of this region is towards a hotter and drier climate, with a significantly higher risk of intense heat wave episodes as well as an increase in fire hazard and occurrence (Good et al. 2008; Giannakopoulos et al. 2009, 2011, 2012).

Recently, there is much consideration about the relationship between climate change and fire occurrence, not only in the Mediterranean but also in global scale. One way to analyse this relationship is by using raw meteorological data (Vázquez and Moreno 1993; Pausas 2004), drought indices (Hall and Brown 2003; Dimitrakopoulos and Bemmerzouk 2003; Collins et al. 2006; Maingi and Henry 2007), fire risk indicators (Piñol et al. 1998) and climatic output of global circulation models (GCMs) (Flannigan and Van Wagner 1991; Torn and Fried 1992; Flannigan et al. 2000; Wotton et al. 2003; de Groot et al. 2003; Brown et al. 2004).

Although climatic conditions play an important role in fire behaviour and wildfire risk, most studies in the Mediterranean have focused mainly on the potential impacts of climate change to fire risk using a variety of approaches. Many studies have focused on the relationship between fire risk and the meteorological conditions using fire data and regional climate model (RCM) output. Karali et al. (2014) have evaluated current fire risk using actual occurrence data and estimated future fire risk projections driven by climate change for Greece. Projections of future fire danger conditions in future climate scenarios for Spain have been performed by Herrera et al. (2013), while Bedia et al. (2013) have developed future fire risk projections based on a multi-model RCM dataset. Furthermore, Amatulli et al. (2013) have estimated future burned areas in the Mediterranean, and in individual EU countries, most affected by forest fires, using different modelling techniques. Moreover, in a recent study, Turco et al. (2014) have investigated the long-term climate-driven changes in burned area and in the number of fires in NE Spain by applying a statistical fire model driven by RCM output.

However, the effects and the possible relationship between climatic change and fire behaviour parameters have not been studied extensively due to the difficulties in obtaining both high-resolution climatic and fuel data as required in spatial fire modelling studies (Mallinis et al. 2008; Fried et al. 2008).

The main objective of this study is to investigate the potential impact of climate change on fire behaviour for a typical Mediterranean area of Greece by employing high-resolution RCM data and fine-scale landscape fire behaviour modelling.

Methods

Study area

Mt. Penteli is situated 30 km north-east of Athens, and the study area covers 16,025 ha (Fig. 1). The maximum altitude of the region is approximately 1200 m with mild slopes (15–30 %). The climate of the area is characterized as typical subtropical Mediterranean, with prolonged hot and dry summers succeeded by considerably mild and wet

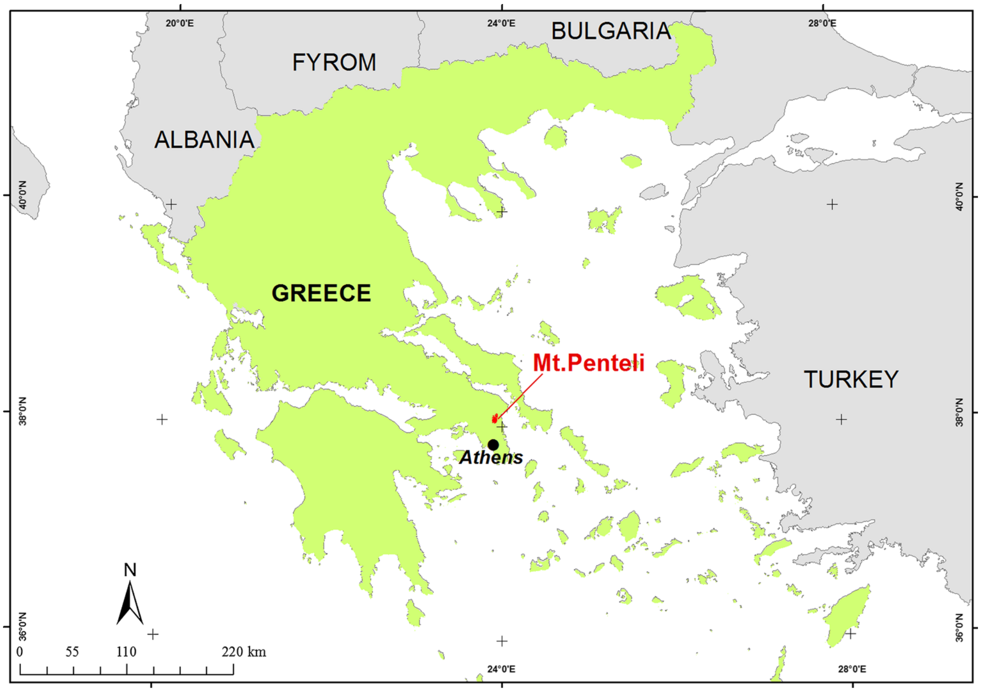

Fig. 1 Mt. Penteli study area is situated north-east of Athens metropolitan area

winters. The climate is characterized as Mediterranean type (Csa) according to the Koeppen classification, and the annual amount of rainfall reaches 413 mm. The highest mean summer temperature reaches 26 °C. The largest part of the area is covered by Aleppo pine (*Pinus halepensis* Mill.) forests followed by dense and sparse patches of shrublands dominated by Kermes oak (*Quercus coccifera*) and agriculture areas. The mountain is nowadays surrounded by rapidly expanding settlements. During the second part of the twentieth century, several fire events and human pressure led to changes in the vegetation cover and the land cover of the mountain. Several large fires affected the area during the last 20 years, which have destroyed hundreds of residential structures and settlements (Xanthopoulos 2009).

Forest fuel sampling

All the areas in the study site were stratified on vegetation maps according to the dominant vegetation type. All the stratified areas were surveyed on site, and 40 representative locations with typical ("average") fuel conditions for each area were selected based on local forest experts' knowledge. Surface fuel load was estimated with the Brown et al. (1982) method for inventorying surface fuel biomass. Eleven fuel parameters were measured in each location as follows (Brown et al. 1982):

1. The 1-, 10-, 100-, 1000-h and total fuel loads were measured with the transect-line method (four 30-m-long transects). The 1-, 10-, 100- and 1000-h fuels time lag corresponds to plant parts (branches) with diameters of 0.0–0.5, 0.6–2.5, 2.6–7.5 and >7.5 cm, respectively (Brown et al. 1982). A fuel's time lag is defined as the time it takes a fuel particle to reach 2/3's of its way to equilibrium with its local environment. The clip-and-weigh method was used to determine all fuel loads by size category.
2. Foliage load, litter load and depth, and shrub (up to 2.0 m in height) and herbaceous (live and dead) vegetation loads were measured in six 10 m^2 sampling plots with the clip-and-weight method.
3. The height of the shrub and herbaceous vegetation layers was also measured in the sampling plot.

The percentage of the total area covered by each fuel type (shrub herbaceous, litter, etc.) was determined with the line intercept method in the fuel transects (30 m long) that were used for fuel measurements (Bonham 1989). All fuel loads (fuel weight per unit surface area) were expressed on a dry-weight basis. Differences in total fuel loads among the fuel models resulted were tested by performing one-way ANOVA and Duncan's multiple range test.

Fuel mapping

Fuel-type mapping relied on the use of 50 cm orthoimagery produced from natural colour aerial imagery acquired in 2007–2009 under the Hellenic National

Cadastre campaign publicly available on a web mapping service (WMS) (Mallinis et al. 2014). Image segmentation applied to the orthoimagery delineated homogeneous land cover polygons. With the bottom-up segmentation algorithm, embedded within the commercial software Trimble eCognition (version 8.7), individual image pixels were perceived as the initial regions, which were then sequentially merged pairwise into larger ones with the intent of minimizing the heterogeneity of the resulting objects. The sequence of the merging objects, as well the size and shape of the resulting objects, was empirically determined by the user (Mallinis et al. 2008). The poor spectral resolution of the orthoimagery put limitations on the use of automated classification techniques. Therefore, fuel types were identified based on manual visual interpretation procedures of various features on the mosaicked orthoimages based on shade, shape, size, texture and association of features. A minimum mapping unit of 0.1 ha was adopted in the mapping process in order to ensure consistency with the resolution of the digital elevation model used in the fire simulation process.

Future climate simulations

In the current study, output from the regional climate model RACMO2 for both the present and the future period was used. RACMO2 was developed within the framework of the EU project ENSEMBLES (www.ensembles-eu.org) by the Royal Netherlands Meteorological Institute widely known as KNMI. The KNMI-RACMO2 regional climate model (Lenderink et al. 2003) is forced with output from a transient run conducted with the ECHAM5 global climate model. The model uses 40 vertical levels on a horizontal 95 × 85 (lat × lon) grid and has a horizontal resolution of 25 km. The future period simulations of the model are based on the IPCC SRES A1B scenario (Nakicenovic et al. 2000) which provides a good midline estimate for carbon dioxide emissions and economic growth (Alcamo et al. 2007). KNMI-RACMO2 RCM has been extensively validated all over Europe (Mediterranean region also included) in the course of EU project ENSEMBLES (www.ensembles-eu.org). The model was selected among various other models available as was the "best-performing" model in Europe and the Mediterranean based on the ENSEMBLES Deliverable D3.2.2 (http://ensembles-eu.metoffice.com) and on the Christensen et al. (2010) work. According to these publications, KNMI-RACMO2 was found to more accurately simulate both the mean climate and the extremes in Europe and the Mediterranean region. Furthermore, Kostopoulou et al. (2012) have performed a regional evaluation of various models (KNMI-RACMO2 included) for the Balkan Peninsula focusing on climate extremes. According to this study, RACMO2 manages to reproduce patterns of extreme temperature and precipitation with reasonable accuracy when compared to the E-OBS gridded observational dataset. The climatic input data used in the current concern daily values of air maximum temperature, minimum relative humidity, maximum wind speed and the meteorological wind direction. In order to calculate the meteorological direction of the wind, the horizontal and vertical wind components were used. In the current study, 10-year periods were used as these are more suitable for fire and forest managers and practitioners who usually make 10-year forest management plans. Therefore, the period 1991–2000 was considered to be the present-day period and was used as reference for comparison with future projections, namely the decades 2045–2055, 2065–2075 and 2091–2100. As the study area falls between two model grid points in order to have a better representation of the prevailing meteorological conditions, the average of these points was used. At each grid point, the average values for each variable for the period June–September were calculated for each decade. Finally, the mean value of the two grid points for each variable was used.

Fire simulation

Fire behaviour simulations were performed using FlamMap version 5 software in order to provide a spatial and temporal simulation of fire spread and behaviour, integrating the large amount of information on fuels, weather conditions and terrain data (Finney 2006). Simulated wildfire spread and behaviour were performed with the minimum travel time (MTT) algorithm. The MTT algorithm replicates fire growth by Huygens' principle where the growth and behaviour of the fire edge are a vector or wave front (Finney 2002). MTT performance, as it is embedded in FlamMap software, has been recently successfully evaluated and calibrated in the study area by comparing its simulation results against recent real fire events (Mitsopoulos et al. 2013). MTT simulations were conducted by using as input data the digital elevation model (DEM) of the area generated from 20-m interval contour lines, the spatial extent of the fuel models and the fuel parameters values of each model in the study area. A 30 m × 30 m raster input file was created for the fire simulations. Furthermore, the themes required to model crown fire behaviour, including stand height, crown base height and crown bulk density, were obtained from species-specific information available at different spatial scales according to Mitsopoulos and Dimitrakopoulos (2014) study. Stand basal area data of Aleppo pine overstory for estimating crown fuels were obtained by the most recent forest management plan (2010) of the study area.

Wind fields for FlamMap simulations in ASCII grid format were obtained by running a mass consistent model

(WindNinja) (Forthofer 2007), from which wind speed and direction were estimated at 6 m above vegetation height. The data of wind speed and direction were provided as inputs to the WindNinja model, taking into account the outputs of the future climatic projections. Fuel moistures per fuel category in each fuel type found in the area for each examined future climatic periods were estimated by using the specific fuel moisture prediction equations for Mediterranean species, developed by Aguado et al. (2007) and Dimitrakopoulos and Bemmerzouk (2003) for dead and live fuel moisture values, respectively. Heat content and surface area-to-volume ratio values for the fuel types developed were obtained by Dimitrakopoulos and Panov (2001). The duration of all fire simulations was set to 480 min (8 h), since according to the historical fire records, all fires in the region are suppressed within that average period (Dimitrakopoulos 2001), while the ignition point for all simulations was set the starting spot of a large fire which burnt 14,000 ha of the mountain on 21 August 2009.

Concerning the FlamMap simulation parameters, perimeter and distance resolutions were set at 30 m, ensuring a satisfactory resolution level for the projections of fire perimeters and fire behaviour parameters. The outputs resulted from the FlamMap runs were shapefiles of the simulated fire perimeters and ASCII files of the simulated fire behaviour. Managing these outputs in a GIS environment, the following information was obtained: final fire perimeters, time of arrival, rate of spread, rate of fire size growth and fireline intensity. Statistical significant differences in simulation outputs among the four examined periods were obtained by using the Tukey's significance test.

Results

The five fuel models that resulted from the field sampling represent all the major vegetation types of the study area (Table 1). The dense shrublands (maquis) fuel model incorporates maquis with heights up to 2.0 m, a high proportion of foliage load and a substantial part of the fuel load distributed to the large size class, while the sparse shrublands fuel model is characterized by low height and ground cover shrubs. The understory of Aleppo pine forests is mainly composed of shrubs that present reduced fuel load values and height compared to the dense shrublands fuel model and increased values compared to sparse shrublands fuel model. Canopy fuel load, canopy bulk density and canopy base height in Aleppo pine forests presented mean values of 1.02 kg/m^2, 0.12 kg/m^3 and 3.3 m, respectively. The grasslands and the agricultural fields (mainly litter from olive trees) demonstrated limited spatial heterogeneity and are represented by fuel model 4 for grasslands (total fuel load of 4.3 t/ha) and fuel model 5 for agricultural areas (total fuel load of 2.2 t/ha). The variation of total fuel load was low in all fuel models, as suggested by the magnitude of the standard deviation (SD). The total loads of all fuel models were found to be statistically different at (one-way ANOVA and Duncan's multiple range test).

The whole study area is mainly of 6189 ha of shrublands (36 % of the area)—2540 ha of them dense shrublands—and 5148 ha of Mediterranean pines (30 % of the area). Significant part of the area is occupied by agricultural areas (12 % or 2055 ha), while non-fuels and grasslands occupy only 6 ha and 1 % of the study area. The sparse shrublands category is located mainly in the eastern and south-east parts of the area, while dense shrublands occupy the central part of the site. On the other hand, pine stands are found mainly in the west and north parts of Penteli mountain, intermixed with agricultural areas (Fig. 2).

The climatic input data for each variable and decade for both current and future climate are shown in Table 2. The maximum temperature, the minimum relative humidity and the maximum wind speed for the broader Attica region for the present-day period are depicted in Fig. 3. Spatial wind fields for present (2000) and 2100 future periods as resulted from WindNinja analysis are shown in Fig. 4.

Table 1 Fuel models and parameters resulted from field sampling in the study area

Fuel model	Average height (cm)	Fuel load by category (t/ha) Branch diameter (cm)				Live	Litter depth (cm)	Litter weight (t/ha)
		0.0–0.5	0.6–2.5	2.6–7.5	>7.5	Foliage		
Dense shrublands	252	8.7	4.5	3.1	–	6.6	2.4	3.1
Sparse shrublands	142	3.1	0.7	0.3	–	4.2	1.8	2.2
Understory of Aleppo pine forests	109	2.2	1.1	0.6	–	3.1	1.6	2.9
Grasslands	50	3.2	0.9	–	–	–	0.6	1.4
Agricultural areas	40	1.8	0.4	–	–	–	1.6	1.5

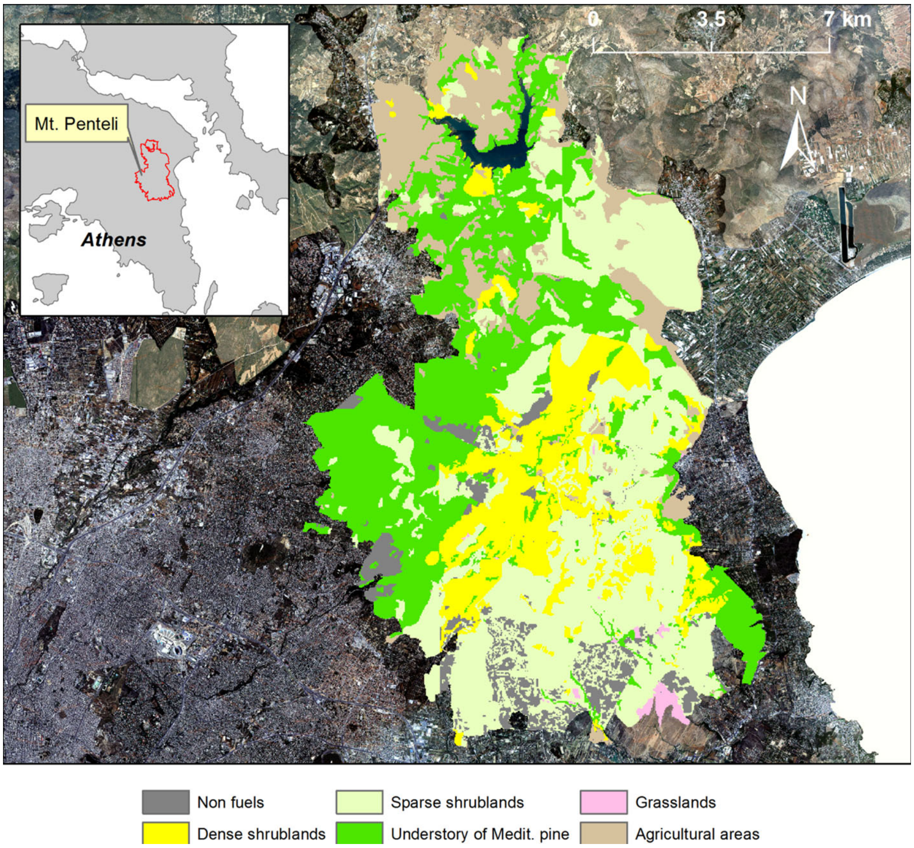

Fig. 2 Spatial explicit distribution of the five forest fuel models of the study area derived upon VHR natural colour orthoimagery

Table 2 Climatic input data used in fire simulations for the four examined periods

	Maximum temperature (°C)	Minimum relative humidity (%)	Maximum wind speed (km/h)	Wind direction (°)
1991–2000	30.1	28	21.7	357
2045–2055	32.0	27	21.7	355
2065–2075	33.5	27	21.7	357
2091–2100	34.2	26	23.0	356

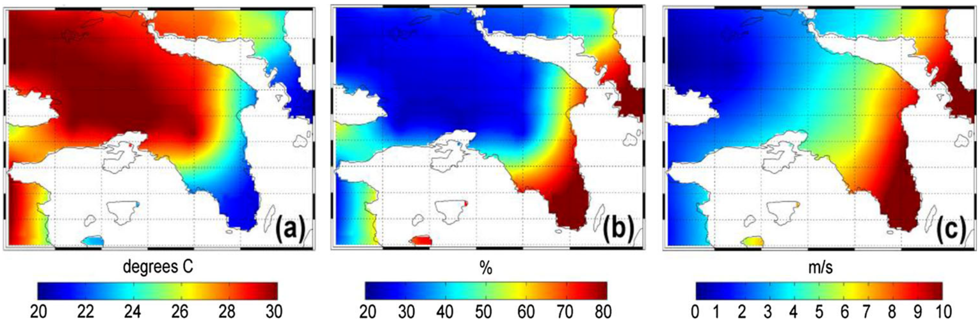

Fig. 3 Maximum temperature **a**, minimum relative humidity **b** and maximum wind speed **c** averaged for the period June–September for the present-day period (1991–2000)

As shown in Table 2, great increases in the maximum temperature of up to 4 °C are expected for the study area by the end of the century as well as small decreases in the minimum relative humidity. Slight increases in the wind speed are projected but only for the last future decade. This is in agreement with a current study for the Greek domain, in which a multi-model ensemble used suggested minor increases in the wind speed during summer period by the end of the century (Bank of Greece 2011). Furthermore, both for the present-day period and for the future periods,

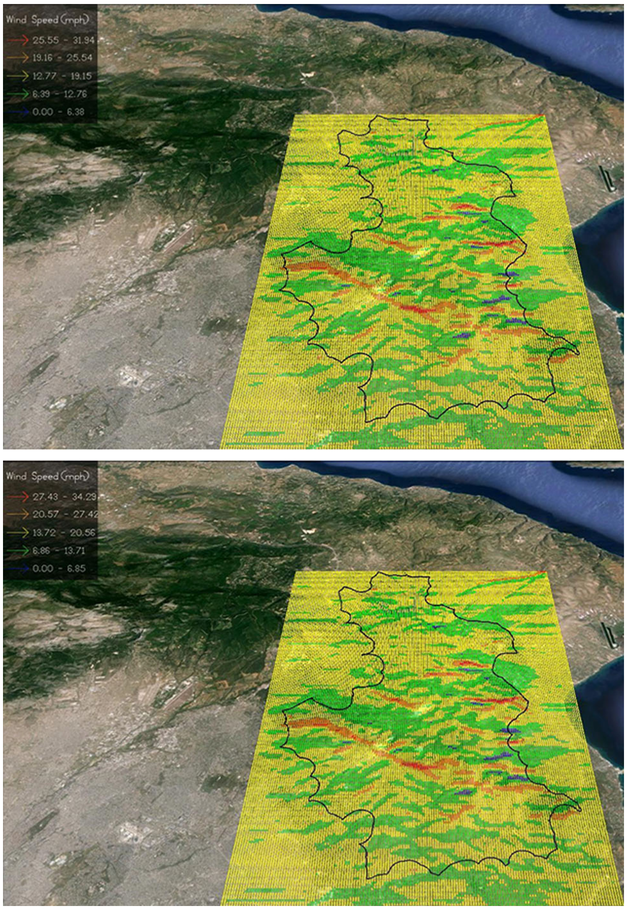

Fig. 4 Wind speed and direction at 6 m above vegetation height for the present day (*upper figure*) and the 2091–2100 period (*lower figure*)

the meteorological wind direction calculated and used in the FlamMap simulations was northern. This is in agreement with the prevailing wind direction during the summer period in the Attica peninsula. Etesian winds with a northerly flow typically blow during the summer and early autumn, especially over the Aegean Sea and eastern continental Greece (including the Attica peninsula) (Kallos et al. 1998; Kotroni et al. 2001).

Figure 5 shows the time of arrival for the 8-h simulation (1-h time step), the fire rate of spread, the fireline intensity and the rate of fire growth per hour resulted from the simulation results. Maximum fire rate of spread reached up to 18 m/min for the present-day period, 20 min/min for the 2045–2055 period, 25 m/min for the 2065–2075 period and 33 m/min for the 2091–2100 future period. Maximum fireline intensities reached up to 15,488 kW/m (mean value: 3516.2 kW/m), 21,312 kW/m (mean value: 5763.1 kW/m), 26,686 kW/m (mean value: 6838.6 kW/m) and 26,747 kW/m (mean value: 6671.3 kW/m) for each period, respectively. Statistical differences among the four periods are presented in Table 3. Analysis of variance (ANOVA) and Tukey's multiple comparison test (95 % confidence level) showed statistical differences among the fire parameter values. The present-day period had the lower fire behaviour parameter values compared to the other periods. However, only the fireline intensity was significantly different among all the periods. Rate of spread presented significant difference only in the 2100 period compared to the other examined periods. This may stem from the fact that wind speed, which heavily affects the rate of spread, presents changes only between the present period and the 2091–2100 future period. The rate of fire growth (burned area per hour) did not show any significant difference among the four examined periods. Final simulated burnt area (fire perimeter) was 3998 ha for the present-day period, 4096 ha for the 2045–2055 period, 4389 ha for the 2065–2075 period and 4512 ha for the 2091–2100 period.

Discussion

The dense shrubland fuel type demonstrated the most severe fire potential in all studied periods due to the heavier fuel load. The grassland and agriculture fuel types produced low-intensity fires due to the reduced fuel load that was comprised of dry fine fuels. As reported by other authors (van Wilgen et al. 1985; Arca et al. 2007; Santoni et al. 2011; Jahdi et al. 2015), Rothermel's fire rate of spread equation as it is embedded to FlamMap's fire simulator has been extensively validated on areas different from those where the models were originally developed and they stated that specific custom model needs to be developed to account for both the fuel characteristics and the high heterogeneity of Mediterranean vegetation. Arca et al. (2007) also suggest that localized, site-specific fuel models give more reliable fire behaviour predictions using FlamMap simulator. Similarly, studies that performed using landscape fire simulation modelling highlight the fact that local-specific fuel data and custom fuel models increase the accuracy of predicted fire behaviour (Miller and Yool 2002). Mitsopoulos et al. (2013) evaluated FlamMap simulator performance and accuracy based on the real fire perimeter of the 2009 large fire event. Their analysis showed that FlamMap predicted correctly 88 % of the total burnt area. Validation of fire simulation accuracy has been also conducted with historical fires and data in other Mediterranean ecosystems with satisfactory results (Arca et al. 2007; Paz et al. 2011). However, these efforts are characterized with high uncertainty due to the fact that it is extremely difficult to obtain accurate fire and weather data of real wildfires (Paz et al. 2011). Fire behaviour values resulted from the simulations were found similar to values reported in typical Mediterranean ecosystems

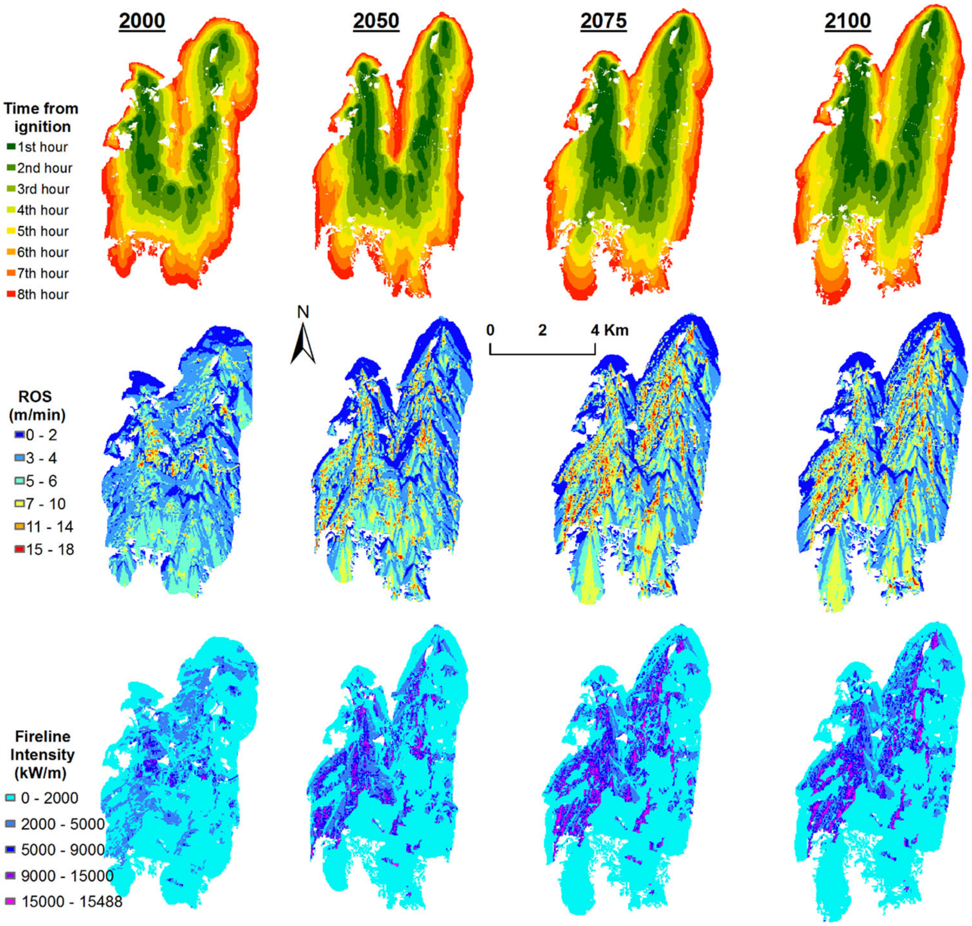

Fig. 5 Time of arrival (*upper row*), rate of spread (*middle row*) and fireline intensity (*lower row*) for the present day and for the 2045–2055, 2065–2075 and 2091–2100 periods

Table 3 Mean fire behaviour parameter values of each examined period

Climate scenario	Rate of spread (m/min)	Fireline intensity (kW/m)	Rate of fire growth (ha/hr)
1991–2000	9^{a} (3.1)	3516.2^{a} (265)	499.8^{a}
2045–2055	10^{a} (3.6)	5763.1^{b} (411)	512.1^{a}
2065–2075	12.5^{a} (5.6)	6838.6^{c} (485)	548.1^{a}
2091–2100	16.1^{b} (9.3)	6671.3^{d} (490)	563.9^{a}

Test of significance was performed by Tukey's multiple comparison test, at $p = 0.05$

Values with the same letter are not significantly different. Standard deviation is shown in parenthesis

(Dimitrakopoulos 2002; Arca et al. 2007). Statistical significant differences in fire behaviour parameters were mainly observed during the 2091–2100 future period compared to the present-day period. This could be expected, since the slight increase in wind speed values during the last future period (2091–2100) resulted on more severe fire behaviour. Wind speed is the main factor affecting fire behaviour in natural ecosystems (Pyne et al. 1996). Fire behaviour models used in this simulation are semiempirical. Nevertheless, they have been tested in high-intensity experimental fires with satisfactory results (Stocks et al. 2004). New landscape fire modelling efforts use MTT algorithm in order to assess spatial wildfire risk and high-value resources assets exposure to fire in Mediterranean fuel complexes (Arca et al. 2012; Salis et al. 2013; 2014). However, that approach is suitable for assessing the important scale-related factors that drive wildfire likelihood at multiple ignition points, does not present essential inputs (e.g. time of arrival, rate of spread, etc.) for fire suppression strategies, such as the use, distribution and allocation of available firefighting resources, fire towers and water tank constructions.

Visual image interpretation is one of the most commonly used techniques for the reliable and accurate mapping of homogeneous land cover, vegetation and fuel types, with high costs associated with this classification approach.

Automated segmentation as preliminary step can significantly reduce the time and human resources needed in this approach (Arroyo et al. 2008, Mallinis et al. 2014). This preliminary step of image segmentation even in poor spectral resolution images can facilitate assignment of image segments to fuel types, balancing costs and precision, particularly when working at fine scales, and is widely employed by governmental agencies (Arroyo et al. 2008).

This study represents one of the first approaches for characterizing fire behaviour within the context of climate change with a modelling approach at local scale in a complex-fuel Mediterranean landscape. Although the choice of a sole study area still not be sufficient to represent the complexity of the fire behaviour in the Mediterranean context, the broad gradient of conditions exist in the study area allows to highlight the benefits of using fire spread models for simulating wildfires under a changing climate in the region. Arca et al. (2012) used the MTT algorithm to simulate fire behaviour under climate change by using a regional climate model with a spatial resolution of 25 km. Their analysis showed an increase in the number of days with extreme fire weather conditions, while fire behaviour values for potential extreme fire days are expected to experience a small decrease, most likely because of the predicted decrease in the wind intensity. In a similar study, Amiro et al. (2001) found that increases in fire behaviour potential could considerably reduce suppression capability in the future and lead to greater area burned by wildfires in Canadian ecosystems. Syphard et al. (2011) have planned and evaluated fuel treatment years in advance by using future fire behaviour estimates based on climate change projections.

Future work is essential to address several key components such as the new climate change emission scenarios released by the Intergovernmental Panel on Climate Change (Moss et al. 2010) which are integrated into existing and new climate models and will produce a new suite of output projections for managing future extreme events and disasters for the remainder of the twenty-first century. Although the RCM we have used has been proven to be the best performer for our domain of study, there is still a degree of uncertainty in our projections as we have used a single model instead of an ensemble mean of RCMs and the future period projections of the model are based only on a single emissions scenario. Furthermore, one of the primary uncertainties in modelling future fire behaviour is the vegetation landscape change. It should be noted that the current approach does not account for possible future changes in fuel/vegetation spatial extent. A key next step is to model future vegetation/fuels utilizing an established vegetation state-and-transition model and then classifying modelled vegetation into fuel models.

Conclusions

This study investigated the potential impact of climate change to fire behaviour values in a typical ecosystem in Eastern Mediterranean. Localized fuel models have been developed for a Mediterranean study area based on extensive fieldwork. Site-specific fuel models should be adopted for providing more reliable spatial fire behaviour predictions, especially in the case of the fragmented and heterogeneous Mediterranean landscape. FlamMap simulations resulted in the most intense fires in the dense shrubland fuel type under the 2091–2100 future period. Furthermore, fireline intensity and rate of fire growth maps were derived, representing the fire suppression difficulty on a spatial scale.

The proposed methodology presents an integration of fuel mapping, projected future climate change and fire behaviour simulation for fire management planning across the landscape. Outputs created from this study will respond to climate change and can be used as valuable components of judicial long-term wildland fire prevention and management in Greece. Overall, the fire behaviour maps generated in this study allowed for quantitative assessment of the future climate change on the expected fire behaviour at a scale that is not possible by other approaches, like, for instance, analysing ignition data and fire occurrence without taking into account fire spread and intensity at landscape level. This work can provide useful guidelines to firefrightening organizations to identify fire suppression difficulty areas and to select the most appropriate fire suppression means and tactics to protect human communities and natural ecosystems from wildfire losses.

Further studies of actual fire behaviour in the field are necessary in order to validate and calibrate the outcomes of the FlamMap fire behaviour simulators, especially in the Mediterranean vegetation conditions. Additionally, the potential future change of fuel/vegetation spatial extent and fuel load values could be further examined in order to allow researchers and land managers to address potential future changes to fire severity and regime and shift in fire behaviour distributions and estimate any additional firefighting resources allocation, future carbon emission released from wildfires and the long-term ecological restoration of degraded ecosystems/landscapes after wildfires.

Acknowledgments This work was partially supported by the European Community's Seventh Framework Programme (2010–2013) FUME: Forest fire under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world (Grant Agreement No. 243888). Regional climate model data were provided by the EU FP6 project ENSEMBLES (www.ensembles-eu.org). We thank the Guest Editor Prof. Marco Bindi and the three anonymous reviewers whose insightful comments helped to substantially improve this manuscript.

References

Aguado I, Chuvieco E, Boren R, Nieto H (2007) Estimation of dead fuel moisture content from meteorological data in Mediterranean areas. Applications in fire danger assessment. Int J Wildland Fire 16:390–397. doi:10.1071/WF06136

Alcamo J, Moreno JM, Nováky B, Bindi M, Corobov R, Devoy RJN, Giannakopoulos C, Martin E, Olesen JE, Shvidenko A (2007) Europe Climate Change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working Group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 541–580

Amatulli G, Camia A, San-Miguel-Ayanz J (2013) Estimating future burned areas under changing climate in the EU-Mediterranean countries. Sci Total Environ 450–451C:209–222. doi:10.1016/j.scitotenv.2013.02.014

Amiro B, Stocks B, Alexander M, Flannigan M, Wotton B (2001) Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int J Wildland Fire 10:405–413. doi:10.1071/WF01038

Andrews P, Heinsch F, Schelvan L (2011). How to generate and interpret fire characteristics charts for surface and crown fire behavior. USDA, Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-GTR-253. Fort Collins, CO

Arca B, Duce P, Laconi M, Pellizzaro G, Salis M, Spano D (2007) Evaluation of FARSITE simulator in Mediterranean maquis. Int J Wildland Fire 16:563–572. doi:10.1071/WF06070

Arca B, Pellizzaro G, Duce P, Salis M, Bacciu V, Spano D, Ager A, Finney M, Scoccimarro E (2012) Potential changes in fire probability and severity under climate change scenarios in Mediterranean areas. In: Spano D, Bacciu V, Salis M, Sirca C (eds) Modelling fire behaviour and risk. Nuova Stampa color, Sassari, pp 92–98

Arroyo L, Pascual C, Manzanera J (2008) Fire models and methods to map fuel types: the role of remote sensing. For Ecol Manag 256:1239–1252. doi:10.1016/j.foreco.2008.06.048

Bank of Greece Study (2011) The environmental, economic and social impacts of climate change in Greece

Bedia J, Herrera S, Camia A, Moreno J, Gutiérrez J (2013) Forest fire danger projections in the Mediterranean using ENSEMBLES regional climate change scenarios. Clim Change 122:185–199. doi:10.1007/s10584-013-1005-z

Bonham C (1989) Measurements for terrestrial vegetation. Wiley, New York

Brown J, Oberheu R, Johnston C (1982) Handbook for inventorying surface fuels and biomass in the Interior West. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-129. Ogden

Brown J, Hall L, Westerling L (2004) The impact of twenty-first century climate change on wildland fire danger in the Western United States: an application perspective. Clim Change 62:365–388. doi:10.1023/B:CLIM.0000013680.07783.de

Christensen JH, Kjellström E, Giorgi F, Lenderink G, Rummukainen M (2010) Weight assignment in regional climate models. Clim Res 44:179–194. doi:10.3354/cr00916

Collins B, Omi P, Chapman P (2006) Regional relationships between climate and wildfire burned area in the Interior West, USA. Can J For Res 36:699–709. doi:10.1139/x05-264

de Groot W, Bothwell P, Carlsson D, Logan K (2003) Simulating the effects of future fire regimes on western Canadian boreal forests. J Veg Sci 14:355–364. doi:10.1111/j.1654-1103.2003.tb02161.x

Dimitrakopoulos A (2001) PYROSTAT—a computer program for forest fire data inventory and analysis in Mediterranean countries. Environ Model Softw 16:351–359. doi:10.1016/S1364-8152(00)00088-8

Dimitrakopoulos A (2002) Mediterranean fuel models and potential fire behaviour in Greece. Int J Wildland Fire 11:127–130. doi:10.1071/WF02018

Dimitrakopoulos A, Bemmerzouk A (2003) Predicting live herbaceous moisture content from a seasonal drought index. Int J Biometeorol 47:73–79. doi:10.1007/s00484-002-0151-1

Dimitrakopoulos A, Mitsopoulos I (2006) Thematic report on forest fires in the Mediterranean Region. In: Vuorinen A (ed) Global forest resources assessment 2005, Forest Fire Management Working Paper 8, FAO

Dimitrakopoulos A, Panov P (2001) Pyric properties of some dominant Mediterranean vegetation species. Int J Wildland Fire 10:23–27. doi:10.1071/WF01003

Dimitrakopoulos A, Vlahou M, Anagnostopoulou C, Mitsopoulos I (2011) Impact of drought on wildland fires in Greece; Implications of climatic change? Clim Change 109:331–347. doi:10.1007/s10584-011-0026-8

ENSEMBLES Deliverable D3.2.2: RCM-specific weights based on their ability to simulate the present climate, calibrated for the ERA40-based simulations (http://ensembles-eu.metoffice.com)

European Commission (2011) Forest fires in Europe 2010. Official Publication of the European Communities, EUR 24910

Finney M (2002) Fire growth using minimum travel time methods. Can J For Res 32:1420–1424. doi:10.1139/X02-068

Finney M (2006) An overview of FlamMap modeling capabilities. In: Andrews P, Butler B (eds.) Fuels Management—how to measure success. In: Conference Proceedings. RMRS-P-41. pp 213–219

Flannigan M, Stocks B, Wotton M (2000) Climate change and forest fires. Sci Total Environ 262:221–229. doi:10.1016/S0048-9697(00)00524-6

Flanningan M, Van Wagner C (1991) Climate change and wildfire in Canada. Can J For Res 21:66–72. doi:10.1139/x91-010

Forthofer J (2007) Modeling wind in complex terrain for use in fire spread prediction Fort Collins, CO. Colorado State University, Ph.D.Thesis

Fried J, Gilless W, Riley T, Moody C, Simon K, Hayhoe M, Moritz M, Stephens S, Torn M (2008) Predicting the effect of climate change on wildfire behaviour and initial attack success. Clim Change 87:193–213. doi:10.1007/s10584-007-9360-2

Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou E, Goodess C (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. Global Planet Change 68:209–224. doi:10.1016/j.gloplacha.2009.06.001

Giannakopoulos C, Kostopoulou E, Varotsos KV, Tziotziou K, Plitharas A (2011) An integrated assessment of climate change impacts for Greece in the near future. Reg Environ Change 11(4):829–843. doi:10.1007/s10113-011-0219-8

Giannakopoulos C, Le Sager P, Moriondo M, Bindi M, Karali A, Hatzaki M, Kostopoulos E (2012) Comparison of fire danger indices in the Mediterranean for present day conditions. i-Forest 5:197–203. doi:10.3832/ifor0622-005

Good P, Morioindo M, Giannakopoulos C, Bindi M (2008) The meteorological conditions associated with extreme fire risk in Italy and Greece: relevance to climate model studies. Int J Wildland Fire 17:155–165. doi:10.1071/WF07001

Haight R, Fried J (2007) Deploying wildland fire suppression resources with a scenario-based standard response model. Inf Syst Oper Res 44:31–39. doi:10.3138/infor.45.1.31

Hall B, Brown J (2003) A comparison of precipitation and drought indices related to fire activity in the US. In: Proceedings of the 5th symposium on fire and forest meteorology. American Meteorological Society, Orlando FL

Herrera S, Bedia J, Gutierrez JM, Fernandez J, Moreno J (2013) On the projection of future fire danger conditions with various instantaneous/mean-daily data sources. Clim Change 118:827–840. doi:10.1007/s10584-012-0667-2

Hewitson B, Janetos A, Carter T, Giorgi F, Jones R, Kwon W, Mearns, L, Schipper E, van Aalst M (2014). Regional context. In: Barros V, Field C, Dokken D, Mastrandrea M, Mach K, Bilir K, Chatterjee M, Ebi K, Estrada Y, Genova R, Girma B, Kissel E, Levy A, MacCracken S, Mastrandrea P, White L (eds) Climate Change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of working Group II to the fifth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, UK and New York, pp 1133–1197

Jahdi R, Salis M, Darvishsefat A, Mostafavi M, Alcasena F, Etemad V, Lozano O, Spano D (2015) Calibration of FARSITE simulator in northern Iranian forests. Nat Hazards Earth Syst 15:443–459. doi:10.5194/nhess-15-443-2015

Kallos G, Kotroni V, Lagouvardos K, Papadopoulos A (1998) On the long range transport of air pollutants from Europe to Africa. Geophys Res Lett 25:619–622. doi:10.1029/97GL03317

Karali A, Hatzaki M, Giannakopoulos C, Roussos A, Xanthopoulos G, Tenentes V (2014) Sensitivity and evaluation of current fire risk and future projections due to climate change: the case study of Greece. Nat Hazards Earth Syst Sci 14:143–153. doi:10.5194/nhess-14-143-2014

Kostopoulou E, Giannakopoulos C, Hatzaki M, Tziotziou K (2012) Climate extremes in the NE Mediterranean: assessing the E-OBS dataset and regional climate simulations. Clim Res 54:249–270. doi:10.3354/cr01110

Kotroni V, Lagouvardos K, Lalas D (2001) The effect of the island of Crete on the Etesian winds over the Aegean Sea. Q J R Meteorol Soc 127:1917–1937. doi:10.1002/qj.49712757604

Koutsias N, Xanthopoulos G, Founda D, Xystrakis F, Nioti F, Pleniou M, Mallinis G, Arianoutsou M (2013) On the relationships between forest fires and weather conditions in Greece from long-term national observations (1894–2010). Int J Wildland Fire 22:493–507. doi:10.1071/WF12003

Lenderink G, van den Hurk B, van Meijgaard E, van Ulden A, Cuijpers J (2003) Simulation of present-day climate in RACMO2: first results and model developments. KNMI Technical Report 252

Maingi J, Henry M (2007) Factors influencing wildfire occurrence and distribution in eastern Kentucky, USA. Int J Wildland Fire 16:23–33. doi:10.1071/WF06007

Mallinis G, Mitsopoulos I, Dimitrakopoulos A, Gitas I, Karteris M (2008) Integration of local scale fuel type mapping and fire behaviour prediction using high spatial resolution imagery. IEEE J Sel Topics Appl Earth Observ 4:230–238. doi:10.1109/JSTARS.2008.2011298

Mallinis G, Koutsias N, Arianoutsou M (2014) Monitoring land use/land cover transformations from 1945 to 2007 in two peri-urban mountainous areas of Athens metropolitan area, Greece. Sci Total Environ 490:262–278. doi:10.1016/j.scitotenv.2014.04.129

Miller J, Yool S (2002) Modeling fire in semi-desert grassland/oak woodland: the spatial implications. Ecol Model 153:229–245. doi:10.1016/S0304-3800(02)00015-7

Mitsopoulos I, Dimitrakopoulos A (2014) Estimation of canopy fuel characteristics of Aleppo pine (*Pinus halepensis* Mill.) forests in Greece based on common stand parameters. Eur J For Res 133:73–79. doi:10.1007/s10342-013-0740-z

Mitsopoulos I, Mallins G, Arianoutsou M (2013) Assessing fire behaviour simulation accuracy with customized fuel models in Mediterranean ecosystems using real-world historical fire data. In: Proceedings of the 16th Hellenic Forestry Conference. 6–9 October 2013. Thessaloniki, Greece, pp 164–174

Moreira F, Vaz P, Catry F, Silva J (2009) Regional variations in wildfire susceptibility of land-cover types in Portugal: implications for landscape management to minimize fire hazard. Int J Wildland Fire 18:563–574. doi:10.1071/WF07098

Moreira F, Viedma O, Arianoutsou M, Curt T, Koutsias N, Rigolot F, Barbati A, Corona P, Vaz P, Xanthopoulos G, Mouillot F, Bilgili E (2011) Landscape—wildfire interactions in southern Europe: implications for landscape management. J Environ Manage 92:2389–2402. doi:10.1016/j.jenvman.2011.06.028

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JF, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756

Nakicenovic N, Alcamo J, Davis D, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Yong Jung T, Kram T, La Rovere E, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) Special REPORT ON EMISSION SCENARIOS. Working group III of the intergovernmental panel on climate change (IPCC), Cambridge University Press, Cambridge

Pausas J (2004) Changes in fire and climate in the Eastern Iberian Peninsula (Mediterranean Basin). Clim Change 63:337–350. doi:10.1023/B:CLIM.0000018508.94901.9c

Pausas J, Llovet J, Rodrigo A, Vallejo R (2008) Are wildfires a disaster in the Mediterranean basin?—a review. Int J Wildland Fire 17:713–723. doi:10.1071/WF07151

Paz S, Carmel Y, Jahshan F, Shoshany M (2011) Post-fire analysis of pre-fire mapping of fire risk: a recent case study from Mt. Carmel (Israel). For Ecol Manage 262:1184–1188. doi:10.1016/j.foreco.2011.06.011

Piñol J, Terradas J, Lloret F (1998) Climate warming, wildfire hazard and wildfire occurrence in coastal Eastern Spain. Clim Change 38:345–357. doi:10.1023/A:1005316632105

Pyne S, Andrews P, Laven R (1996) Introduction to wildland fire, 2nd edn. Wiley, New York-Chichester

Salis M, Ager A, Arca B, Finney M, Bacciu V, Duce P, Spano D (2013) Assessing exposure of human and ecological values to wildfire in Sardinia, Italy. Int J Wildland Fire 22:549–565. doi:10.1071/WF11060

Salis M, Ager A, Finney M, Arca B, Spano D (2014) Analyzing spatiotemporal changes in wildfire regime and exposure across a Mediterranean fire-prone area. Nat Hazards 71:1389–1418. doi:10.1007/s11069-013-0951-0

Santoni P, Filippi J, Balbi J, Bosseur F (2011) Wildland fire behaviour case studies and fuel models for landscape-scale fire modeling. J Combust 2011, Article ID 613424. doi:10.1155/2011/613424

Stocks B, Alexander M, Wotton B, Stefner C, Flannigan M, Taylor S, Lavoie N, Mason J, Hartley G, Maffey M, Dalrymple G, Blake T, Cruz M, Lanoville R (2004) Crown fire behaviour in a northern jack pine–black spruce forest. Can J For Res 34:1548–1560. doi:10.1139/x04-054

Syphard A, Keeley J, Brennan T (2011) Factors affecting fuel break effectiveness in controlling large fires on the Los Padres National Forest, California. Int J Wildland Fire 20:764–775. doi:10.1071/WF10065

Torn M, Fried J (1992) Predicting the impacts of global warming on wildland fire. Clim Change 21:257–274. doi:10.1007/BF00139726

Turco M, Llasat M-C, von Hardenberg J, Provenzale A (2014) Climate change impacts on wildfires in a Mediterranean environment. Clim Change 125:369–380. doi:10.1007/s10584-014-1183-3 van Wilgen B, le Maitre D, Kruger F (1985) Fire modeling in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. J Appl Ecol 22:207–216. doi:10.2307/2403338

Vázquez A, Moreno J (1993) Sensitivity of fire occurrence to meteorological variables in Mediterranean and Atlantic areas of Spain. Landsc Urban Plan 24:129–142. doi:10.1016/0169-2046(93)90091-Q

Wotton B, Martell D, Logan K (2003) Climate change and people-caused forest fire occurrence in Ontario. Clim Change 60:275–295. doi:10.1023/A:1026075919710

Xanthopoulos G (2009) Wildland fires: mediterranean. Crisis Response J 5:50–51

Yoder J (2004) Playing with fire: endogenous risk in resource management. Am J Agric Econ 4:933–948. doi:10.1111/j.0002-9092.2004.00644.x

Terms and Conditions

Springer Nature journal content, brought to you courtesy of Springer Nature Customer Service Center GmbH (“Springer Nature”).

Springer Nature supports a reasonable amount of sharing of research papers by authors, subscribers and authorised users (“Users”), for small-scale personal, non-commercial use provided that all copyright, trade and service marks and other proprietary notices are maintained. By accessing, sharing, receiving or otherwise using the Springer Nature journal content you agree to these terms of use (“Terms”). For these purposes, Springer Nature considers academic use (by researchers and students) to be non-commercial.

These Terms are supplementary and will apply in addition to any applicable website terms and conditions, a relevant site licence or a personal subscription. These Terms will prevail over any conflict or ambiguity with regards to the relevant terms, a site licence or a personal subscription (to the extent of the conflict or ambiguity only). For Creative Commons-licensed articles, the terms of the Creative Commons license used will apply.

We collect and use personal data to provide access to the Springer Nature journal content. We may also use these personal data internally within ResearchGate and Springer Nature and as agreed share it, in an anonymised way, for purposes of tracking, analysis and reporting. We will not otherwise disclose your personal data outside the ResearchGate or the Springer Nature group of companies unless we have your permission as detailed in the Privacy Policy.

While Users may use the Springer Nature journal content for small scale, personal non-commercial use, it is important to note that Users may not:

1. use such content for the purpose of providing other users with access on a regular or large scale basis or as a means to circumvent access control;
2. use such content where to do so would be considered a criminal or statutory offence in any jurisdiction, or gives rise to civil liability, or is otherwise unlawful;
3. falsely or misleadingly imply or suggest endorsement, approval , sponsorship, or association unless explicitly agreed to by Springer Nature in writing;
4. use bots or other automated methods to access the content or redirect messages
5. override any security feature or exclusionary protocol; or
6. share the content in order to create substitute for Springer Nature products or services or a systematic database of Springer Nature journal content.

In line with the restriction against commercial use, Springer Nature does not permit the creation of a product or service that creates revenue, royalties, rent or income from our content or its inclusion as part of a paid for service or for other commercial gain. Springer Nature journal content cannot be used for inter-library loans and librarians may not upload Springer Nature journal content on a large scale into their, or any other, institutional repository.

These terms of use are reviewed regularly and may be amended at any time. Springer Nature is not obligated to publish any information or content on this website and may remove it or features or functionality at our sole discretion, at any time with or without notice. Springer Nature may revoke this licence to you at any time and remove access to any copies of the Springer Nature journal content which have been saved.

To the fullest extent permitted by law, Springer Nature makes no warranties, representations or guarantees to Users, either express or implied with respect to the Springer nature journal content and all parties disclaim and waive any implied warranties or warranties imposed by law, including merchantability or fitness for any particular purpose.

Please note that these rights do not automatically extend to content, data or other material published by Springer Nature that may be licensed from third parties.

If you would like to use or distribute our Springer Nature journal content to a wider audience or on a regular basis or in any other manner not expressly permitted by these Terms, please contact Springer Nature at

onlineservice@springernature.com