Mapping fire behaviour in a Mediterranean landscape under different future climate change scenarios

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Abstract

Purpose: The aim of this study was to investigate the potential effect of different future climate scenarios on fire behaviour for an area in Eastern Mediterranean.

Methods: We applied the Minimum Travel Time (MTT) fire simulation algorithm by using the FlamMap software to characterize potential response of fire behaviour to a range of future climate scenarios. Site specific fuel models of the study area were created by measuring in the field fuel parameters in representative natural fuel complexes, while the spatial extent of the different fuel types characterized by heterogeneous vegetation was determined using photointerpretation procedures of large scale natural orthophotographs. Climatic data and future climate change projections were obtained from the high resolution regional climate model RACMO2-KNMI.

Results: The results consisted of simulated spatially explicit fire behavior parameters of the present climate and three future summer periods of 2050, 2070 and 2100, under the A1B emissions scenario. Statistical significance differences in simulation outputs among the four scenarios were obtained by using the Tukey's significance test.

Conclusions: The results of this study can be used as valuable components of decision support systems for long-term predictions of fire behaviour potential and contribute to judicial wildland fire suppression and management in Greece.

Keywords: fire behaviour, climate change scenarios, landscape fire modeling, Mediterranean ecosystems.

Introduction

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. Both the number and the average size of large fires have shown an increasing trend over the last several decades causing extensive economic and ecological losses and often human casualties [1]. The development of appropriate fire suppression strategies for wildland fires is complex. Fire managers are required to consider and balance threats to multiple socioeconomic and environmental resources and need the ability to identify, in real time, the likelihood that wildfire will affect valuable resources. Additionally, they need to understand where aggressive fire suppression is required to protect resource values and when fire may be allowed to burn to protect and enhance ecosystem values [2]. The deployment of suppression resources requires consideration of multiple decision factors such as potential fire behavior, topography, firefighter safety and exposure, transportation logistics, resource availability, and productivity. This decision-making environment is characterized by great uncertainty. The difficulties are especially prevalent with respect to potential fire behavior, the effects of fire on valued resources, relative priorities across valued resources and suppression efficiency [3].

Greece is considered a ''hot spot'' for fire studies, not only because of its high sensitivity to changes in recent decades such as processes of rural depopulation, land abandonment and reduction of traditional forest use 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 [4-6]. Fire statistics show a significant increase in both the number of wildfires and area burned in Greece. The number of fires doubled and the area burned tripled during the last years 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, etc. [1]. Increase of area burned demonstrates that the last years occur in a more severe mode in terms of fire behavior parameters, such as fire size, fire rate of spread and fireline intensity, thus creating major difficulties in fire suppression efficiency.

Recently, there is much consideration about the relationship between climatic change and fire occurrence, globally. One way to analyze this relationship is by using raw meteorological data [7-8]. Moreover, drought indices [9-12], fire weather index systems [13] and Global Circulation Models (GCMs) [14-19] have also been used for this purpose. The primary source of information for understanding the climate and climate change is the Global Climate Models (GCMs), which simulate the dynamics and the physics of the climate components, including the atmosphere and the ocean, for different forcings of the system, as given by future emission scenarios [20]. However, several difficulties prevent from the direct application of GCM outputs to local climate studies, particularly their coarse horizontal resolution, which does not properly represent local climate features. In order to fill this gap, regional climate models (RCMs) were developed as a form of dynamical downscaling. In these models the GCM outputs are used to provide boundary conditions to other models running at a higher resolution, providing a higher spatial resolution of local topography ($0.5° \times 0.5°$ resolution) and a more realistic simulation of fine scale atmospheric features. Current studies have proven the suitability and applicability of regional climate models to regional studies concerning wildfire risk [21-23] and climate change impact studies [24-25]. However, the effects and the possible relationship between climatic change and fire behavior parameters has been limited studied due to the difficulties in obtaining high resolution climatic and fuel data as required in spatial fire modeling studies [26-27].

The main objective of this study is to investigate the potential effect of different future climate scenarios on fire behaviour for an area in Eastern Mediterranean by employing fine scale future climate change scenarios and landscape fire behaviour modelling.

Methodology

Study area

Mt.Penteli is situated 30 km northeast of Athens and the study area covers 10300 hectares (Figure 1). The anaglyph in general is abrupt while it reaches an altitude of 1200m in the centre of the site. In the East-South East parts of the area, the mild slopes and the low elevation, favored traditionally agricultural activities. Geologically, the area belongs to the Attiko-Cyclades geotectonic zone. The parent rock materials are mainly limestone and schists and a small part is covered by sedimentary formations. The slope gradient is 15%–30%. The climate is characterized as Mediterranean type (Csa) according to Koeppen classification. The annual amount of rainfall is 413 mm and the dry period has an average duration of 5–6 months, lasting from April to September. Extended woodlands found in the area over the 50s and 60s were replaced with areas of low vegetation and tree-covered patches as a result of the recurrent large fires. The ecosystem is dominated mainly by Aleppo pine (*Pinus halepensis* Mill.) with a shrub understory of maquis species and transitional woodland-shrub (which occupied approximately 16% of the landscape) followed by sclerophyllous vegetation areas.

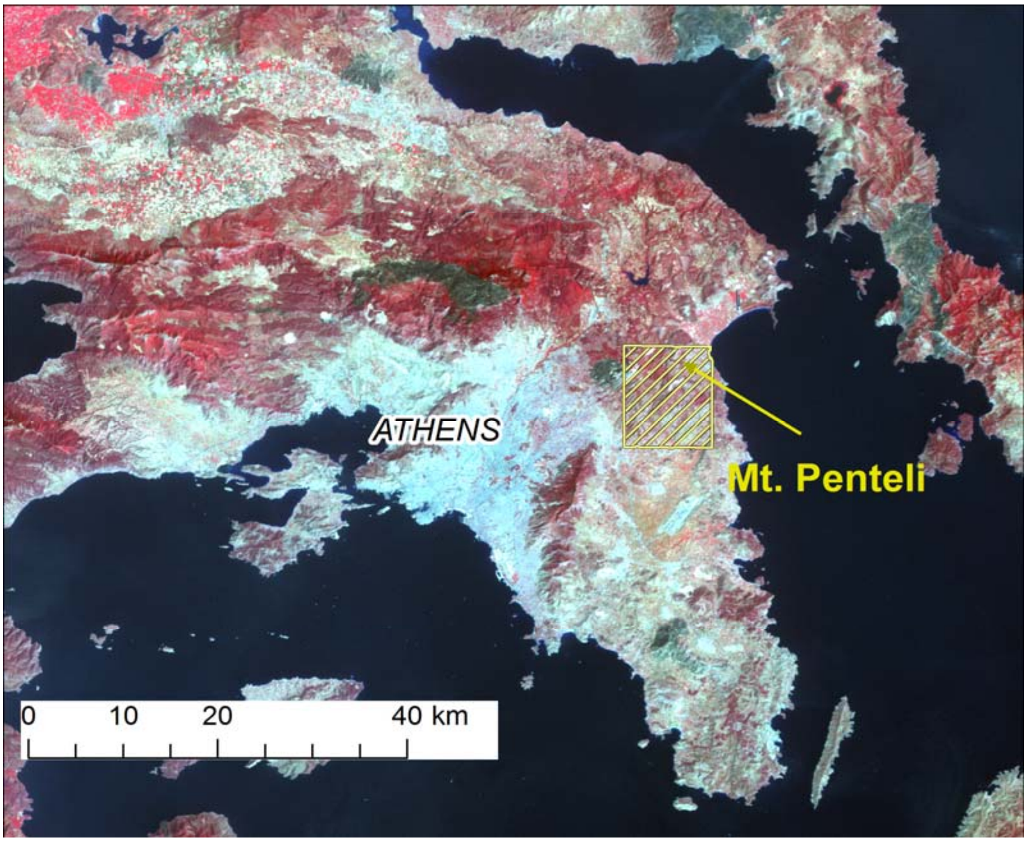

Figure 1. Study area

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 10 representative locations with typical ("average") fuel conditions for each area were selected. Surface fuel load was estimated with the Brown et al., [28] methods for inventorying surface fuel biomass. Eleven fuel parameters were measured in each location as follows:

• The 1 h, 10 h, 100 h, 1000 h, and total fuel loads were measured with the transect-line method (four 30-m long transects)

• Foliage load, litter load and depth, shrub (up to 2.0 m height) and herbaceous (live and dead) vegetation loads were measured in six 10 m2 sampling plots with the clip and weight method.

• The height of the shrub and herbaceous vegetation layers were also measured in the sampling plot.

The 1-h, 10-h, 100-h, and 1000-h fuels correspond to plant parts (branches) with diameters of 0.0–0.5, 0.6–2.5, 2.6–7.5 cm and >7.5 cm, respectively [28]. Clip-and-weigh method was used to determine all fuel loads by size category. The percentage of the total area covered by each fuel type (shrub herbaceous, duff, etc.) were determined with the line intercept method in the fuel transects (30-m long) that were used for fuel measurements [29]. All fuel loads (fuel weight per unit surface area) were expressed on a dry-weight basis.

Forest fuel mapping

Fuel type categories were reconstructed based on b/w aerial photographs on a scale of 1:30000 acquired in 2000, provided by the Hellenic Military Geographical Service. The images were radiometrically corrected prior to the mosaic process to adjust black and white tonal variation by using an empirical linear spectral normalization technique [30]. Due to the poor spectral resolution of the grey scaled aerial photos that limit the use of automated, fuel type categories were identified based on visual stereoscopic photointerpretation of panchromatic aerial photographs.

Future climate scenarios

In the current study present and future climatic output from the regional climate model RACMO2 was used. The model has been developed within the framework of the EU project ENSEMBLES (www.ensembles-eu.org). RACMO2 was provided by the Royal Netherlands Meteorological Institute widely known as KNMI. The KNMI- RACMO2 regional climate model [31] is forced with output from a transient run conducted with the ECHAM5 Global Climate Model. The model uses 40 vertical levels on a horizontal 95x85 (lat x lon) grid and has a horizontal resolution of 25km. The future period simulations of the model are based on the IPCC SRES A1B scenario [32] which provides a good midline estimate for carbon dioxide emissions and economic growth [33]. The selection of this specific model was based on an assessment performed within the ENSEMBLES project. All the models' ability to simulate the present climate was assessed and KNMI-RACMO2 was found to more accurately simulate climate and extremes for the Mediterranean region.

The climatic input data used 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.

Fire modeling

Fire behavior simulations were performed using FlamMap ver. 5 software in order to provide a spatial and temporal simulation of fire spread and behavior, integrating the large amount of information on fuels, weather conditions, and terrain data [34]. Simulated wildfire spread and behavior was performed with the Minimum Travel Time (MTT) algorithm. The MTT algorithm replicates fire growth by Huygens'principle where the growth and behavior of the fire edge is a vector or wave front [35]. MTT simulations were conducted by using as input data the Digital Terrain Model (DTM) of the area, the spatial extent of the fuel models and the fuel parameters values of each model in the study area. A 30 m x 30 m raster input files was created for the fire simulations. Furthermore, the themes required to model crown fire behavior, 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 [36] study.

Wind fields for FlamMap simulations in ASCII grid format were obtained by running a mass consistent model (WindNinja) [37], 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 models. Fuel moistures per fuel category in each fuel type found in the area for each examined future climatic scenario were estimated by using the fuel moisture prediction equations developed by Aguada et al [38] and Dimitrakopoulos and Bemmerzouk [39] 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 [40]. The duration of all fire scenarios was set to 480 minutes (8 hours), since according to the historical fire records all fires in the region are suppressed within that average period [41], while the ignition point was for all scenarios was set the starting spot of a large fire which burnt large area of the mountain on the 21st of 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 behavior parameters. The outputs resulted from the FlamMap runs were shapefiles of the simulated fire perimeters and ASCII files of the simulated fire behavior. 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 significance differences in simulation outputs among the four scenarios were obtained by using the Tukey's significance test.

Results and discussion

The five fuel models that resulted from the field sampling represent all the major vegetation types of the study area (Figure 2). The dense shrublands (maquis) fuel model incorporates maquis with height up to 2.0 m with 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 comprised by shrubs which present reduced fuel load values and height compared to the dense shrublands fuel model and increased values compared to sparse shrublands fuel model. The grasslands and the agricultural fields (mainly litter of olive trees) demonstrated limited spatial heterogeneity and are represented by fuel model 4 for grasslands (total fuel load 4.31 t/ha), and fuel model 5 for agricultural areas (total fuel load 2.28 t/ha). The variation of total fuel load was low in all fuel models, as suggested by the magnitude of the standard deviation (S.D.). The total loads of all fuel models were found to be statistically different at ?? (one-way ANOVA and Duncan’s multiple range test). The fuel values represented by the models fall well within the range reported for vegetation types in Greece and for Mediterranean vegetation types in other parts of the world [42].

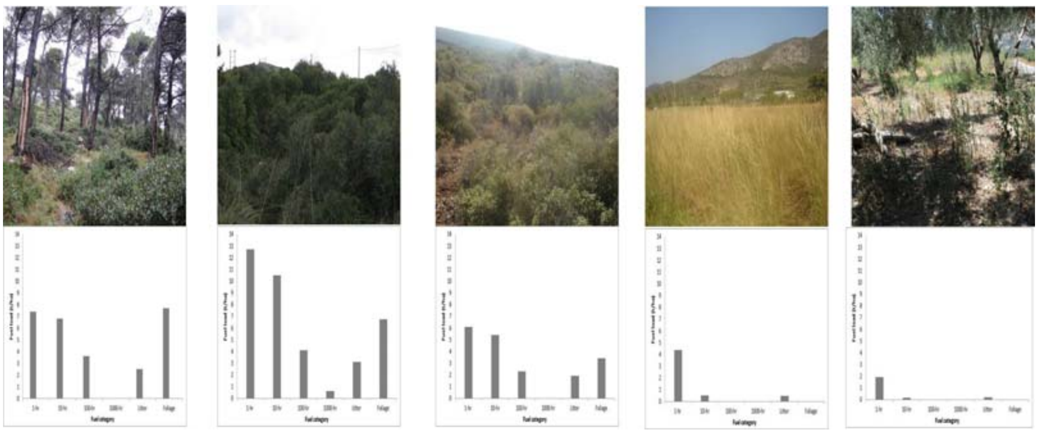

Figure 2. Fuel types and load values resulted from field sampling in the study area.

The whole study area consists mainly of 6189 hectares of shrublands (36% of the area) and 5148 hectares of Mediterranean pines (30% of the area). Significant part of the area is occupied by dense shrublands (15% or 2540 hectares), followed by agricultural areas (12% or 2055 hectares) while non-fuels and grasslands occupy only 6 hectares 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 (Figure 3).

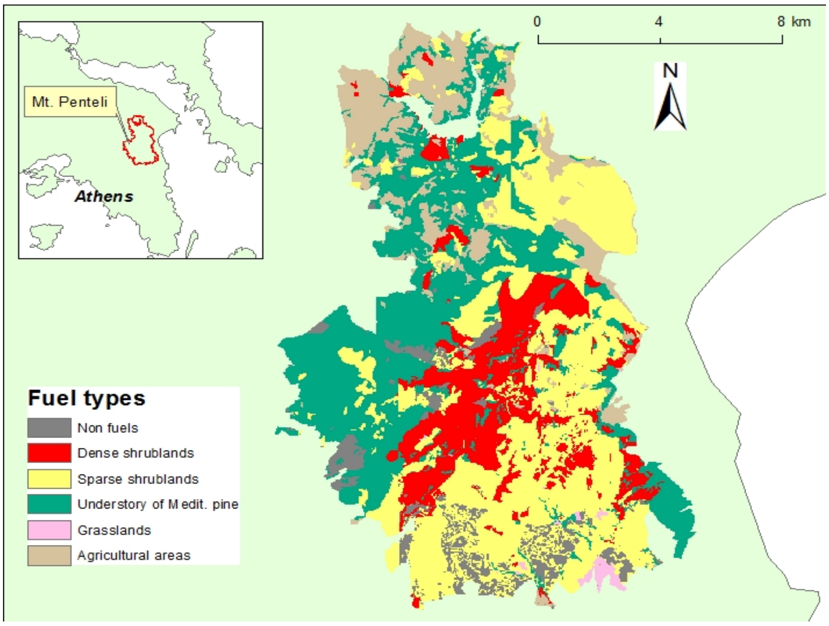

Figure 3. Forest fuel types spatial extent in the study area

In order to project future climate, the present-day period that of 1991–2000 and three future periods, namely, the decades 2045-2055, 2065-2075 and 2091-2100, were defined. Daily values of the aforementioned variables were used for two grid points of the model that are representative for the study area. At each grid point, the average values for each variable for the summer period and September were calculated for each decade. Finally, the mean value of the two grid points for each variable was used. The climatic input data for each variable and decade are shown in Table 1.

Table 1: Climatic input data for the four selected periods.

	Maximum Temperature (°C)	Minimum Relative Humidity (%)	Maximum Wind Speed (km/h)	Wind direction (degrees)
1991-2000 (2000 scenario)	30.1	28	21.7	357
2045-2055 (2050 scenario)	32.0	27	21.7	355
2065-2075 (2070 scenario)	33.5	27	21.7	357
2091-2100 (2100 scenario)	34.2	26	23.0	356

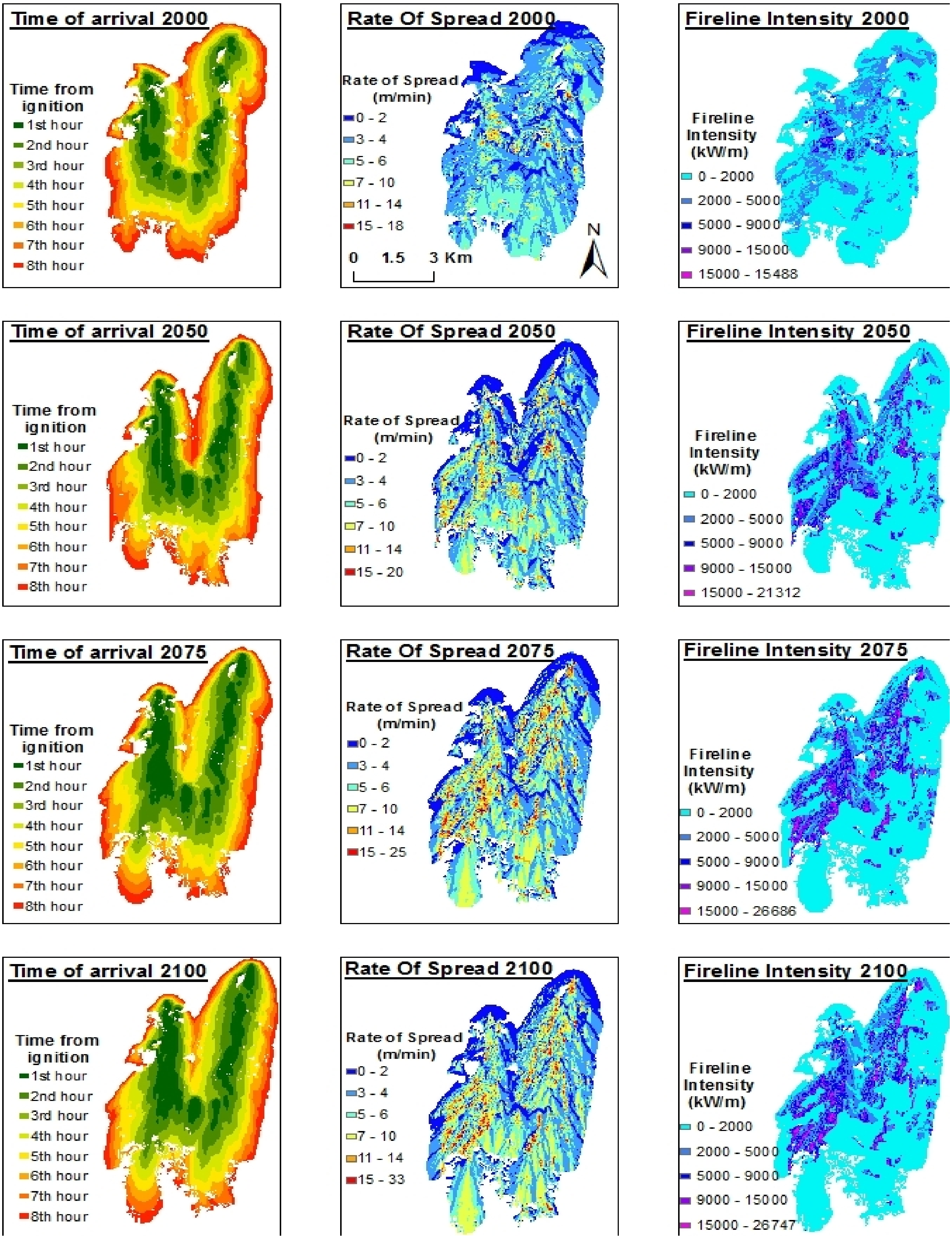

Figure 4. Fire behaviour maps of each climate scenario

Figure 4 shows the time of fire time of arrival for the 8 hours simulation (1 hour time step), the fire rate of spread and the fire line intensity resulted from the simulation results. Maximum fire rate of spread reached up to 18 m/min for the 2000 scenario, 20 min/min for the 2050 scenario, 25 m/min for the 270 scenario and 33 m/min for the 2100 scenario. Maximum fileline intensities reached up to 15488 kW/m, 21312 kW/m, 26686 kW/m and 26747 kW/m for each climate scenario, respectively. Statistical differences among the four scenarios are presented in table 2. Analysis Of Variance (ANOVA) and Tukey's multiple comparison test (95% confidence level) showed statistical differences among the fire parameters values. The 2000 climate scenario had the lower fire behaviour parameters values compared to the other scenarios. However, only the fire line intensity was significant different among all the scenarios. Rate of spread presented significant difference only in the 2100 scenario compared to the other examined periods. Final simulated burnt area (fire perimeter) was 3998 hectares for the 2000 scenario, 4096 hectares for the 2050 scenario, 4389 hectares for the 2070 scenario and 4512 hectares for the 2100 scenario.

Table 2. Mean fire behaviour values of the climate scenario examined. Test of significance was performed by Tukey's multiple comparison test, at p = 0.05. Values with the same letter are not significantly different.

Climate Scenario	**Rate of Spread (m/min)**	**Fireline Intensity (kW/m)**
2000	9 ^{a}	3516.2^{a}
2050	10^{a}	5763.1^{b}
2070	12.5^{a}	6838.6^{c}
2100	16.1^{b}	6671.3^{d}

The dense shrubland fuel type demonstrated the most severe fire potential in all climate scenarios 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 [43], FlamMap's fire growth equations, 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. [44] also suggest that localized, site specific fuel models give more reliable fire behaviour predictions using FlamMap simulator. Fire behaviour values resulted from the simulations were found similar to values reported in typical Mediterranean ecosystems [42,44]-.Fire behaviour models used in this simulation are semi-empirical. Nevertheless, they have been tested inhigh intensity experimental fires with satisfactory results [45].

Conclusions

This study mapped the fire behaviour values and investigated the potential effect under different future climate scenarios for an area 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 2100 climate scenario. Furthermore, fireline intensity 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. The final fire behaviour maps are the end product and they can be fully exploited operationally by local fire management authorities without further processing. 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. 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 only 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.

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 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, shifts in fire behaviour distributions, estimate any additional fire fighting resources allocation, future carbon emission released from wildfires and the long-term ecological restoration of degraded ecosystems/landscapes after wildfires.

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