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Fire Behavior Simulation in Mediterranean Forests Using the Minimum Travel Time Algorithm

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Abstract

Recent large wildfires in Greece exemplify the need for pre-fire burn probability assessment and possible landscape fire flow estimation to enhance fire planning and resource allocation. The Minimum Travel Time (MTT) algorithm, incorporated as FlamMap's version five module, provide valuable fire behavior functions, while enabling multi-core utilization for the calculations. The primary goal of this study was the MTT implementation for two study areas in Mediterranean forest types of Greece, *i.e.* Lesvos Island (in North Aegean Sea) and Messenia (in Southwestern Peloponnesus) by calculating burn probabilities, fire size and flame length probability from thousands of simulated fire events (located either randomly or based on historical ignitions). A second goal aimed on estimating fire hazard and vulnerability for several values-at-risk of the study areas. To achieve these goals the necessary geospatial datasets were created by field inventories, remote sensing techniques, geo-statistics and Geographic Information Systems (GIS). Weather and fuel moisture inputs were retrieved from nearby weather stations. Maps showing the most fire-prone and high-risk parts of each area were created, along with fire hazard scatter plots for values-at-risk. Interpretation of the results may suggest possible fire fighting strategies, places that need vegetation management, areas that require more patrols and surveillance and areas with increased fire intensity.

Additional Keywords: Wildfire; burn probabilities; FlamMap; MTT; ArcFuels; values-at-risk.

Introduction

The ever-increasing occurrence of large-scale wildfire events in Greece is a concern for the firefighting agencies, public safety and government authorities. The size of Greece and the configuration of its terrain and municipalities create "islands", either natural in the sea or "ecosystem enclaves" surrounded by urban development. The density of human activities near wildland areas means that even small wildfires can have high consequences. The recent example of Chios Island fire that burned over 15,000 ha (almost 1/6 of the islands size) devastated part of the island's economy and most of the forest ecosystems in 2012. It also proved that the situation is getting worse in several parts of Greece in terms of vegetation condition, preparedness of local or national firefighting agencies and resources availability. The new challenges and realities coming from the country's economic situation emphasize the need for pre-fire burn probability assessment and possible landscape fire flow estimation to enhance fire planning and resource allocation. This study reports on an implementation of the Minimum Travel Time algorithm (MTT) (Finney 2002) to explore its potential to estimate and calculate fire hazard for several values-at-risk for two study areas of Greece, Lesvos Island and Messenia. These areas face the risk of future large-scale fires due to their fire history, human practices, and physiographic characteristics. The results of this research are essential for early warning/protection and need to emphasize not only to where a fire can initiate and spread, but also to those particular values and assets that must be protected to avoid a new catastrophe. Results can also be used for vegetation management planning and fuel treatment practices to reduce the risk of a wildfire to attain characteristics of megafires.

The bulk of the analysis was conducted with the command-line version of MTT called "Randig" (Finney 2006*a*). MTT computes fire growth between the cell corners at an arbitrary resolution and fire growth is computed under the same assumptions as the basic fire behavior, holding all environmental conditions constant in time (Finney 2006*b*; Stratton 2009). The new version of FlamMap 5.0[1] also enables end-users to create all the necessary results and files from multiple ignition simulations (burn probabilities, fire perimeters, flame length probabilities, fire size list) ready to be used for a quantitative wildland fire risk assessment. Furthermore, MTT results can be used both for fuel management planning and for single event fire propagation (spread and intensity); a convenient way to conduct this kind of analysis is by using ArcFuels, developed to streamline fire behavior modeling and spatial analyses for fuel treatment planning through macros that are executed via custom toolbars in ArcMap (Vaillant 2013). ArcFuels is used to rapidly design and test fuel treatments at the stand and landscape scale via linkages to models such as FVS-FFE (Forest Vegetation Simulator with the Fire and Fuels Extension; Reinhardt and Crookston 2003), SVS (Stand Visualization System; McGaughey 1997), FARSITE (Fire Area Simulator; Finney 2004), FlamMap (Finney 2006*a*), Nexus (Scott 1999), and FVS (Forest Vegetation Simulator; Crookston and Dixon 2005) within a spatial interface.

Currently, there are several studies that used FlamMap, MTT and ArcFuels for quantitative wildland fire risk assessment. Ager *et al.* (2007) modeled wildfire risk to northern spotted owl habitat by calculating spatially explicit probabilities of habitat loss for fuel treatment scenarios on a 70,245 ha study area in Central Oregon, USA. Simulations revealed that a relatively minor percentage of the forested landscape (20%) resulted in a 44% decrease in the probability of spotted owl habitat loss averaged over all habitat stands. Ager *et al.* (2010) conducted a comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. The burn probabilities were used to calculate wildfire risk profiles for each of the 170 residential structures within the urban interface, and to estimate the expected (probabilistic) wildfire mortality of large trees. Salis *et al.* (2013) used simulation modeling to analyze spatial variation in wildfire exposure relative to key social and economic features on the island of Sardinia, Italy. Historical fire data and wildfire simulations were used to estimate burn probabilities, flame length and fire size. These risk factors were examined to understand how they varied among and within highly valued features located on the island. Ager *et al.* (2012) used simulation modeling to analyze wildfire exposure to social and ecological values on a 0.6 million ha national forest in central Oregon, USA. They simulated 50,000 wildfires that replicated recent fire events in the area and generated detailed maps of burn probability (BP) and fire intensity distributions. Results were used to create scatter plots showing patch-scale variation within selected land designations (human values, wildlife habitat and ecological values) for burn probability versus fire size and versus conditional flame length.

[1] http://www.firemodels.org/downloads/flammap/5.0/ReleaseNotes_FMP5.pdf

In our study, simulations of 100,000 fire events were conducted for two study areas of Greece, *i.e.* Lesvos Island (in North Aegean Sea) and Messenia (in Southwestern Peloponnesus), both with randomly located ignitions and based on a historical ignition probability grid. Results are interpreted to understand the fire hazard produced by the different ignition patterns. FARSITE simulations from recent fire events were simulated to assess the modeling accuracy and to understand which parameters should be changed to better capture the actual fire patterns of each area. The next step of the analysis involves the usage of ArcFuels to assess the fire hazard and risk for several values-at-risk of the two areas. This will be achieved by constructing fire hazard scatter plots and identifying which values face the greater fire risk. Finally, several maps were created to describe and portray the results of each area.

Materials and methods

Study areas

This study is focused on two areas of Greece that have unique features and characteristics and different fire history. Lesvos is an Aegean Sea island, located on the east part of Greece, close to coast of Asia Minor, Turkey (Figure 1). It covers an area of about 1,650 km^2, with about 121 km^2 located on areas of over than 500 m elevation, 312 km^2 between 300 and 500 m, 713 km^2 between 100 and 300 m and 469 km^2 located across the coastal areas, below 100 m a.s.l. Land degradation and desertification problems occur on an extensive part of the island (1/4 of its total size) due to overgrazing, frequent fire events and lack of precipitation. These lands are semi-arid, while the rest of the island is dry to sub-humid with 450 mm to 700 mm average precipitation (Kosmas *et al.* 2000). During the summer, the island is affected by the yearly influence of Etesian winds having high speeds (usually 5-7 Beaufort or BF) from NE to NW directions. In the island, several world heritage sites and monuments exists, such as a 20 million year-old petrified forest, medieval monasteries, historical settlements and castles, prehistoric sites and ancient Greek and Roman temples. Furthermore, the island is an important bird habitat and immigration route, with rare local species (*Sitta krueperi, Buteo buteo, Circaetus gallicus, Accipiter gentilis*).

Its touristic sector is of medium size in terms of infrastructure and small scale in terms of the overall island's economic activities, with only few developed areas of large tourist concentration. In terms of vegetation, the island is covered by the largest pine (*Pinus spp.*) forest complex of all the Aegean Sea islands relatively to its size (300 km^2, *i.e.* about 20%), while the rest of the island is covered by olive groves (500 km^2), phryganic ecosystems and grasslands (580 km^2), broadleaf forests and oak (80 km^2) and evergreen shrublands (30 km^2). Significant parts of the island face land abandonment with the subsequent reforestation, and due to the fact that forests are mostly unmanaged privately owned, no fuel management exists on these lands and the risk for increased fire intensities and ignitions is of great concern for the local firefighting agency. Finally, small-scale wildland-urban interface areas (WUI) are located on the SE, where 1/3 of the total population resides in a densely vegetated area.

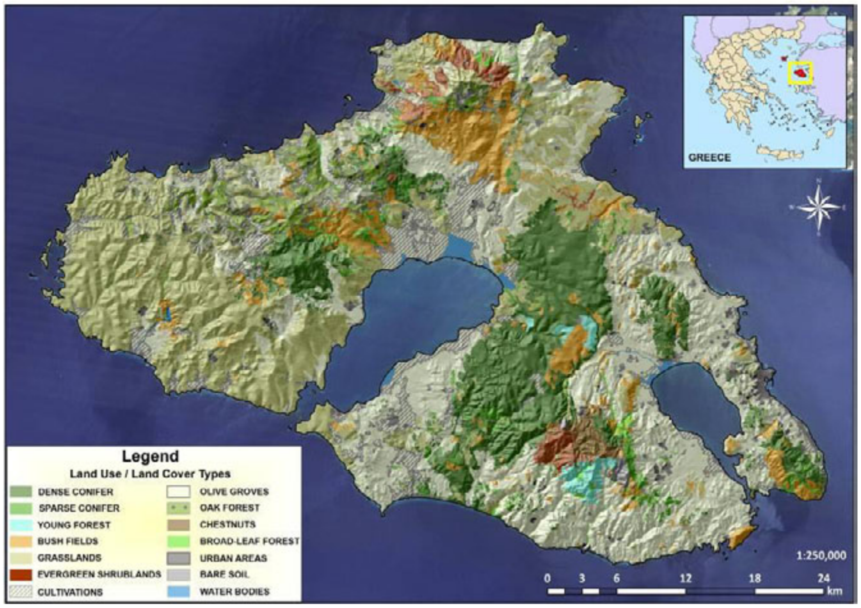


Figure 1: Land use / land cover types of Lesvos Island, Greece

Regarding the island's fire history, 900 incidents were recorded during the last 40 years resulting in about 10,000 ha of burned land (Figure 2). The vast majority of these events (92%) were of minor importance with size less than 10 ha, while only four events burned more than 500 ha and nine between 100 and 500 ha. The most common cause of ignitions is arson for land clearance and agricultural/livestock production improvement, followed by negligence/accidents and arsons from people with economic or other interests.

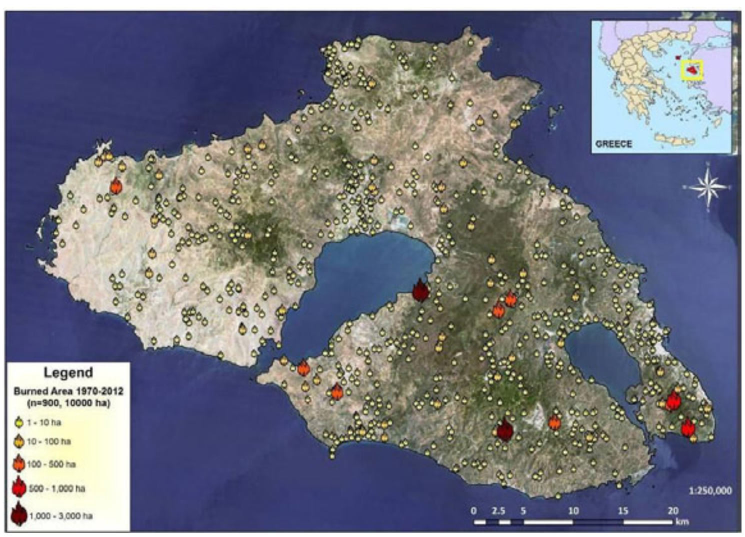


Figure 2: Fire history map of Lesvos Island for the years 1970–2012

Messenia is located on the SW tip of Greece, Peloponnesus, having shores to the Ionian Sea (Figure 3). It covers an area of about 3,000 km^2, with about 45 km^2 located on areas of more than 1,500 m elevation (Mt. Taigetos peak), 254 km^2 between 1,000 and 1,500 m, 660 km^2 between 500 and 1,000 m, 560 km^2 between 300 and 500 m, 860 km^2 between 100 and 300 m and 620 km^2 located across the coastal areas, below 100 m a.s.l. The average annual precipitation of Messenia is higher than Lesvos Island, with a range between 600 to 900 mm. During the winter, the area is affected by the passage of depressions forming over the Mediterranean Sea, while in the summer it is influenced from heat waves coming from N. Africa. The steep and differentiated topography creates several local and diurnal wind regimes and forms local microclimates.

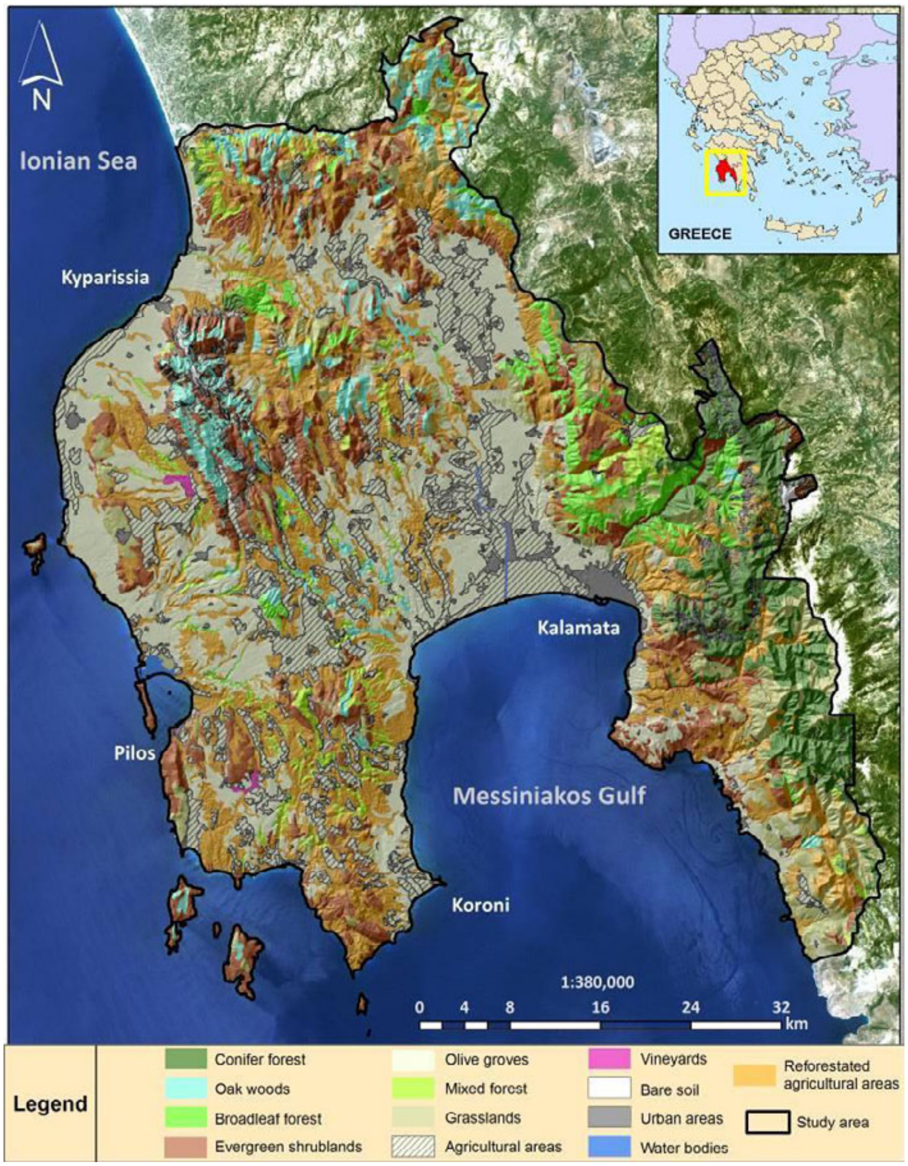


Figure 3: Land use / land cover types of Messenia, Greece

Several archaeological sites of world importance (dated back to 2000 B.C.) exist on forested and densely vegetated areas. Furthermore, extensive WUI areas can be found around the 400 urban areas, villages and settlements and, in conjunction with land abandonment and reforestation, increase the risk for causalities. The tourist infrastructure of the area is widespread across the coasts and one of the largest and most luxurious hotel complexes of Greece is located there. In addition, several people camp (either legally or illegally) close or inside high fire risk areas during the summer fire season.

Vegetation of Messenia consists of 140 km^2 covered by oak forests (*Quercus conferta, Quercus ilex, Quercus coccifera, Quercus pubescens, Quercus ithaburensis Decaisne subsp. Macrolepis*), 85 km^2 with *Pinus nigra* ssp. *pallasiana* and *Pinus halepensis*, 127 km^2 with *Abies cephalonica,* 116 km^2 with broadleaf forests (*Castanea sativa*, *Platanus orientalis*, *Acer pseudoplatanus*, *Sorbus domestica*, *Fraxinus ornus*, *Alnus glutinosa*, *Prunus cerasus*), 1,150 km^2 with evergreen shrublands, 250 km^2 with grasslands and phryganic ecosystems, while the rest of the area is mainly covered by olive cultivations (600 km^2) and agricultural areas (orchards, crops, vineyards, etc.).

Frequent fire events have been recorded during the past 20 years, with more than 600 fire events resulting in over 45,000 ha of burned forests and other lands (Figure 4). A 78% of fires burned an area of less than 10 ha each, a 16% burned from 10 to 100 ha and a 5% burned from 100 to 1,000 ha each. Seven events burned an area exceeding 1,000 ha each, six of which occurred during the catastrophic summer of 2007. There is evidence that several ignitions are caused by lightning's (Mazarakis *et al.* 2008; Defer *et al.* 2005), but the vast majority initiated from agricultural practices, arson and accidents/ negligence, similar to Lesvos Island and typical for Greece.

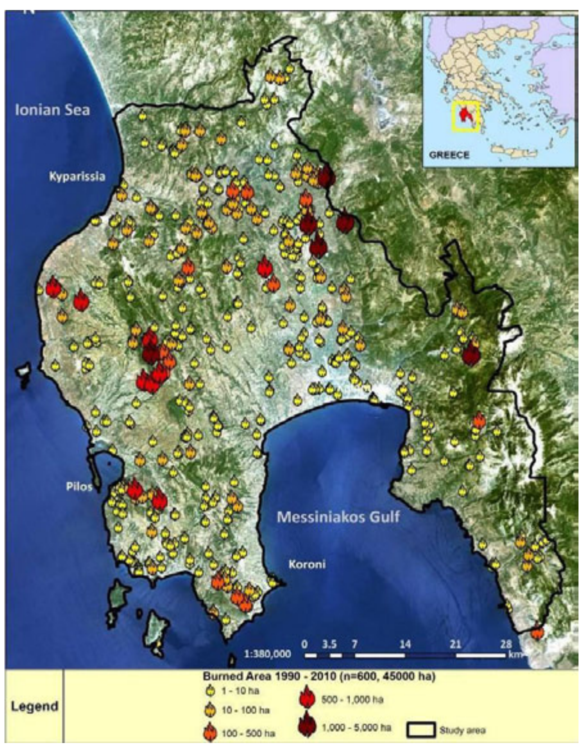


Figure 4: Fire history map of Messenia for the years 1990 – 2010

MTT simulations

For simulations, we used the command line version of MTT called "Randig". This version is more stable and lightweight compared to FlamMap, while it enables the simulation of thousands of fire events. Furthermore, it allows the usage of multiple weather scenarios by selecting a random sequence among the scenarios defined in a specific input file according to their relative probability. MTT produces minimal distortion to fire shapes because there are no limits on angles or distances for searching (unlike Cellular Automata, etc.). It is very reliable for the huge numbers of simulations, very sensitive to complex environmental conditions (space and time) and can represent influences of spotting. The MTT algorithm replicates fire growth by Huygens' Principle where the growth and behavior of the fire edge is a vector or wave front (Richards 1990; Finney 2002).

Randig can take advantage of multi-core processors and simulation time is substantially reduced when more processors participate in the procedure. When running many fires, it is most efficient to use one core/thread per fire. Each fire will run slower but it is the most efficient for the entire run. If running one fire or just a few (fewer fires than processors) then it is more efficient to have two or more cores/threads running each fire. The parallelization is done in two levels and hierarchical – among fires and within fires. By choosing one core/thread per fire, then each fire will have its own thread and run simultaneously on as many processors as available. For example, if you have 16 processors, then 16 fires will be run at once. With 16 processors, choosing two cores/threads per fire will result in eight fires running at once. MTT simulations is parallelized only if you have one fire, though the processing is not perfectly scalable, it shows good scaling from two to four cores/threads per fire if the fire is large. Simulations were conducted with one thread per fire on a 32-core machine (Four Intel Xeon CPU E5-4640 with 32 cores and 64 threads, 128 GB RAM, model PowerEdge R820, DELL Inc.), located at the Oregon State University, College of Agricultural Sciences, Biological and Ecological Engineering, USA.

The necessary inputs for Randig are the landscape file, a fuel moisture file (FMS), a custom fuel model file (if any used), the weather scenario file (contains information about one or more weather scenarios; *i.e.* FMS, wind speed and direction, fire duration, spot probability and probability of selection for each scenario) and the ignition probability grid (if defined). Furthermore, users must provide the number of scenarios involved in each fire, resolution, number of ignitions, number of threads for each fire, output file, units, crown fire calculation method and usage of WindNinja (Forthofer 2007), as arguments in Randig executable file.

Results of Randig are a burn probability grid, fire perimeters shapefile, flame length probabilities (text file and binary grid) and fire list (text file with coordinates and area in ha of each fire). Burn probability is defined as (1):

$$BP = F/n \qquad (1)$$

where, F is the number of times a pixel burns and n is the number of simulated fires.

The BP for a given pixel is an estimate of the likelihood that a pixel will burn given a random ignition within the study area and burn conditions similar to the historic fires (Ager *et al.* 2012). Flame length probabilities are calculated in 20 classes (0.5 m interval) or six classes (2 ft internal). The fireline intensity (FI – kW/m) for a given fuel type and moisture condition can be calculated from the fire spread rate normal to the front (Byram 1959; Catchpole *et al.* 1982), and then it is converted to flame length (FL – m) based on Byram's (1959) equation (2):

$$FL = 0.0775\,(FI)^{0.46} \qquad (2)$$

Conditional flame length is the probability weighted flame length given a fire occurs and acts as a measure of wildfire hazard (Ager *et al.* 2010), while it is calculated by incorporating the flame length distribution generated from multiple fires burning each pixel in equation (3):

$$CFL = \sum_{i=1}^{20} \left(\frac{BP_i}{BP} \right) (Fi) \qquad (3)$$

where, *BP* is Burn Probability and F_i is the flame length midpoint of the ith category.

Wildfire transmission among land designations was measured by a source–sink ratio (*SSR*) of wildfire calculated as the ratio of fire size (*FS*) generated by an ignition to burn probability (4):

$$SSR = \log\left(\frac{FS}{BP} \right) \qquad (4)$$

The SSR ratio measures a pixel's wildfire contribution to the surrounding landscape (in terms of the fire size it produces) relative to the frequency with which it is burned by fires that originated elsewhere or were ignited on the pixel (expressed by the burn probability). In relative terms, pixels that have a high burn probability but do not generate large fires from an ignition are wildfire sinks, and those that generate large fires when an ignition occurs and have low burn probability are wildfire sources (Ager 2012). By using the Randig output text file with information about fire size of the simulated fires, we analyzed their spatial variation by calculating a density surface with the Inverse Distance Weighting (IDW) method (smoothed with 12 neighbors).

Ignition probability grid

The current Randig version cannot use an ignition point file. The only way to influence the position of the ignition is by providing an ignition density grid made either with Kernel Density Smoothing (KDS) or IDW. There is some subjectivity as to how smooth it should be. Typically, it is made quite smooth over broad areas rather than highly detailed. The KDS is very useful for using the information and can produce a variety of density surfaces from the data.

Ignition probability grids for the two study areas were created with historic ignitions points, based on the actual fire size they produced (Koutsias *et al.* 2004). In particular, fire sizes where categorized in a scale from 1 to 11, where 1 was assigned to fire sizes less than 1 ha, 2 from 1 to <10 ha, 3 from 10 to <100 ha, 5 from 100 to <500 ha, 7 from 500 to <1,000 ha, 9 from 1,000 to <2,000 ha and 11 for fire sizes greater than 2,000 ha. These values served as weighting parameter in the KDS method. A bandwidth (search radius) of 4 km for Lesvos Island (Figure 5) and 7 km for Messenia (Figure 6) was assigned; and these values were selected to ensure that only minor parts of each study area will fail to receive a density value and to avoid over-smoothing.

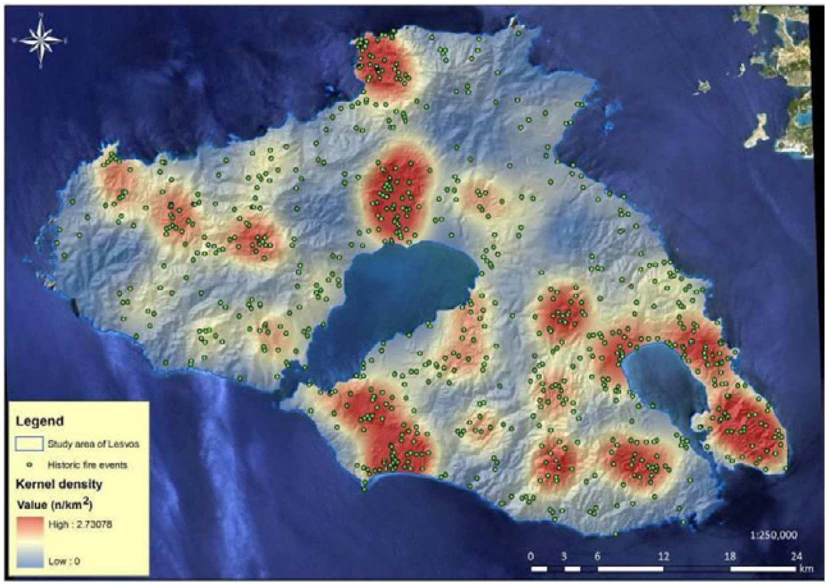


Figure 5: Ignition density map of Lesvos Island

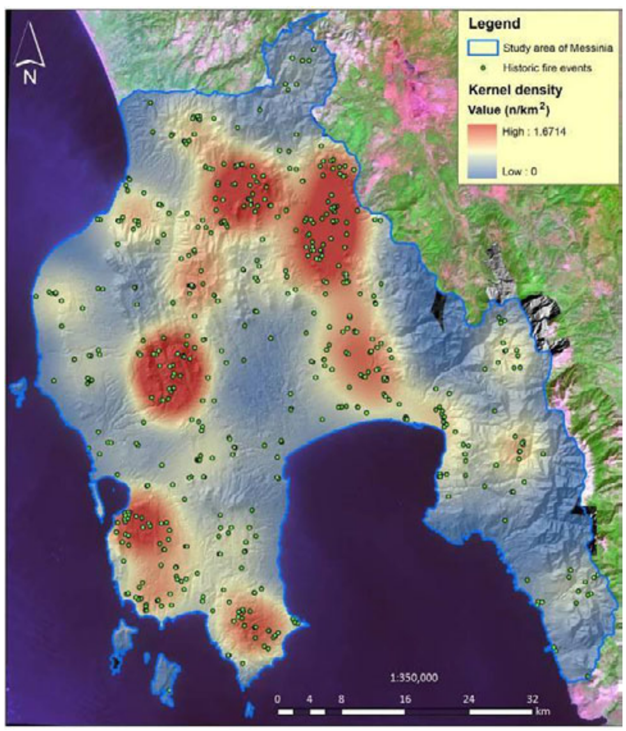
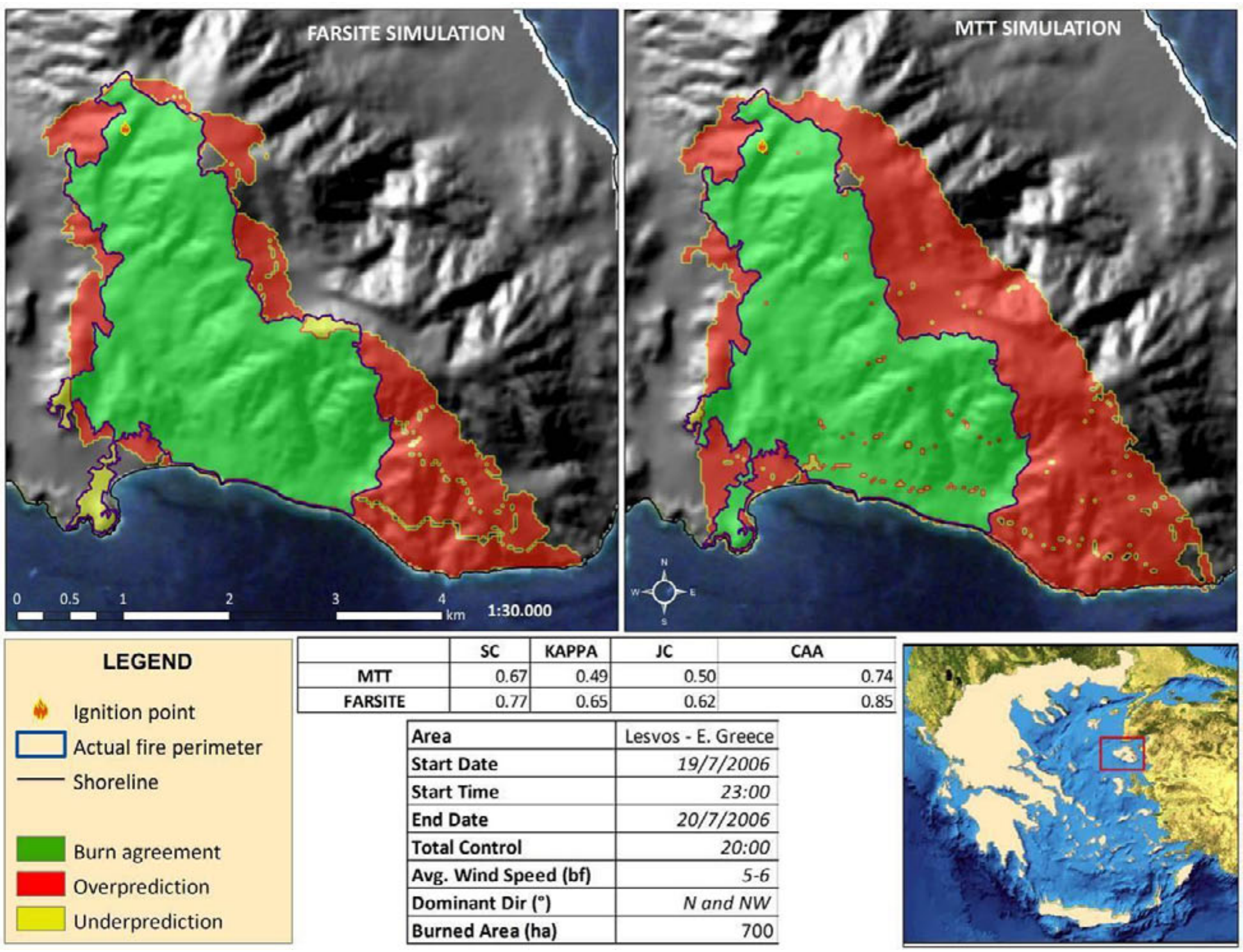


Figure 6: Ignition density map of Messenia

Data critique and model calibration

To test the modeling accuracy, two recent fire events, one on each study area were simulated, both on FARSITE and FlamMap. Prediction and modeling accuracy was assessed by calculating statistics and measures of similarity such as Sørensen coefficient (SC) (Greig-Smith 1983), Cohen's kappa coefficient (kappa) (Cohen 1960), Jacard’s similarity coefficient (JC) (Jaccard 1901) and Coefficient of Areal Association (CAA), which includes the similarity of both burned and unburned regions, and ranges from 0.0 to 1.0 in the same way as Jacard’s coefficient. For FARSITE simulations, hourly wind speed and direction data were retrieved from nearby Remote Automated Weather Stations (RAWS), while for FlamMap wind direction and speed were kept constant for the entire simulation. No suppression activities were modeled, even though they were intense and with large firefighting forces.

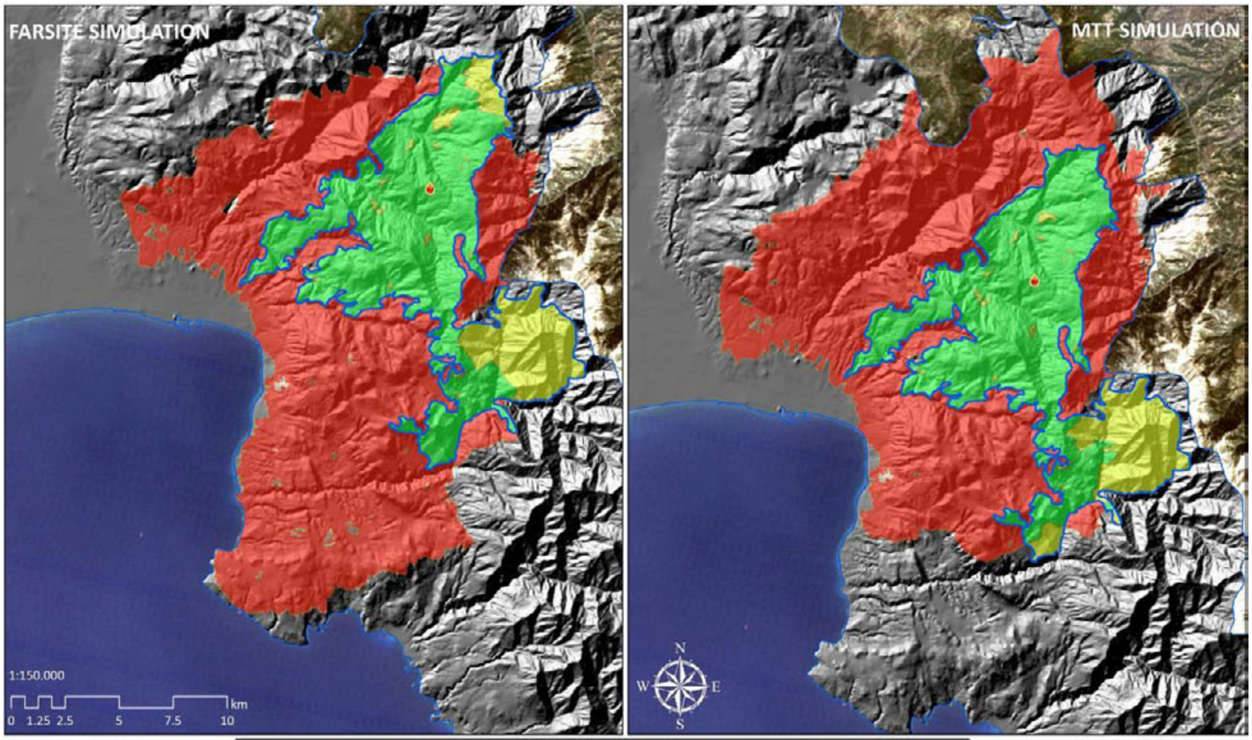


	SC	KAPPA	JC	CAA
MTT	0.67	0.49	0.50	0.74
FARSITE	0.77	0.65	0.62	0.85

Area	Lesvos - E. Greece
Start Date	19/7/2006
Start Time	23:00
End Date	20/7/2006
Total Control	20:00
Avg. Wind Speed (bf)	5-6
Dominant Dir (°)	N and NW
Burned Area (ha)	700

Figure 7: Lesvos fire simulation results and statistics

In Lesvos Island, the fire started on 19/7/2006 and its duration was about 20 hours, burning under average wind speed on 5-6 BF from N and NW directions, resulting in 700 ha of burned forests (Figure 7). Results revealed that FARSITE simulation statistics were slightly better compared to the FlamMap ones for all indices, but their difference was small (about 0.1). Serious over-prediction was noted on the E (flanks) and S (head) parts of the fire.



	SC	KAPPA	JC	CAA
MTT	0.43	0.28	0.27	0.71
FARSITE	0.41	0.26	0.26	0.70

Start Date	23/8/2007
Start Time	14:00
End Date	26/8/2007
Total Control	14:00

Avg. Wind Speed (bf)	6-7
Dominant Dir (°)	N and NNE
Burned Area (ha)	10500

Figure 8: Messenia fire simulation results and statistics

The fire of Messenia was a large-scale fire event occurred during the 2007 extreme fire season. During this summer, several simultaneous fires occurred throughout the region, several of them spread inside Messenia from nearby regions. The simulated fire lasted for three days and resulted in 10,500 ha of burned area, spreading from NE to SW, with an enclave on the SE, probably ignited from spotting (Figure 8). Both simulations seriously over-predicted fire spread on the fire front (SW and S) and on the flanks (N and NW), while under-prediction was noticed on the enclave. Accuracy of simulations was moderate for all statistical measures of similarity.

Vegetation and fuel data

For Lesvos Island, the geospatial datasets regarding canopy characteristics (Cover, Canopy Base Height - CBH, Canopy Bulk Density - CBD and Tree Height) were created by field inventories, remote sensing techniques, geo-statistics and Geographic Information Systems (GIS) (Palaiologou *et al.* 2013). A combination of custom and standard fuel models was used. Four standard fuel models (Scott and Burgan 2005) were assigned; *i.e.* GR1 on agricultural areas, GS1 on oak dominated lands, GS2 on olive groves and TL2 on broadleaf forests. Eight custom fuel models were used, four of them from the research of Dimitrakopoulos and Panov (2002) defining eight new Mediterranean fuel models that can be applied on Greece, and the rest four were created from field sampling conducted inside Lesvos pine forests (see Palaiologou *et al.* 2013 for sampling methods). The characteristics of the eight custom fuel models used are presented on Table 1.

Table 1: Parameters of the custom fuel models used in Lesvos simulations

FUEL MODEL	Fuel Model Code	1 - h Fuel Load (tons/acre)	10 - h Fuel Load (tons/acre)	100 - h Fuel Load (tons/acre)	Live Herbaceous (tons/acre)	Live Woody (tons/acre)	Fuel Depth (ft)	Dead Fuel Moisture of Extinction	1-h SA/V (1/ft)	SA/V Lh (1/ft)	SA/V Lw (1/ft)
XO01	205	1.76	0.19	0	0.3	0	0.98	14	2000	1800	1500
AS01	206	1.41	0.41	0.12	0.36	0	1.31	14	2000	1800	1800
SC01	208	2.99	2.75	1.45	0	3.11	3.67	14	750	1800	1600
SC02	209	5.86	5.38	3.43	0	4.28	7.15	14	750	1800	1600
FM01	210	3.53	1.27	1.47	0.03	5.08	1.97	15	750	1800	1600
FM02	211	3.43	1.45	0.73	0.04	1.32	0.82	25	1500	1800	750
FM03	212	3.05	1.09	0.98	0.04	0.88	0.52	35	1800	1800	1600
FM04	213	1.12	1.00	0.49	0.06	0.79	0.49	20	2000	1800	1600

In Table 1, fuel models 205-209 (Dimitrakopoulos and Panov 2002) are referred to Mediterranean grasslands (205), phrygana (S*arcopoterium spinosum*) (206), Evergeen-sclerophyllous shrublands (maquis) with a height up to 1.5 m (208) and from 1.5 to 3 m (209). Fuel models 210-213 are generally referred to Mediterranean pine forests (Palaiologou *et al.* 2013):

- with maquis dominating understory (>20% cover) and an average height of over 1.5 m (*Pistacia lentiscus, Quercus coccifera, Arbutus unedo, Phillyrea media*), mixed with litter from *Pinus brutia* (210);
- with a mixture of brush and short phrygana dominating understory (>20% cover) and an average height lower than 1.5 m (*Erica malipuliflora, Sarcopterium spinosum, Cistus creticus, Cistus savofolius, Genista acanthoclada, Juniperus oxycedrus*), mixed with litter from *Pinus brutia* (211);
- with litter and other downed dead fuels dominating understory (>70% cover), mixed with short brush (<30% cover) (212); and
- grazed, burned, or managed (timber or resin collection) with enclaves of regeneration where the general fire carrier is low loading of canopy litter mixed with annuals, short brush, seedlings and saplings (213).

For Messenia, one fuel model was assigned to every vegetation type, regardless of the appearance area (elevation, slope, aspect, distance from sea and human influences). The selected fuel model types came from the same references as we did for Lesvos Island, but there were notable differences between the two areas for the same vegetation types (Table 2). For example, oak dominated lands in Lesvos are sparse with phrygana on the understory with little litter, while in Messenia they are dense and the primary fire carry agent is low load of grass and shrub with litter. Another example is the olive trees, which in Messenia are cultivated mostly in flat areas, with low tree height and cleaned understory, while in Lesvos most are located in terraced elevated sites with grass and shrub understory.

Table 2: Vegetation types, fuel models and fuel moistures used for Messenia simulations

Vegetation type	Fuel model	1-h fuel moisture	10-h fuel moisture	100-h fuel moisture	Live herbaceous	Live woody
Oak forest	TU1	4	5	6	40	70
Sparse oak forest	SH4	4	5	6	40	70
Mixed oak with Quercus ilex	TL6	4	5	6	60	90
Fir forest	TU3	6	7	8	90	120
Pinus nigra	FM03	4	5	6	60	90
Pinus halepensis	FM02	4	5	6	60	90
Broadleaf forest	TL9	4	5	6	60	90
Mixed forest	TU5	4	5	6	60	90
Shrubs	SC02	4	5	6	60	90
Sparse shrubs	SC01	4	5	6	60	90
Mixed forests and shrubs	SH5	4	5	6	60	90
Plane trees and chestnuts	TL2	6	7	8	60	90
Pine reforestation	SH6	3	4	5	40	70
Brush and grass (phrygana)	AS01	5	6	7	60	90
Olive groves and WUI	GR2	3	4	5	40	70
Abandoned and reforestated agricultural areas	GS2	4	5	6	40	70
Agricultural areas	GS1	3	4	5	30	60
Orchards and vineyards	GR1	4	5	6	40	70
Non-burnable areas	NB9	n/a	n/a	n/a	n/a	n/a

Weather inputs

Weather scenarios were created by using data from several RAWS located across the two study areas. In Lesvos Island, a network of four RAWS is recording data from 2003 (Palaiologou *et al.* 2011). In contrast to FARSITE, the MTT algorithm assumes constant weather and is used to model individual burn periods within a wildfire rather than continuous spread of a wildfire over many days and weather scenarios. For each year, the 98th percentile wind speed value was calculated for the high fire risk season (May to September). For the same period, wind rosegrams were created to portray the dominant directions and prevailing wind speeds (Figure 9). It is clear that there are two wind direction trends on the island, one with NE and NNE winds, and another with NW and NNW winds, while frequent winds appear also from N. Based on these facts, five scenarios were created, each with a fire period of 5 hours which is the common average duration, and 0.1 spot probability (Table 3).

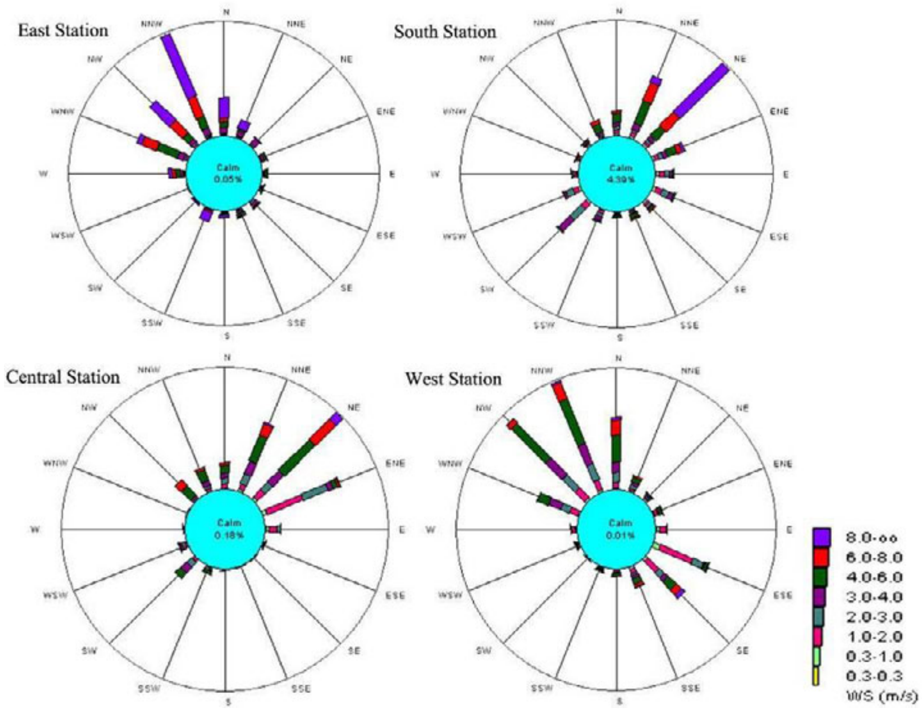


Figure 9: Wind roses of the four RAWS of Lesvos Island

Table 3: Parameters and weather scenarios for Lesvos Island simulations

Scenario number	Wind Speed	Direction	Duration	Spot Probability	Probability
1	27	330	300	0.1	0.20
2	31	45	300	0.1	0.25
3	16	40	300	0.1	0.20
4	14	315	300	0.1	0.15
5	24	10	300	0.1	0.20

Fuel moisture values were also retrieved by calculating average values per month for the 10-year working period of RAWS (sensor CS506 Campbell Scientific). The vast majority of serious fire events appear during July and August, and there are three trends for 1-h, 10-h and 100-h fuel moisture values. The high altitude parts of the island have low dead fuel moisture with 2/3 cured herb and low live woody moisture values (*i.e.* 5%, 6%, 7%, 60%, 90%), the lower elevated dry parts have very low dead fuel moisture with 2/3 cured herb and low live woody moisture values (*i.e.* 4%, 5%, 6%, 60%, 90%) and the very dry west parts with extremely low dead fuel moisture with fully cured herb and very low live woody moisture values (*i.e.* 3%, 4%, 5%, 30%, 60%). Based on these trends, a fuel model specific moisture file was created with adaptations made by considering canopy cover and tree density, altitude, actual rate of spread and understory vegetation (Table 4).

Table 4: Vegetation types, fuel models and fuel moistures used for Lesvos Island simulations

Fuel model	Vegetation type	1-h fuel moisture	10-h fuel moisture	100-h fuel moisture	Live herbaceous	Live woody
101	Agricultural areas	3	4	5	30	60
121	Oak	3	4	5	60	90
122	Olives	4	5	6	60	90
182	Broadleaf trees	6	7	8	60	90
205	Mediterranean grasslands	6	7	8	90	120
206	Phrygana	6	7	8	90	120
208	Shrublands < 1.5 m	5	6	7	60	90
209	Shrublands > 1.5 m	5	6	7	60	90
210	Pines with shrubs > 1.5 m	5	6	7	60	90
211	Pines with shrubs < 1.5 m	5	6	7	60	90
212	Pines with short brush	4	5	6	30	60
213	Pines cleared undestory	4	5	6	30	60

For Messenia, weather inputs were retrieved from four RAWS, of different types and available data range. The oldest station is located on the W very close to the sea (11 m a.s.l.), recording data from more than 50 years. Records revealed that weak winds frequency (<2 BF) is about 30% during the year, while moderate winds (3-5 BF) frequency is about 58%, with 65% during July and August. Strong winds (6-8 BF) have a frequency of 8% during the winter and 3% during the summer. Regarding wind direction, W winds are the strongest compared to other directions and have an appearance frequency of 30% annually, but exceed 50% during the summer months. Northern winds have also high frequency during the summer (about 10%), while E winds appear for less than 10% and NW winds for about 20% frequency. Another station on the SE is recording data for two years on Mt. Taigetos (1,310 m a.s.l.), with frequent winds from NE and ENE and average wind speeds of 6-7 BF during windy days. The third station is located inland on the N part of Messenia (509 m a.s.l.), recording data for two years. Records revealed that wind speeds during the summer are moderate (4-5 BF) mainly from SSW and with lower frequency from NE directions. The fourth station is located on the NE mountainous part of Messenia (723 m a.s.l.), recording data for two years with winds coming mainly from SE with moderate winds (5-6 BF) during windy days. Six scenarios were created by considering the above results (Table 5).

Table 5: Parameters and weather scenarios for Messenia simulations

Scenario number	Wind Speed	Direction	Duration	Spot Probability	Probability
1	15	10	300	0.1	0.13
2	24	300	300	0.1	0.15
3	27	330	300	0.1	0.24
4	22	210	300	0.1	0.12
5	30	55	300	0.1	0.24
6	24	135	300	0.1	0.12

Results

Randig results revealed several places with high burn probability around study areas. For Lesvos, high BP is noticed on the SE, NW, W and S parts of the island, mainly covered by evergreen shrublands and phrygana (Figure 10). The main pine forest complex (central part) has only a few sites with high values, while the pine forest of the SE, which is also a WUI area has very high values. Compared to random ignitions results, the pattern is the same with only more extended areas with high values on the west (Figure 10b). There are also some small parts which had few ignitions due to low or zero kernel values (e.g. small islands and islets), creating data gaps in the results (Figure 10a).

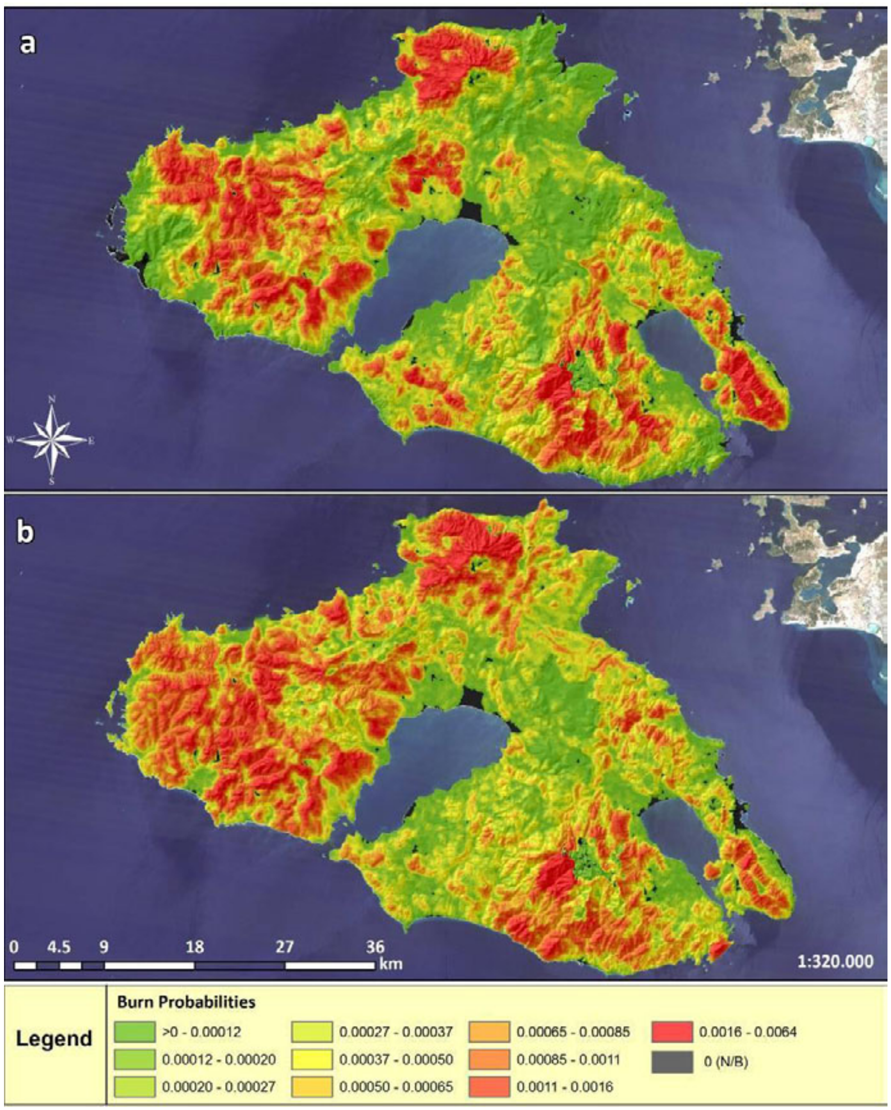


Figure 10: Burn probabilities for historic ignitions (a) and random ignitions (b) in Lesvos Island

The average fire size of historic ignitions is 108 ha, with minimum and maximum size of 1.44 and 917 ha, while percentiles (of 25, 50 and 75) have fire sizes of 45, 82 and 117 ha, respectively; results that are in agreement with the recorded fire sizes. Conditional flame length values are high only in places with evergreen shrublands (>2.5 m), while pine forests have moderate values (1-2 m) and the rest of the island has low values (up to 1.5 m) (Figure 11). Several parts of the island create fires with large size, especially on the west and north. Points with large values in the source sink ratio map had ignitions that generated large fires relative to the probability of being burned by other pixels (burn probability). Conversely, pixels with small values generated small fires relative to the probability of being burned by a fire originating elsewhere (Ager 2012).

Patch variation within land designations is described by scatter plots of average patch values for simulation outputs. Scatter plots helped in locating which of these features are in greater fire risk. For Lesvos, scatter plot in Figure 12 shows which vegetation types have the potential of frequent and large fires. Evergreen shrublands has both high burn probabilities and conditional flame length, followed by sparse *Pinus brutia* forests, while the lowest values are found on agricultural areas and chestnut trees. For the creation of the other scatter plots, buffer zones were defined around each feature. In particular, scatter plot in Figure 13a shows fire risk for monuments and sites of important historic value, calculated within a 300 m buffer zone. All of the sites have a small fire hazard, with CFL less than 1 m and only four sites have burn probabilities greater than 0.001. In Figure 13b, houses outside urban areas have been buffered with a 50 m zone, the majority of which have low CFL (<1 m), but several sites were identified to have high hazard (BP >0.001 and CFL >1.5 m). In Figure 13c, touristic sites such as beaches and hotels have a buffer zone of 300 m around them, and only five sites were identified with high hazard. Finally, the important nesting places of bird populations in the island are showed in Figure 13d scatter plot (*Sitta krueperi* and raptors: *Buteo buteo, Circaetus gallicus and Accipiter gentilis*). Several nests where identified of having high fire hazard, especially for *Sitta krueperi*, while raptors reside in more safe areas.

For Messenia, kernel based BP (Figure 14) have higher values compared to random based BP, especially in the areas of N and central parts. High BP can be noticed on the S and SW edge on chaparral sites, places that have important tourist activities. On central and N, vegetation types are mostly abandoned and reforestated old agricultural areas dominated by a mixture of grass, phrygana, evergreen shrublands and olive and oak trees. Also, high BP values can be seen on the SE part on the leeside of Mt. Taigetos, where dense forests exist (fir and pine trees). The average fire size of historic ignitions is 206 ha, with minimum and maximum size of 1.44 and 1,640 ha, while percentiles (of 25, 50 and 75) have fire sizes of 66, 120 and 300 ha, respectively. Fire sizes are larger compared to Lesvos Island results, similar to the real fire pattern.

There are several extensive areas with CFL values greater than 2 m, but the majority of the study area has values less than 1 m in Messenia (Figure 15). The parts that produce the largest fire events are mostly located centrally and on the SW and N. The source sink ratio reveals that big fires are originated mostly on the SE and in several parts of the west coast where strong western winds prevail. From the scatter plot of vegetation types (Figure 16) it is evident that the higher hazard is produced on shrublands, mixed forest with shrublands and *Pinus halepensis* forests (sparse and dense). High BPs are produced on oak forests and grasslands. Orchards and vineyards have very low hazard and the rest vegetation types have CFL values less than 1.5 m.

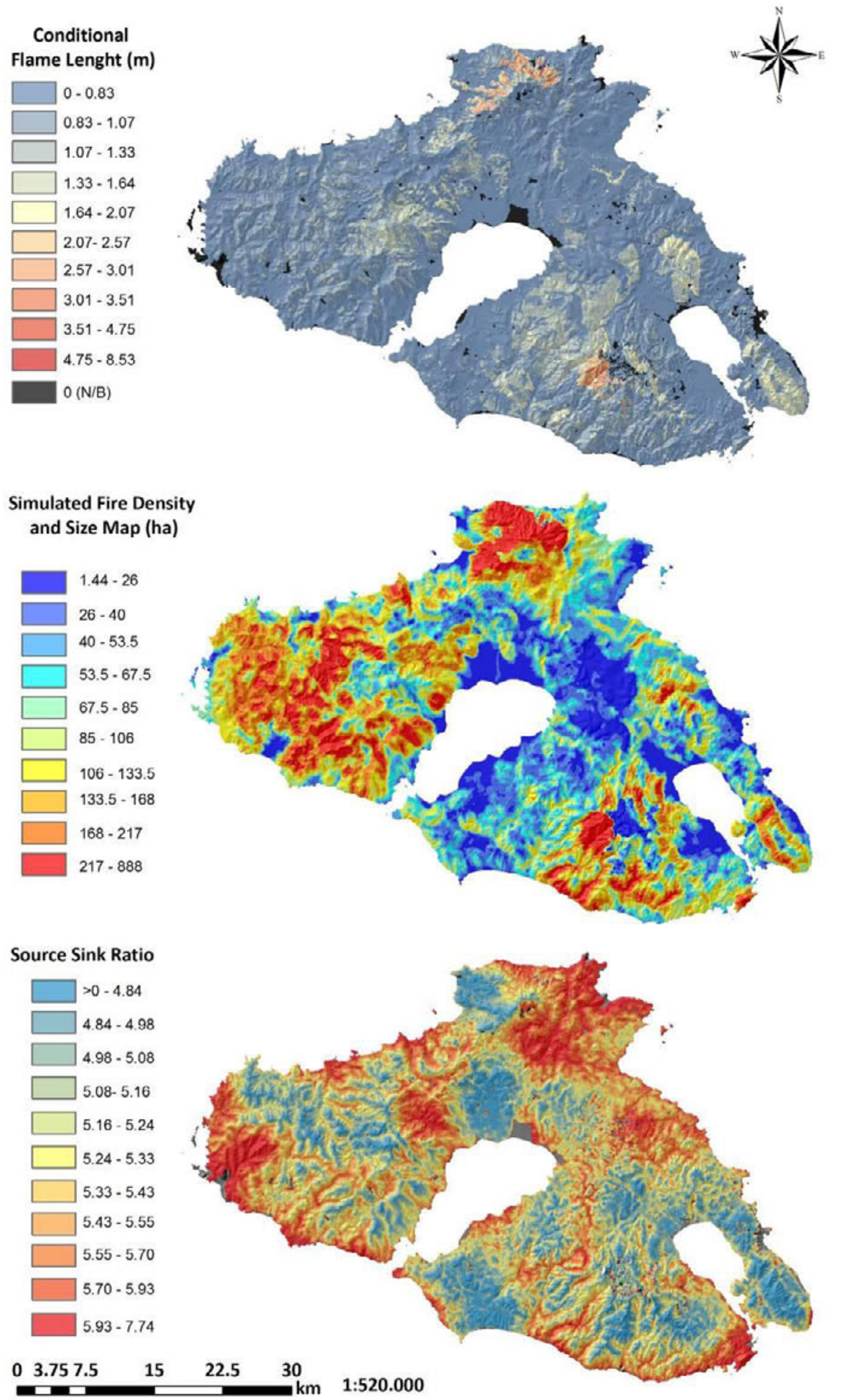


Figure 11: Conditional flame length, fire density and source sink ratio maps of Lesvos Island

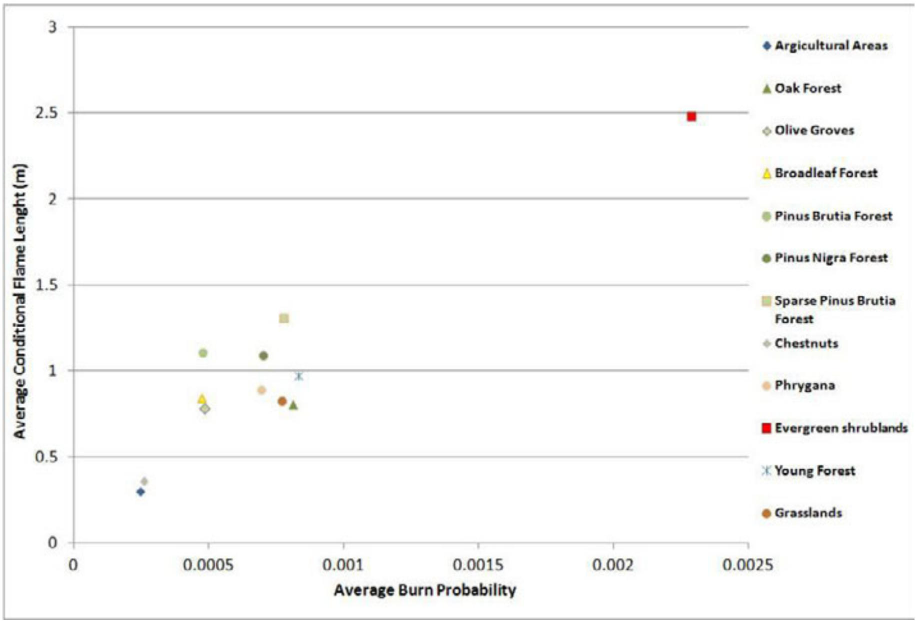


Figure 12: Fire risk for each vegetation type of Lesvos Island

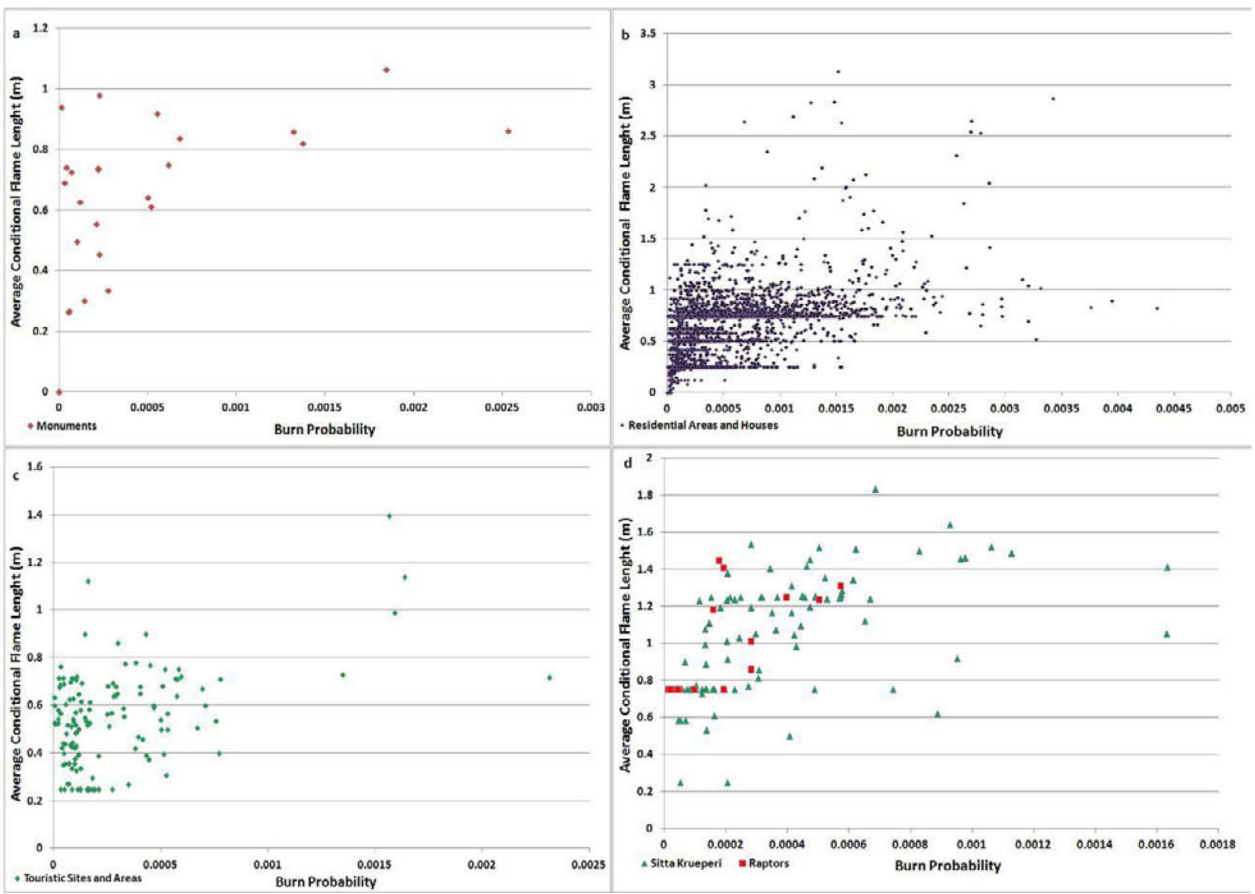


Figure 13: Fire risk for monuments (a), houses in WUI areas (b), touristic sites and places (c) and important bird nesting sites (d) of Lesvos Island

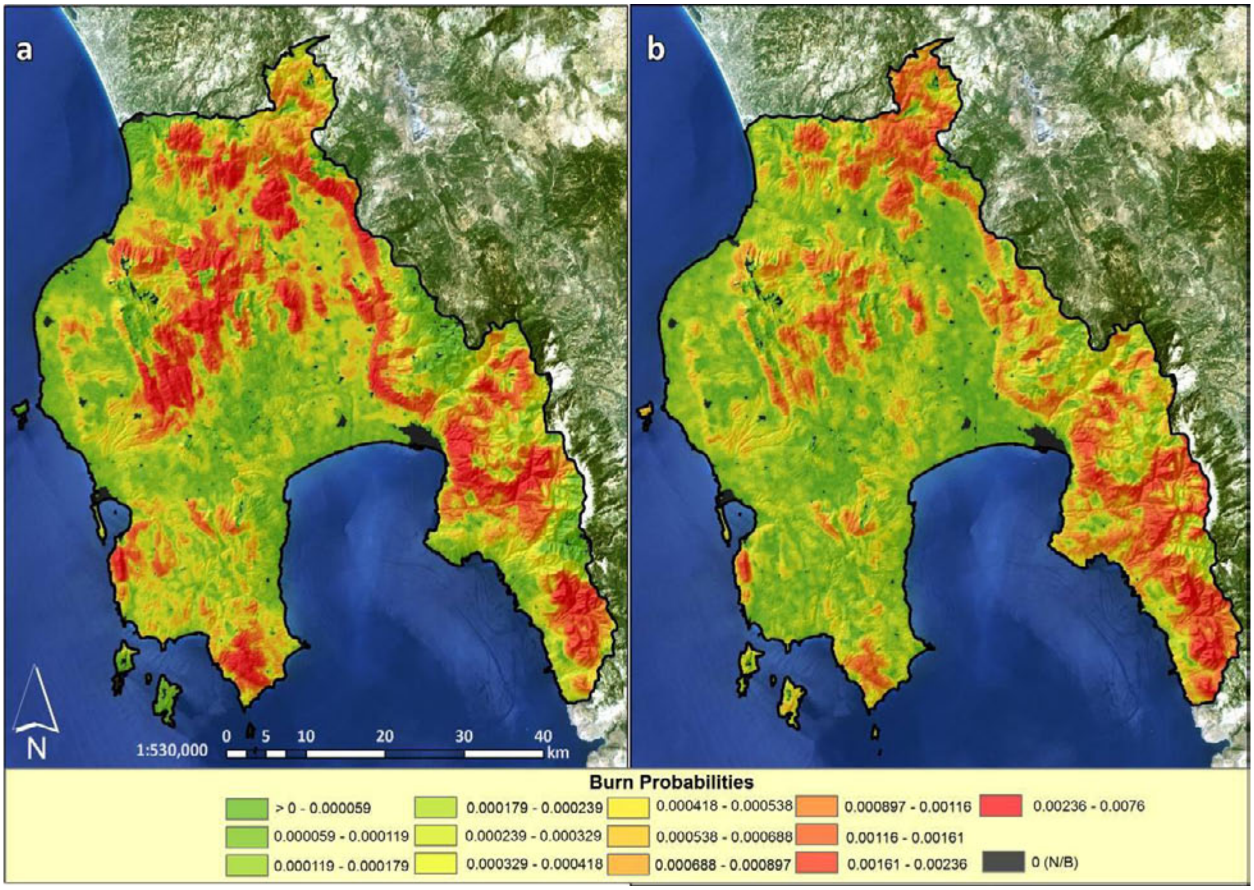


Figure 14: Burn probabilities for historic ignitions (a) and random ignitions (b) in Messenia

Fire hazard in Messenia for monuments was calculated on a buffer zone of 300 m around monasteries and 100 m around archaeological sites (Figure 17a). In contrast to Lesvos monuments, fire hazard is high for several sites, having high BP and CFL values (>0.002 and >2 m, respectively). The majority of WUI areas (Figure 17b) exhibit low fire hazard expect for 30 sites. Regarding touristic places (Figure 17c), only very few sites have high fire hazard. Finally, the vast majority of wildlife habitats (Figure 17d) have moderate to low fire hazard in Messenia.

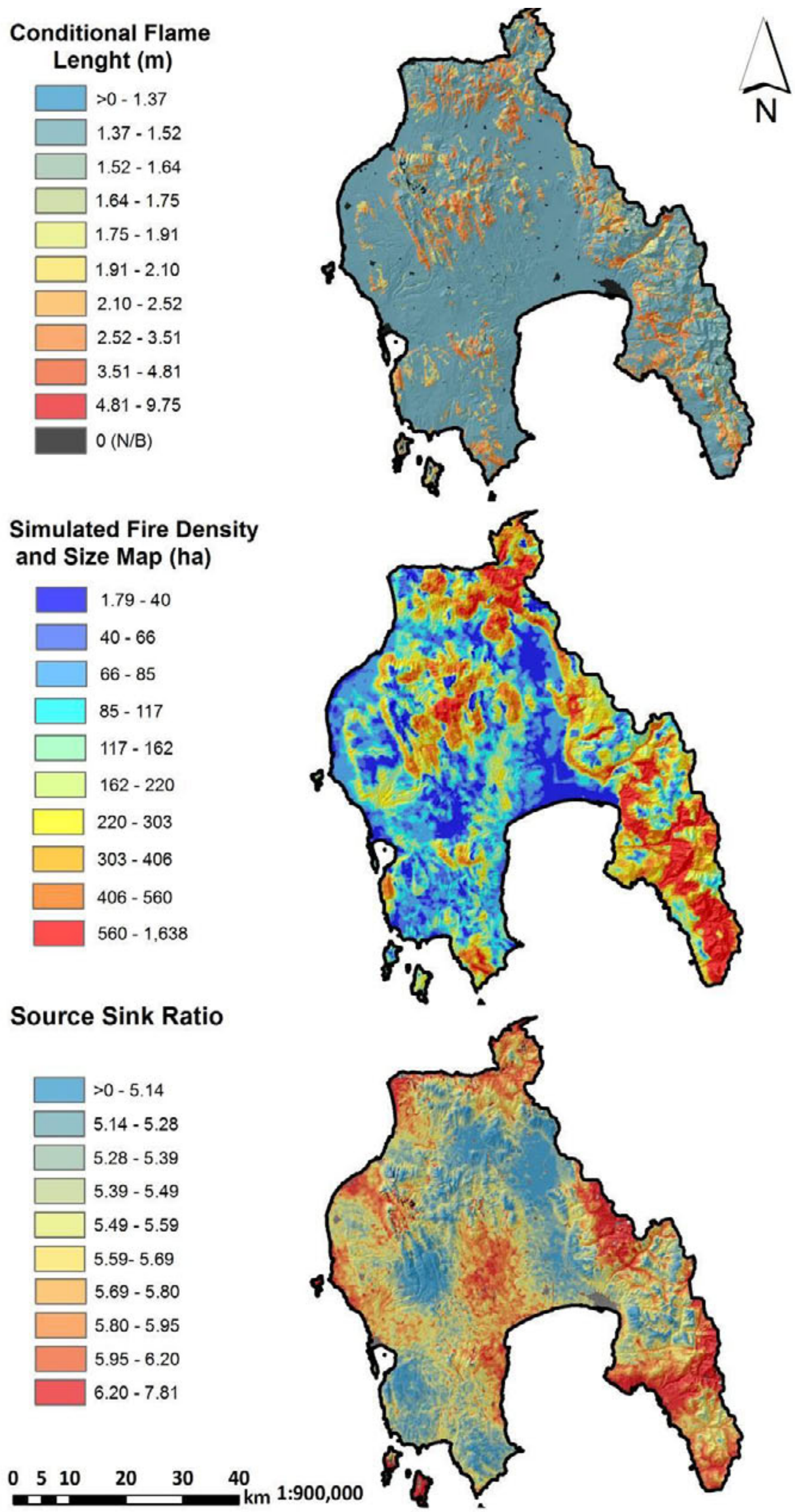


Figure 15: Conditional flame length, fire density and source sink ratio maps of Messenia

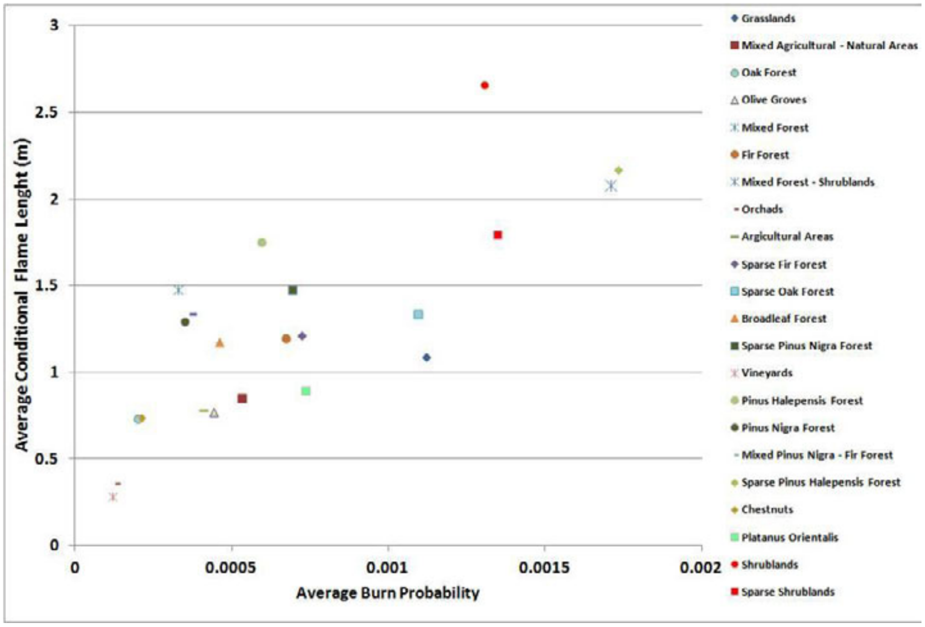


Figure 16: Fire risk for each vegetation type of Messenia

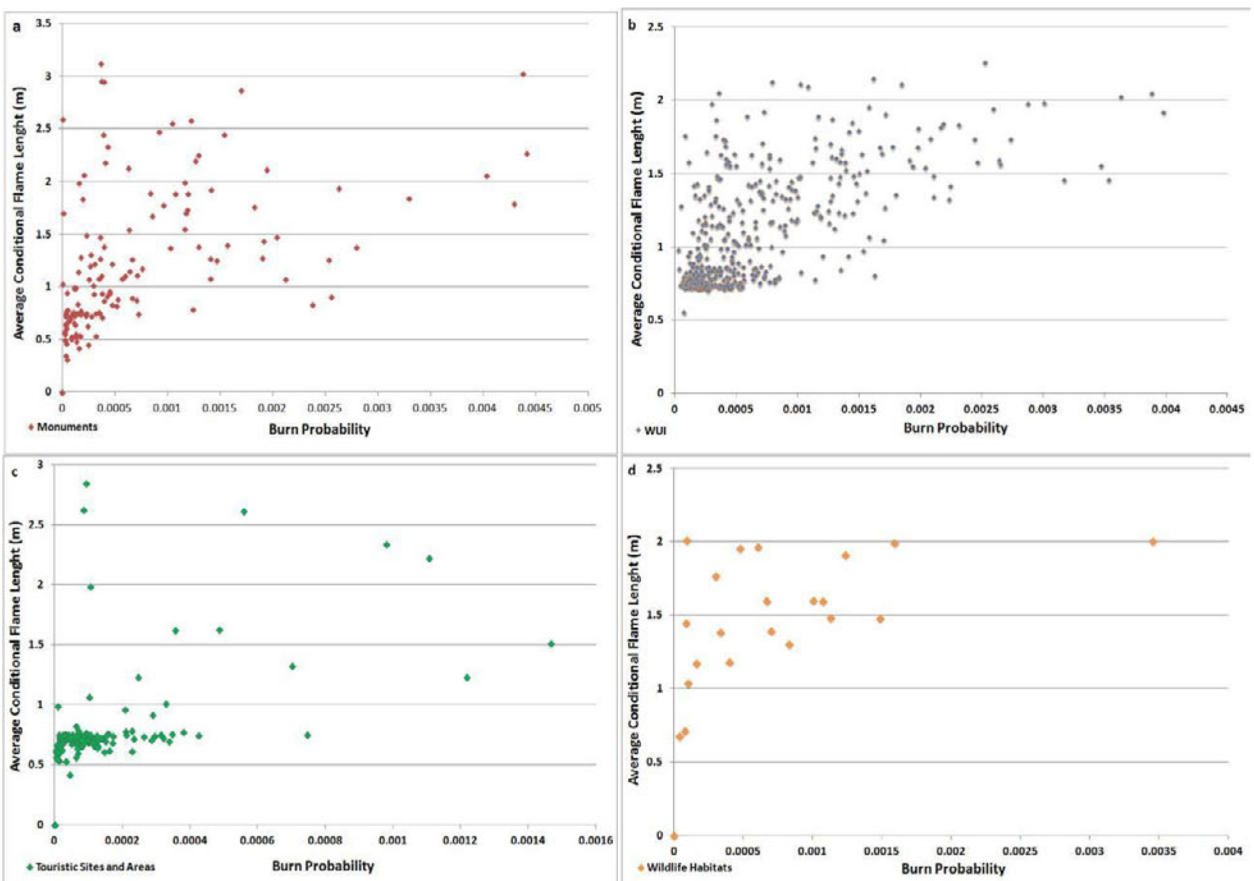


Figure 17: Fire risk for monuments (a), WUI areas (b), touristic sites and places (c) and wildlife habitats (d) of Messenia

Conclusions

The calculation of fire hazard through thousands of fire simulations with Randig revealed an underlying pattern of the phenomenon for two study areas in Greece. The most hazardous parts of Lesvos Island are located in the west in terms of burn probabilities and fire size, while the most intense fire events can be produced in the N and S. For Messenia, the SE part has the highest BP, followed by the N, central and SW areas, with high fire intensities in several places and substantially increased compared to Lesvos Island. Different ignitions patterns revealed that there are no substantial differences of whether the simulation is conducted with historic or random ignition, except for the exclusion of some areas that had low kernel values and had only few ignitions; while CFL values were identical with minor differences. This suggests that burn probability patterns are largely created by fire growth under combinations of weather and fuel patterns rather than ignition sources.

Regarding simulation of historic fire events, FARSITE achieved better fire prediction results but MTT results were not much different. The simplicity of inputs to MTT compared to FARSITE means that it is efficient for risk analysis involving thousands of simulations. For Messenia, fire prediction accuracy is moderate, but for Lesvos is high. Wind speed and direction inputs played an extremely important role in the prediction accuracy, dependant on weather station type and specifications (e.g. wind measurement height, instrument accuracy, data recording intervals etc.), location / elevation (exposure of installation area, terrain ruggedness, presence of wind obstacles etc.) and proximity to the fire, wind direction input method (e.g. uphill, gridded, user defined) and wind speed data type (e.g. time interval, gusts, averages). Errors may also be introduced from possible insufficient fuel model assignment and coarse-scale canopy characteristics layers, especially for the case study of Messenia. Simulations revealed key factors that should be altered before conducting simulations with Randig. It proved extremely important to have fuel model specific fuel moisture values instead of similar values, based on weather station measurements close to certain vegetation types. Adjustments were also made based on the knowledge gained from observations of the actual fire behavior on each vegetation type. Another adjustment was made on the geographic data used to define the fire environment (landscape file). Messenia is not an island like Lesvos that has boundaries defined by shoreline, but an intact land with adjacent regions that produce fires that can enter inside the study area (a usual and noticed event). As a result, we need to provide data from the adjacent regions to create a broader area that will enable fire to spread back and forth and then clip data to Messenia's borders. Simulations needed a very powerful machine to support them, otherwise the amount of time required to finish the simulations of 100,000 fires exceeded a four-day period on a regular four-core machine.

The use of scatter plots to identify fire hazard revealed several sites and values-at-risk that have the potential to be harmed by a future fire event. Maps or coordinates could be used to warn and inform both the owners (in case of hotels and houses) and the state (for the case of wildlife habitats) to take the necessary measures and precautions for protection. Finally, future research will implement further this method to study areas of Greece and will propose fuel treatment and fire risk reduction measures.

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