



Assessing fire risk using Monte Carlo simulations of fire spread

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ARTICLE INFO

Article history:

Received 29 January 2008

Received in revised form 2 September 2008

Accepted 4 September 2008

Keywords:

Fire risk

Fire behavior

Fire spread model

Monte Carlo simulation

Fire management

ABSTRACT

Understanding the spatial pattern of fire is essential for Mediterranean vegetation management. Fire-risk maps are typically constructed at coarse resolutions using vegetation maps with limited capacity for prescribing prevention activities. This paper describes and evaluates a novel approach for fire risk assessment that may produce a decision support system for actual fire management at fine scales. FARSITE, a two-dimensional fire growth and behavior model was activated, using ArcView VBA code, to generate Monte Carlo simulations of fire spread. The study area was 300 km² of Mt. Carmel, Israel. FARSITE fuel models were adjusted for Mediterranean conditions. The simulation session consisted of 500 runs. For each simulation run, a calendar date, fire length, ignition location, climatic data and other parameters were selected randomly from known distributions of these parameters. Distance from road served as a proxy for the probability of ignition. The resulting 500 maps of fire distribution (the entire area burnt in a specific fire) were overlaid to produce a map of 'hotspots' and 'cold spots' of fire frequency. The results revealed a clear pattern of fires, with high frequency areas concentrated in the northwestern part. The spatial pattern of the fire frequency map bears partial resemblance to the fuel map, but seems to be affected by several other factors as well, including the location of urban areas, microclimate, topography and the distribution of ignition locations (which is affected by road pattern). These results demonstrate the complexities of fire behavior, showing a very clear pattern of risk level even at fine scales, where neighboring areas have different risk levels due to combinations of vegetation cover, topography, microclimate and other factors.

Comparing the distribution of historic fires in the region against the map of simulated fire frequency indicated that most fires tended to coincide with higher risk levels. This fact supports the hypothesis that simulated fire frequency may serve as a reliable surrogate for fire risk. Thus, Monte Carlo simulations of a fire spread model may produce high-resolution fire-risk maps that could be used for long-term strategic planning of fire prevention activities.

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1. Introduction

Fires are a major source of forest destruction in the Mediterranean Basin, causing enormous ecological and economic damage, as well as loss of human life (Maselli et al., 2000). Mediterranean fires are largely determined by climatic conditions; long, dry summers with high temperatures reduce the moisture content of forest litter to below 5%. Consequently, even a small flame (such as a smoldering cigarette), can potentially lead to severe wildfire (FAO, 2006). Environmental factors such as fire history, vegetation cover, soil type or topography, all affect fire ignition and behavior (Calabri, 1990). Natural fires were a major

force in the biological evolution of the Mediterranean biota (Naveh, 1975). Today, the majority of fires are caused by humans (Naveh, 1994; FAO, 2006).

During the past several decades, a sharp increase in fire events in Mediterranean forests has been observed, especially where the anthropogenic pressure is high (FAO, 2001). This tendency became obvious in the Mediterranean ecosystem of Mt. Carmel in northwestern Israel, which experienced increasing numbers of forest fires to various extents and levels of severity, as a result of increasing human activities (Wittenberg et al., 2007). Fire-risk evaluation, and in particular, understanding the spatial pattern of fire, are essential for Mediterranean vegetation management (Maselli et al., 2000). This fact is crucial in regions such as the Mediterranean, where high ecological value coincides with dense population (Shoshany and Goldshleger, 2002). To this end, fire-risk maps have become widely used in many countries (Bonazountas

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et al., 2005). These risk maps are typically constructed at coarse resolutions (pixel size = 10^2 – 10^4 ha) using fuel models or vegetation maps (Keane et al., 2001; Riano et al., 2002; Chuvieco et al., 2004; Hessburg et al., 2007; Jolly, 2007). Several studies dealt with risk mapping of different factors in the Mediterranean forests (Maselli et al., 2000). They classified vegetation cover types by integrating spectral and ancillary data using satellite data collected in spring and summer periods. Other studies used remote sensing to construct fuel maps as surrogates for fire risk (Lasaponara and Lanorte, 2007).

Nevertheless, such risk maps have limited capacity for prescribing fire prevention activities. Allocation of such activities at local scales would require a high-resolution risk map (pixel size = 10^{-1} – 10^1 ha), where the hotspots of high risk would be delimited at local and landscape scales. The typical method for mapping fire risk using vegetation maps cannot produce such fine resolutions, and a different approach is required. Fuel load is a major component of fire risk. However, the risk level is also affected by other factors, such as weather conditions, ignition sources and topography.

This paper presents an approach that evaluates fire risk using most of the factors affecting fire behavior at high resolution. An important advantage of such high-resolution fire-risk maps is that they may enable managers to plan long-term strategic fire prevention activities, such as blocking interventions or border zones (Galtie et al., 2003), based on a detailed, fine resolution fire-sensitivity map. The use of mathematical models of fire spread (Rothermel, 1972) within Monte Carlo simulations may be able to produce such high-resolution risk maps.

Fire spread models have been investigated in many scientific studies (reviewed by Pastor et al., 2003), and applied as predictive tools in various managing agencies (reviewed by Scott and Burgan, 2005). These reviews indicate that such models have not been used previously to construct fire-risk maps. However, a first step to this end was taken by Mbow et al. (2004), who used multiple simulations of fire spread to highlight (simulate) burnt vs. non-burnt areas at a very fine resolution. This paper presents an improved approach, by including the spatial distribution of potential ignition sources and subsequent spread, activated through a Monte Carlo technique in the fire spread simulation. The goal here is to investigate the potential usefulness of this approach as a possible tool for fire-risk mapping at high resolution. The major product ultimately will be a decision support system for actual fire management.

2. Methods

2.1. The simulation model

The main tool used in this risk analysis is FARSITE, a two-dimensional fire spread simulation model developed by the USDA Forest Service (Finney, 1998). FARSITE uses spatial information on topography and fuels along with weather conditions. It is widely used by the US National Park Service, USDA Forest Service and other land management agencies to simulate the spread of wildfires across the landscape (Keane et al., 2001; Stratton, 2004; Dasgupta et al., 2007; Ryu et al., 2007).

The model requires a variety of inputs, including landscape information (various topography and vegetation cover maps), fuel information (fuel models, moisture, conversions and adjustments), weather conditions based on a concatenation of three weather stations located in the study area (e.g., wind direction, air temperature, relative humidity) and other miscellaneous data (Table 1).

2.2. Study area

The study area (330 km² with an altitude range of 40–520 m) is the entire region of Mt. Carmel, Israel, and surrounding lands, excluding urban areas (Fig. 1). The Mt. Carmel ridge (35°E, 32°N) rises from the northeastern Mediterranean Sea shore. Its Mediterranean climate is characterized by dry, hot summers and rainy winters (annual precipitation ranges from 550 mm near the coastal plane to 750 mm at the highest elevations).

Naveh (1975) characterized the region as a Mediterranean fire bio-climate. The area provides a complex scene for mapping fire spread, owing to its fine-scale heterogeneity in topography and vegetation. Mt. Carmel has an annual average of 11 wildfires, mostly during the dry period, from May through September (Wittenberg et al., 2007). Eight large wildfires were recorded on Mt. Carmel during the past 27 years, which consumed areas of 80–530 ha each, and dozens of smaller fires. The sources of all fires in the region are anthropogenic.

2.3. Simulation framework

The simulation session consisted of 500 runs, where each run represented a single simulated fire. Ignition location and all fire parameters were selected randomly for each run from predetermined distributions (see below). To automate the process of multi-simulation, we activated the FARSITE GUI using ArcView VBA Code, and additional analysis scripts. The resulting 500 maps of fire distribution were overlaid (fire distribution is the entire area burnt in a specific fire); location-specific fire frequency served as a surrogate for fire risk.

2.4. Model parameters

For each of the simulations, a calendar date was randomly drawn from a uniform distribution of dates during the typical fire period (June–August). The length of the fire was selected randomly from a uniform distribution between 1 and 24 h, reflecting the typical fire length in this region.

Climatic data (wind direction and intensity, air temperature and relative humidity) were selected for the respective dates and times of fire in each simulation, using actual data collected at 0.5 h intervals during 2004 (this year represents typical average weather) at three climatic stations: Haifa University, Ein Hashofet

Table 1

List of inputs and parameters used in FARSITE simulation.

Input type	Input
Landscape (GIS layers)	Latitude Elevation map Slope map Aspect map Fuel map Vegetation map Cover map
Fuel	Adjustment Fuel moisture
Climatic	Wind speed and direction Relative humidity Temperature
Ignition probability	Road probability map Random percentage Number of simulations
Miscellaneous	Burn period
Ignition point	Ignition point

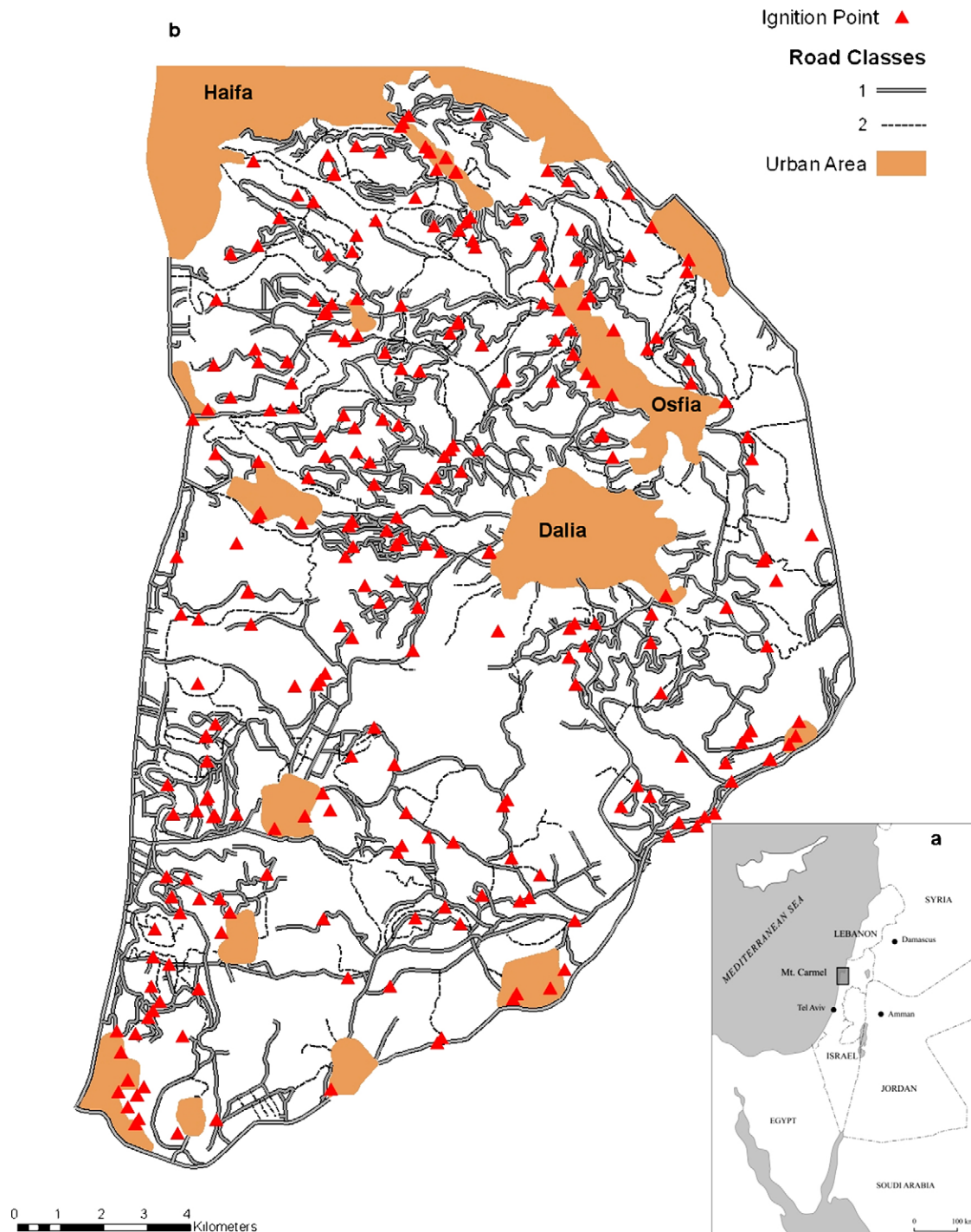


Fig. 1. Maps of the study area: (a) regional map showing the location of the Mt. Carmel study area in Israel, and (b) detailed map of the study area, showing roads and ignition locations.

and Ein Carmel (Data source: Israel Meteorological Service). In each simulation, a date + time and the corresponding climatic record were drawn at random. Digital layers of elevation, aspect and slope angle were derived from a digital elevation model (DEM) at a spatial resolution of 25×25 m. All urban areas were digitized using an orthophoto of the study area. In these urban regions, fuel model #93 was applied without ignitions or fire propagation (Anderson, 1982).

A canopy cover layer, used in FARSITE simulation, was constructed for the entire study area. Canopy cover was defined

as the proportion of woody cover in a pixel (25×25 m). The basis for this layer is a 2002 color orthophoto at a high spatial resolution of 1 m per pixel. Cover was classified into two categories (woody vegetation vs. open/herbaceous) using a supervised classification system. Accuracy assessment was conducted against 100 sites, which were visited in the field. Overall accuracy was 0.92. Woody vegetation density at each 25×25 m cell was calculated, and this density map was used in the simulation as the canopy cover layer. The process and the product were described in detail in Carmel and Stoler-Kavari (2006).

2.5. Ignition risk

Most wildfires in Israel are anthropogenic, and thus a map of human activity intensity would be a plausible surrogate for ignition risk. Here, distance from the nearest road was used as a surrogate for human activity (Riitters and Wickham, 2003) and of ignition risk. All roads and hiking trails in the study area were digitized, and buffer zones were created around them. A buffer zone of 30 m was constructed around paved and non-paved roads, and a buffer of 10 m was constructed around hiking trails and footpaths (Fig. 1b). In the simulation session, 80% of all ignition locations were selected randomly within the buffer zones, and 20% were selected randomly within the entire study area.

2.6. Fuel models

A prerequisite of this type of study is to adjust the model in order to account for Mediterranean conditions. In the present study, fuel models of FARSITE (Anderson, 1982; Scott and Burgan, 2005) were applied to the Mediterranean vegetation (Tabara et al., 2003; Arca et al., 2006; Duguay et al., 2007). The basis for the fuel map was a detailed map of Mediterranean vegetation formations on Mt. Carmel, based on an intensive survey of the entire area (Lahav, 1983). Various changes have taken place in the region since the map was constructed, and in particular, woody vegetation age and density have typically increased (Kadmon and Harari-Kremer, 1999). However, the basic vegetation formations were not replaced. A single fuel model was assigned to each major vegetation formation in the eastern region (Table 2), and adjustments were made to the fuel models of Scott and Burgan (2005). The Mediterranean woodland scrub is much less flammable than California chaparral, probably since there is much more dead fuel in the chaparral (Jose Moerno, personal communication). The documented rates of fire spread in Chaparral range between 15 and 80 km/h under moderate wind speeds of 2 m/s (Fujioka, 2002), while the fastest reported rates of spread in Mediterranean woodland scrub are 8–10 m/min (Gil Sapir, personal communication). The respective fuel model #4 (chaparral) was therefore suppressed by a factor of two, as a conservative estimate. Fuel model #1, applied to the Mediterranean herbaceous vegetation, was also suppressed by a factor of two, since the herbaceous layer in Mediterranean uplands is lower and thinner than in California, due to heavy grazing (Naveh, 1967). Fuel model #10 (conifer forests) was applied to the Eastern Mediterranean pine forests with an adjustment factor of 4. This decision was made based on ubiquitous indications from Spain, Greece, and Israel (Naveh,

1994; Liodakis et al., 2003, 2006; Maestre and Cortina, 2004) on the extreme flammability of Aleppo Pine (*Pinus halepensis*), which is the species that forms the pine forests of Mt. Carmel. A rate of fire spread of 70 m/min was recorded for this species in Greece (Vakalis et al., 2004), which is much more than typical rates of spread in pine forests in North America (Alexander and Cruz, 2006). Fig. 2 illustrates the distribution of fuel models in the study area.

2.7. Simulation model and historic fires

A general correspondence between the hotspots on the risk maps and the location of historic fires may provide some indirect support for the model. A spatial database of historic fires on Mt. Carmel was compiled by Tesler et al. (2007). This database contains the fire distribution (the entire area burnt by a specific fire) for all large fires that occurred on Mt. Carmel between 1983 and 2006. To assess the degree of correspondence between the simulated fire frequency map and historic fires, distributions of historic fires were overlaid on the fire frequency map. For each historic fire, the proportion of fire distribution coinciding with each frequency level was tabulated. Each frequency level corresponded to 10% of the study area. The null hypothesis here is that the distribution of historic fires would be evenly spread across frequency levels.

3. Results

The buffer zones that were drawn around all roads and paths on the mountain comprised a total of ~25% of the study area. There was a high density of ignition locations in the 500 simulation runs, but in some areas away from roads, only few ignition locations existed (Fig. 1b). The distribution of fuel models in Mt. Carmel (Fig. 2) is characterized by a fine mosaic of models 10, 4, and 93 (planted pines, evergreen scrub, and agriculture, respectively). A single large patch of model 1 (short grass) exists in the south part of the mountain.

The results of 500 simulation runs of fire spread revealed a clear pattern of fire frequency on Mt. Carmel, with most of the high frequency areas concentrated in the northwestern part of the region (Fig. 3). Areas that had been simulated burnt more than eight times (hereafter termed hotspots) comprise ~20% of the entire region. The major hotspots are, from north to south: The University Forest, Beit Oren Forest, Nir Etzion Forest and Ofer Forest (Fig. 3). The overall pattern of the risk map bears some resemblance to the fuel map, where most of these hotspots correspond to pine forests. However, some hotspots consist of oaks or mixed forests (such as Nir Etzion), while some pine forests are assigned as low-risk areas. The analysis of hotspot characteristics corroborates this observation: the composition of fuel models in the areas of hotspots was similar to the composition in the entire study area. Similarly, there were no significant differences between the hotspots and the rest of the area in the topography or in the density of woody vegetation.

To assess the degree of correspondence between the risk map and historic fires, the distributions of historic fires on Mt. Carmel mapped by Tesler et al. (2007) were selected and overlaid on the risk map. This analysis revealed that historic fires were strongly associated with the zones of high fire frequency in the simulations map (Fig. 4). In most fires, the burnt area corresponded mostly to areas within the top 30% percentiles in the map of simulated fire frequency, while only small parts of the distribution of those fires was associated with lower fire frequencies map (i.e. areas of lower risk in the simulated map). Two fires occurred more or less evenly on high and low fire probability areas (1998b and 1999a). The area of a single fire (1999b) corresponded mostly to areas of low fire

Table 2
List of fuel models used in this study.

Eastern Mediterranean vegetation type	USFS model name	Model #
Anthropogenic elements	Agricultural	93
Bare ground	Bare ground	99
Calicotome dominated shrubland	Low load humid climate shrub	146
Ceratonia dominated woodland forest	Chaparral	4
Herbaceous vegetation	Short grass	1
Evergreen Oak (<i>Quercus calliprinos</i>) dominated forest	Chaparral	4
Deciduous Oak (<i>Quercus ithaborensis</i>) dominated woodland park	Chaparral	4
Pine dominated forest	Timber	10
<i>Pistacia lentiscus</i> dominated shrubland	Low load humid climate shrub	146
<i>Sarcopoterium spinosum</i> dominated shrubland	Moderate load dry climate shrub	142

Fuel Models 1–99 follow (Anderson, 1982), and models 142 and 146 follow (Scott and Burgan, 2005).

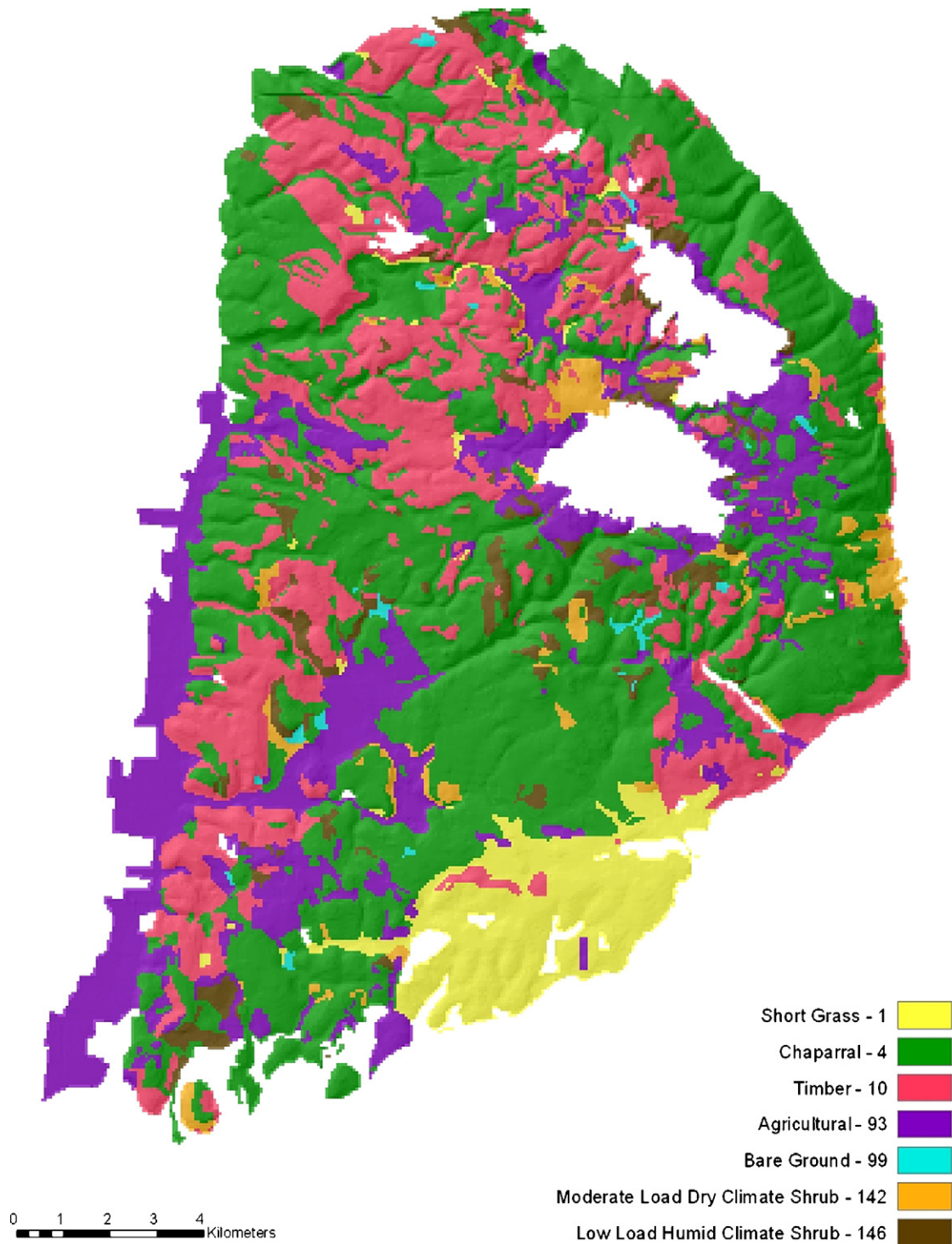


Fig. 2. Map of the spatial pattern of fuel models for the Mt. Carmel region.

probability. Analysis of the traits of all fires (e.g., season, wind, area) did not find any unique characteristics of those fires.

4. Discussion

Existing fire danger maps show fire risk at coarse spatial resolution. For example, the fire-risk map currently used in Israel assigns the same risk level to the entire study area (300 km²) (John Woodcock, personal communication). In contrast, these results show a very clear pattern of risk at fine resolution, where

neighboring areas (hundreds of meters apart) may have very different risk levels due to combinations of topography, vegetation cover, etc. The Mt. Carmel risk map highlights high risk as well as low-risk regions (for example, the village of Ein-Hod is located within a high-risk area, while other urban areas such as Osfia, Dalia and Haifa are much less endangered).

Fire risk assessment focuses primarily on vegetation and fuel, and risk maps are typically based on fuel models and/or vegetation maps (e.g. Chuvieco et al., 2004; Hessburg et al., 2007; Jolly, 2007). However, fire behavior (and therefore fire risk) is a complex

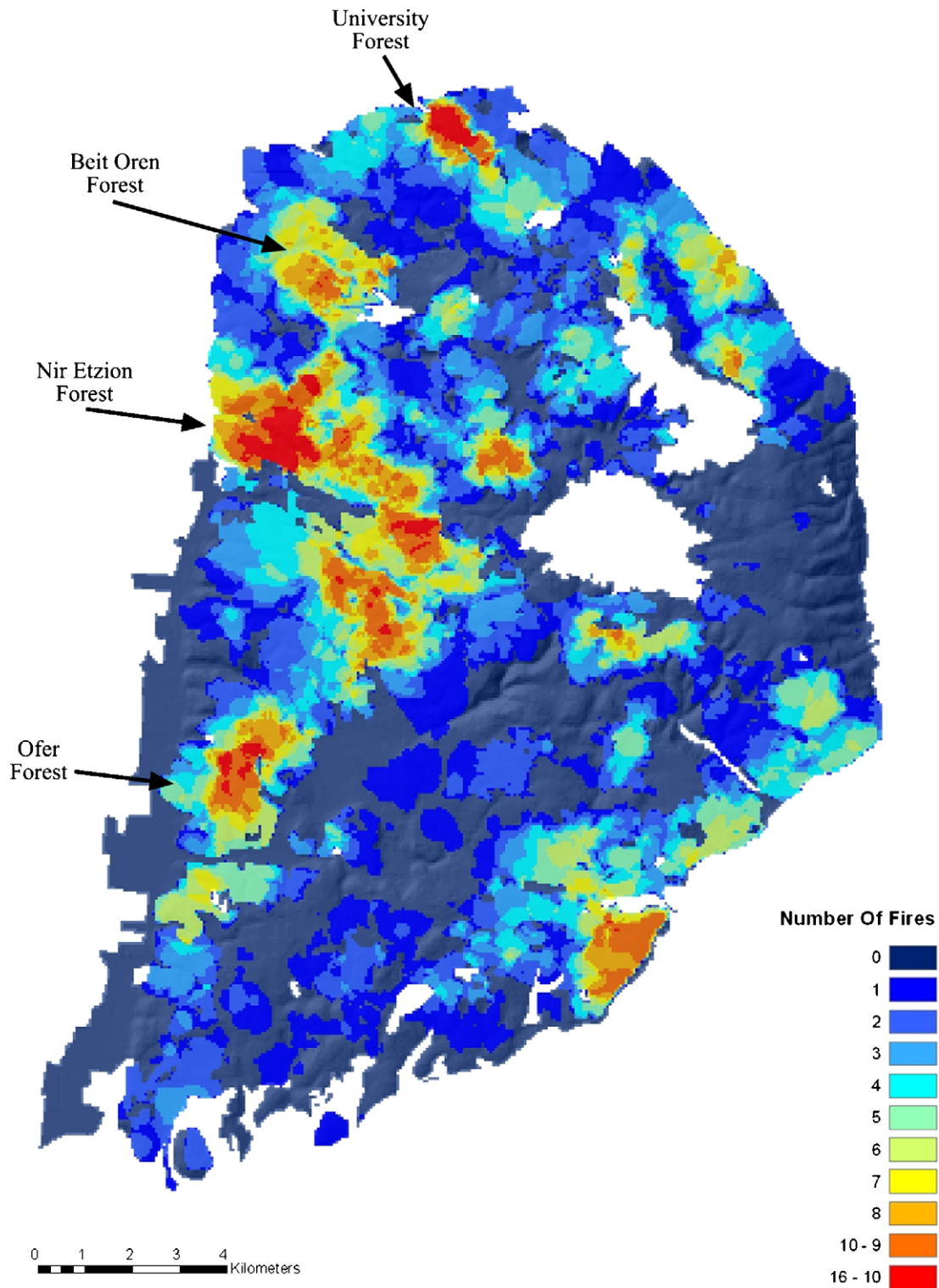


Fig. 3. Spatial pattern of fire frequency in Mt. Carmel derived from 500 simulations of fire spread.

phenomenon, affected by local topography, microclimate, and human impact, in addition to vegetation cover. The results of this analysis demonstrate these complexities. The emerging pattern of simulated fires seems to correspond to several layers independently: fuel model map, the spread of ignition points (which, in this study, is affected by the road pattern), and human impact. These findings echo several recent studies that link the spatial pattern of fires to factors such as the pattern of fuel (Chuvieco et al., 2004),

topography (Hessburg et al., 2007), weather (Arca et al., 2006), and human impact (Tabara et al., 2003). Human impact is apparent at agricultural and settlement locations that act as artificial blocks. It was found (Tesler et al., 2007) that the distribution of the historic fires on Mt. Carmel was not coincidental. Most fires occurred near areas of intense human activity.

An existing fire-risk map currently in use by the Israel Forest Authority portrays the entire Mt. Carmel as a homogeneous region

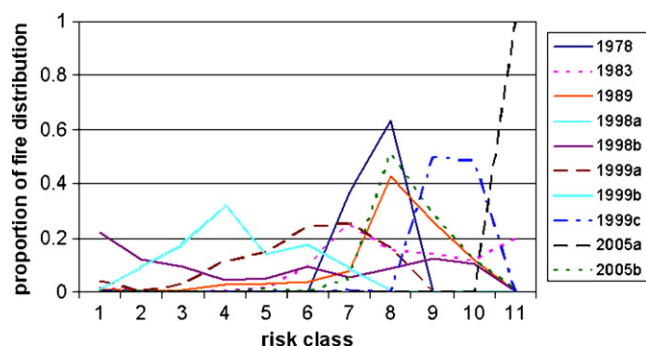


Fig. 4. Proportion of fire distribution corresponding to each risk level for historic fires on Mt. Carmel during the period 1970–2005 (data on fire distribution taken from Tesler et al., 2007). Fires are listed by the year of event where two or more fires in the same year are denoted by small letters.

with a single fire risk level. In contrast, these results reveal a complex pattern at fine scales, where some local areas have higher fire risk than others (Fig. 3). The patterns revealed in this figure, resulting from many simulations, are supported by the distribution of the majority of the large historic fires (Fig. 4).

Previous studies have presumed that fuel levels are the single most important factor that would determine fire risk. In contrast, these results show that there is no single main factor that determines fire risk. No clear correspondence was found between the spatial pattern of the fuel map, and the pattern frequency of simulated fires. Other major factors such as topography and vegetation also did not alone dominate the resulting pattern of fire frequency. Apparently, there is an entirety of factors which, together, act synergistically to affect fire risk.

These findings indicate the complex nature of forest fires, and demonstrate that fuel load by itself may not be a sufficient predictor of fire risk. This approach evaluates fire risk at high resolution using most of the factors affecting fire behavior. These efforts demonstrate the feasibility of this approach, and the value of its product.

Recently, there have been several studies that assessed the performance of FARSITE in predicting actual fires (Fujioka, 2002; Arca et al., 2007; Duguy et al., 2007). These studies showed some differences between the predicted and actual distribution of fire, in a single specific fire. The approach used here involves numerous simulations, where there is no attempt, or need, to predict the exact location of any single fire. The focus is on the overall spatial pattern of fire occurrence. This pattern would be depicted coherently, regardless of the performance of the model for a single fire, since mismatches in a single simulation are likely to be cancelled out within the Monte Carlo process. The validation of this approach should not be at the level of a single fire, but at the level of the general pattern. The overall correspondence between the simulations map and distributions of historic fires points to the robustness of this method. It is therefore justified to use the frequency map of simulated fires as a risk map for the relevant region.

5. Conclusions

The general correspondence between areas of high fire frequency in the simulations and areas of historic fires supports the interpretation that areas of high simulated fire frequency are high-risk areas. The Monte Carlo simulations of a fire spread model described in this paper appear to be very useful in producing a high-resolution fire-risk map. Such risk maps can prescribe fire prevention activities at fine scales: border zoning, forest thinning

and allocation of fire fighting forces. In short, high-resolution fire-risk maps will enable local managers to plan long-term strategic fire prevention activities.

Acknowledgments

This study was funded by a KKL Forest Research Grant. Data on historic fires were kindly provided by Lea Wittenberg, Dan Malkinson, and Naama Tesler.

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