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Spatio-temporal perspectives of forest fires regimes in a maturing Mediterranean mixed pine landscape

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Abstract It has been suggested that during the past several decades, the frequency and the intensity of wildfires have markedly increased in the Mediterranean basin. We came to assess this postulation in the forested region of Mount Carmel, Israel. This region is characterized by *Quercus* spp. and *Pistacia* spp. maquis and has been intensely afforested with *Pinus* spp. stands since the 1920s. We compiled a GIS-based database of the fires recorded in the region since 1983, in addition to archiving data beginning from the 1940s. The data were collected from land stewardship agencies' archives, fire departments and aerial photographs. Prior to the early 1980s, no systematic documentation of the fires was available, rather just sporadic qualitative documentation of the large forest fires that occurred. Between 1944 and 1982, only 6 large fires were documented, while after that 11 large fires occurred. Analysis indicated that the spatial distribution of the fires does not occur at random, and their locations are significantly closer to roadsides compared to an expected random distribution. The annual number of fires and the areas burned during the last two decades were not correlated with annual precipitation in any manner. Accordingly, we suggest that the increased number of large forest fires during the last decades is associated with the maturation and senescence of the planted forest coupled with increased human activities.

Keywords Forest fires · Mt. Carmel · Mediterranean fire regime · Afforestation · Ignition cause · Fires spatial distribution

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Introduction

The Mediterranean bioclimatic region has endured a long period of human-induced perturbations (Naveh and Carmel 2003). Many centuries of severe human pressure resulting in burning, cutting and grazing of non-arable lands and clearing, terracing, cultivating and later abandonment of arable portions have created strongly human-influenced landscapes (Pausas and Vallejo 1999). Long-term history of human presence in the Mediterranean basin has provoked intense disturbance regimes compared to other Mediterranean bio-climatic regions in the world (Fox and Fox 1986).

The recent fire history indicates that since the 1960s there is a general increase in the number of fires and the total area of burned regions in the Mediterranean basin, namely in the Iberian, Italian and Greek Peninsulas and surrounding islands (Pausas and Vallejo 1999). Fire statistics compiled from Spain show a clear increase in the number of fires and surface area burned, especially since the mid-1970s. From 1960 to 1973, the mean annual area burned was about 50 kha and the annual number of fires was less than 2,000. Since 1974, the mean annual area burned is about 215 kha, caused by a mean of 8,550 annual fires, and during the late 1990s the area burned was more than 400 kha (Pausas and Vallejo 1999). In recent years, however, it is evident that although the number of forest

fires continues to increase, the total area burned annually is highly variable with a slight decrease during the past 27 years. For Portugal, Spain, France, Italy and Greece, the decadal number of fire increased from 34,645 (1980–1989) to 58,851 (1990–1999) and during the period 2000–2006, more than 61,000 forest fire were recorded. The total area that was burned during these time periods decreased from 557 kha (1980–1989) to 448 kha during the following decade, and slightly increased during the last 6 years as 462 kha were burned during 2000–2006 (JRC-EFFIS 2006). This decrease may possibly be attributed to the public information campaigns and to the improvements in the prevention and fire-fighting capacities carried out in all these countries. In Israel, a similar trend of changes in fire regime is apparent and an evident increase in the number of fire events and total burned area was observed in recent years (Keidar 2001).

The global increase in wildfires is attributed to the possible combined effects of two main factors: climate change (Torn and Fried 1992; De Luis et al. 2001; Pausas 2004; Moriondo et al. 2006) and the general increase of anthropogenic activities and profound land use transformations (Giovannini et al. 2001). The climatic conditions of the Mediterranean basin significantly affect the forest situation. Long and dry summers with average temperature of more than 30°C reduce the moisture content of the forest litter to less than 5%. Under these conditions, conflagration risks are remarkably high (Velez 2002).

In recent decades, industrialization and massive migration from rural areas have led to the abandonment of many fields, increasing the cover and continuity of early successional species, changing the landscape pattern and consequently the fire regime (Moreira et al. 2001; Pausas et al. 2008). The abandonment of crop lands implies a change in vegetation community composition, and structure and accumulation of large and continuous fuel beds that are prone to burn. This phenomenon is coupled with the absence of livestock grazing and natural grazing herbivore populations. Moreover, many of these lands have been covered by extensive pine plantations, which are more fire-prone (Pausas et al. 2004). It is thus assumed that land-use change is the main driver for the increases in fire patterns in recent decades. In addition, the increase in semi-urban populations in rural areas, often in abandoned fields, further contributes to the risk of fire ignitions. As a consequence, it is evident that both the number of ignitions and the area affected by fire increased exponentially from the 1960s to the 1980s (Pausas and Vallejo 1999; Pausas 2004).

In anthropogenic landscapes, however, the relationships between fire characteristics and climate, soil and vegetation properties may be less pronounced (Vázquez et al. 2002). Socio-economic factors bring about two main conflicts: between rural and forest uses (forest–farmland interface) and between urban and forest activities (forest–urban land interface; Velez 2002).

During the past 100 years, extensive areas of the Mediterranean basin have been afforested predominantly with *Pinus* spp. resulting in large and homogeneous areas covered with flammable even-aged pine stands. Such stands are characterized by increased susceptibility to fire and facilitate the spread of the large fires occurring in the last decades (Pausas et al. 2008). Fire risk depends on the amount and type of accumulated flammable organic components. A study conducted in Hungary correlated between stand age and biomass and indicated that Austrian pine stands are subjected to increased risk of fire, especially in the age class of 61–80, due to the accumulation of needle litter, twigs and cones (Cseresnyés et al. 2006). Consequently, large fires are common in the maturing Mediterranean pine forests; e.g., 33% of the areas burned in the Mediterranean basin (Le Houérou, 1974) and 17% of the burned areas in Greece were of *P. halepensis* forests, while the area occupied by these species is only about 8.7% of the forested area (Arianoutsou and Ne'eman 2000). It is suggested that not only the flammability of the pine increases with forest age, but also its susceptibility to diseases and pests (Taylor and Carroll 2004). Yesil et al. (2005) examined the effect of pests on the growth parameters of *Pinus brutia* and indicated that the average age of the infested stands was 75 years old in comparison to 85-year-old trees in the non-infested stands.

In Israel, one of the major damages inflicted to pine stands is associated with the Israeli pine bast scale, *Matsucoccus josephi*, which develops on the three major pine species used for afforestation: *P. halepensis*, *P. brutia* and *P. eldarica*. The typical damage to *P. halepensis*, the major host of the pest, consists of accelerated drying of infested growth. Drying of young seedlings within a few months of infestation is common on natural regeneration sites and in 2- to 5-year-old plantations close to mature stands. In older plantations, the damage is characterized by drying of branches from the lower to the upper parts of the trees, resulting in drying of the tree crown (Mendel and Liphschitz 1988). High population densities of this pest have been observed in plantations and natural forests of *P. halepensis* in Israel leading to severe injury in these forests (Mendel et al. 1994).

In light of the complexity of the landscape and the coupled human–nature interactions and conflicts, we tested the changes of the forest fire regime at the Mt. Carmel region in northern Israel since the beginning of the twentieth century. Additionally, we analyzed to what degree the recent spatio-temporal patterns of wildfires are associated with human activities and environmental factors, and the possible factors dictating the observed patterns. This study

was conducted in light of the clear trend of increasing fire hazards and occurrences in the Mediterranean basin, of which the causes and roots of these recent patterns are relatively ambiguous.

Study site

The Mt. Carmel area represents a system of varied Mediterranean landscapes, differentiated by lithology, soils and vegetation, and by extended anthropogenic activities. The Mediterranean type climate at Mt. Carmel is characterized by dry and hot summers and rainy winters; the average annual precipitation ranges from 550 mm near the coastal plain to 750 mm at the highest elevations.

Its ecological significance was recognized by the declaration of a part of it as a ''biosphere reserve'' (Safriel 1997). Accelerated urbanization is the main anthropogenic processes affecting the region. Thus, the severity of the conservation–development conflict is due to the fact that there are large numbers of urban, peri-urban and rural areas, in a continuous process of expansion and development. In addition, the penetration of urban development into areas of high ecological value considerably increases disturbances and pollution (Shoshany and Goldshleger 2002).

Forest–agriculture transitions and conflicts have shaped the landscape of Mt. Carmel for decades. It is evident, however, that pine forests were not among the dominant vegetation landforms. Written evidence on the historical geography and botany of the region are mainly attributed to travelers and pilgrims, some of them botanists and scientists, who visited Palestine during the nineteenth century (Liphscheitz and Biger 2001). The British Reverend H·B. Tristram who visited Palestine during 1857 and 1863 described the vicinity of Usfia (a Druze village; see Fig. 1) as a scattered pine forest with trees of no great size (Tristram 1865). The French traveler V. Guerin who explored the area during 1852–1875 described the Mt. Carmel forest as consisting mainly of oaks of various species, lentisk, small scattered pine trees and carobs. C.R. Conder, an officer in the Royal Engineers who conducted a survey of western Palestine during 1872 under the auspices of the Palestine Exploration Fund (P.E.F.) reported that Mt. Carmel was covered by various trees, among them dwarf pines (Weitz 1970). In the P.E.F. map, printed during 1880–1889, small patches of natural maquis are scattered in the Mt. Carmel region besides spotted stands of natural pines (which are stated to be a rare species). Anderlind, a botanist who traveled to Mt. Carmel in 1884–1885, reported that the forest was composed of bushes dominated by *Quercus calliprinos* and *Quercus boissieri*, *Pistacia palaestina*. *Styrax* and *Lotus* (Anderlind 1885). In the

center of the mountain and in some upland locations, a high forest existed, with large numbers of *P. halepensis* appearing in many places. Most of the reported pines were 10–12 years old, while older pines were absent. In a deep valley in the southeast part of the mountain, he encountered approximately 100 pine trees, 20–35 years old, mixed together with *Quercus boissieri*, *Phillyrea*, *Pistacia*, *Lotus* and several wild *Ceratonia*.

First plantings of various pine species in the Mt. Carmel region are attributed to German settlers, the Templars, in the nineteenth century. Massive afforestation efforts starting in the northeasterly bare slopes were conducted by the British mandatory government during 1925–1929, and further afforestation resumed in 1935. Between 1952 and 1966, the Jewish National Fund and the Governmental Afforestation Unit planted 1,600 ha predominantly of *Pinus halepensis*, *P. brutia*, *Pinus pinea*, and *Pinus canariensis*, accompanied by *Cupressus sempervirens*, *Eucalyptus camaldulensis* and *Ceratonia silliqua*. According to a survey, from 1954 the natural maquis of Mt. Carmel occupied 8,845 ha and consisted of: open park, 173 ha; open maquis, 5,570 ha; and 3,102 ha of dense maquis (Weitz 1970). Due to afforestation efforts between 1954 and 1966, natural maquis areas further increased by 15%, as pines and cypresses were additionally planted. Not only had the forested area markedly increased, but also tree densities significantly increased from 0.2 to 0.4 trees per hectare in 1945 to 10–14 trees per hectare in 1984 (Safriel 1997). Nowadays, the forest that covers an area of approximately 15,700 ha is thus a patchwork of natural Mediterranean vegetation and planted non-native trees of various ages. Each of these land units is characterized by different adaptations and responses to disturbances such as forest fires. Nature preservation efforts, including proclamations of reserves and parks, introduce diverse management approaches, which further increase the landscape's heterogeneity.

Methods

Information regarding forest fires, which occurred in the study region during 1940 and 2006 was gathered from various sources and in different formats. The local fire department provided point data of the fires, which included the date and the centroid coordinates of the events. Polygon data for some of the fires were obtained from the Jewish National Fund and from other agencies in charge of the forestry practices in the region. Additional data were obtained from digitizing fire outlines from aerial photographs, and archive records of large fires occurring in the region since the 1940s were also collected. Whenever possible, the information was entered into a GIS polygon-based database, which enabled the assessment of the spatial

Fig. 1 The Carmel region and the spatial extents of large fires 1983–2006
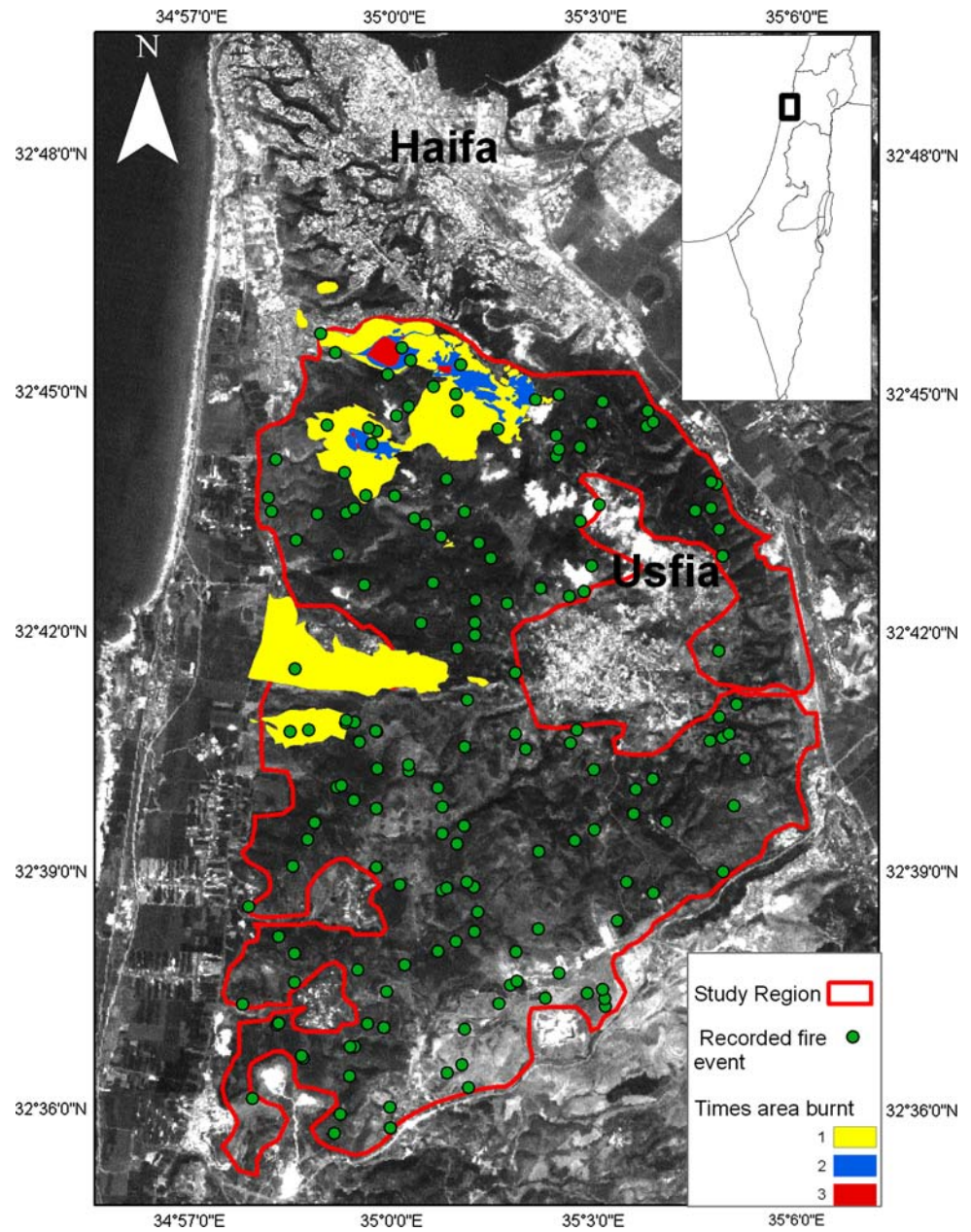
extent of the fires. Otherwise, an alternative point-based database was established, which contained information on all known fires. For the purpose of this study, fires occurring in urbanized or settled areas were excluded from the database.

We analyzed the spatial and temporal patterns of wildfire occurrence. First, we tested whether any correlation exists between the annual number of fires or the total area burned annually, with precipitation during the years in which the fires occurred, precipitation amounts of the year prior to the fires and 2 years preceding it. The precipitation data were obtained from the Beit-Oren meteorological station, which is located at the middle elevation of the Carmel ridge. Other studies have shown that such

correlations exist in the Mediterranean basin (Pausas 2004). The assumption is that in this system, herbaceous biomass correlates with the precipitation values. Hence, following high precipitation years, fuel loads in the herbaceous communities will be high. Next, we tested whether fires occurred randomly throughout the study region, and whether there exists any correlation between elevation and the probability of fire occurrence. This multiple analysis approach enabled us to test whether the distance from roads, which serves as a proxy for human activity, affects the probability of fire occurrence. Additionally, elevation serves as a proxy for environmental conditions. In lower elevations, the lower precipitation values combined with the higher temperatures generate more arid conditions.

Consequently, if such conditions affect fire occurrence probabilities, we expect to observe higher fire frequencies in the lower elevations. To test these hypotheses, we conducted a logistic regression (JMP software version 6.0.0, SAS Institute), which compared among the characteristics of the observed fires compared to "random" ones. This method is commonly used to evaluate the occurrence probability of a binary response variable, i.e., in this case a point location where a fire occurred compared to a point in which it had not occurred. Therefore, we simulated fire occurrence in the study area by randomly selecting a similar number of fire locations to that of the number of fires recorded during the study period. Applying standard GIS techniques, we calculated the distance of each fire location to the closest road (including recreation rest areas), and the elevation of each of the points was extracted from a digital elevation model of the area.

The final analysis pertained to the areal properties of the large fires distributions and their spatial distribution, which occurred during the study period. Large fires in this region were previously defined as fires, which consumed areas >20 ha (Levin and Saaroni, 1999). In addition, using overlay analysis techniques of GIS layers, we computed the probability of each point in the region to burn more than a single time during the study period. The spatial patterns of the fires were analyzed in relation to the different vegetation communities present in the study region. An extensive vegetation survey was conducted in the Carmel ridge in 1985 (Lahav and Farkash 1986), and based on this survey vegetation communities were classified into either natural maquis vegetation or forested pine areas. Accordingly, we analyzed whether fires occurred at random in relation to these two vegetation classes, and whether the pine forest areas consumed by the fires were proportional to the relative area occupied by pine forests in the region.

Results

Temporal patterns

Altogether, during the period of 1987–2004, 384 fire were recorded in the region, of which for 167 we obtained their assumed ignition coordinates, as only after 1991 information of the exact locations was recorded. The average annual number of fires was 21.3 and ranged from only 5 fires during 2000 to 38 during 1988. These fires consumed a total of 2,400 ha (see Table 1), i.e., 15% of the study region was burned during this period. The total forested and natural vegetation that was burned annually varied by more than three orders of magnitude, and ranged from 0.3 ha during 2000 to 874 ha during 1998. We did not find any correlation between the number of fires or total area burned annually and precipitation (Fig. 2). This was true

Table 1 The large fires during the study period

Date	Area burned (ha)
3 November 1983	284
19 September 1989	530
11 October 1998	162
12 October 1998	517
4 December 1999	158
6 December 1999	130
8 April 2005	154
4 January 2006	132
11 July 2006	125

Fig. 2 Precipitation and total area burned annually
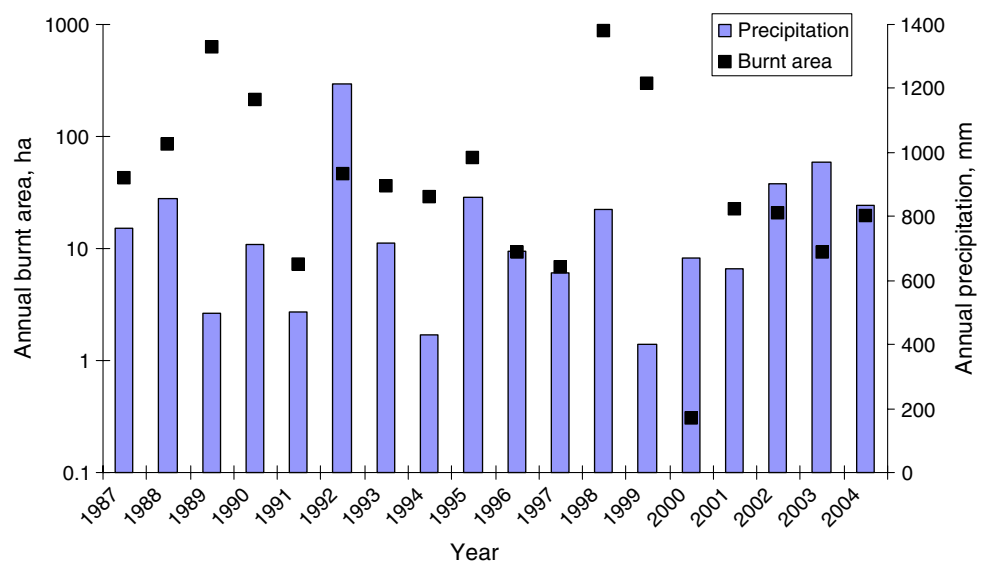
for precipitation values of the given fire year, 1 or 2 years preceding the fires. Records of large fires were obtained from as early as 1945. The exact extent and outlines of large fires was only available for fires that occurred during 1978 or later. Hence, we were able to quantify changes of large fire frequencies and unable to evaluate changes in fire extents. This provides only circumstantial evidence for the areas consumed by fires during this period. During 1944–1982, six large fires occurred, a frequency of one large fire every 6.3 years. During 1983–2006, nine large fires occurred in the region, yielding a frequency of one large fire every 2.5 years. Following the 1989 fire, which consumed ∼450 ha, a scientific committee was established to provide management recommendations for future large fire events. This strengthens the notion that prior to that year the region has not experienced severe fire events.

Spatial patterns

To analyze the frequency and the spatial distribution of the fire's point locations, only the 167 fire locations for which exact coordinates were available, were used for the analysis. Logistic regression analysis results indicate that elevation is not a significant predictor of fire occurrence ($P = 0.2905$), while distance from road is ($P = 0.0004$). Consequently, the model predicts that fire occurrence probability decreases with increasing distance from roads and recreation sites according to the following relationship:

$$p(f) = \frac{1}{1 + e^{0.515 \times d}}$$

where $P(f)$ is the probability of fire occurrence, and d is the distance to the nearest road in kilometers.

During 1983–2006 nine large fires occurred within the study region (Table 1) and consumed approximately 1,947 ha of forested and natural vegetation, i.e., about 12% of the region (Fig. 1). Of this area, 201 ha burned twice (10.3% of the burned area), and 38 ha burned three times (1.9% of the burned area). The large fires were not distributed uniformly across the landscape. Eight fires occurred in the northern part of the Carmel ridge, north of Oren stream. The large fires were concentrated non-proportionally in a relatively small area of the mountain ridge (33.1 km^2, 21.1% of the study region). Within this subregion, 1,168 ha burned during a period of 28 years, which is 35.3% of this area.

Analysis of the vegetation categories consumed by wildfire revealed that pine forests are more susceptible to fire propagation. Of the approximately 15,660 ha of the study area, 2,392 ha are covered by pine forests, primarily *P. halepensis*, i.e., 15.3% of the area. The number of fires that were recorded in pine forests during 1987–2004 was 20, of the total 167 recorded, which amounts to 11.9% of the fires. Although the proportion of fires occurring in pine forests is lower compared to the total area covered by pine forests, this value is not significantly different compared to the fires expected to occur at random in this community type ($\chi^2 = 2.62$, 2 *df*, $P = 0.27$). In contrast, the total area of pines forests consumed by the large wildfires amounts to 769.2 of the total 1,709.4 ha burned in the same period, which amounts to approximately 45% of the burned areas. This value is significantly higher compared to the proportion of the pine forests ($\chi^2 > 13.8$, 2 *df*, $P < 0.0001$), and is three times larger than expected by chance.

Discussion

During the past 100 years the Carmel ridge has experienced an intensive afforestation history, which formed a mosaic of landscape vegetation patches. In light of these changes, we investigated the possible factors affecting the changes in fire regime at the Mt. Carmel region. During the afforestation process, approximately 50% of the trees planted were *Pinus halopensis*, which is presumed to be a rare species in the native historical vegetation communities (Liphschitz and Biger 2001). Most of the other trees planted during this period were non-native species (Weitz 1970), which have different ecological characteristics compared to the native ones. *P. halepensis* adaptations to the local semi-arid climate and its fast growing rates led to the intensive use of this species in the afforestation of the country (Gindel 1944). The plantations, however, cover a wide range of habitats beyond those where the species occurred historically (Liphschitz and Biger 2001). One of the negative effects of these plantations is the invasion of pine trees into natural or semi-natural ecosystems (Richardson 1998). Pine invasion has been perceived as a major ecological problem leading to substantial changes in the invaded ecosystems, including an increased biomass and consequently an increase in the number of fire events (Richardson and Higgins 1998). In Israel, reports on pine invasions into nature reserves are increasing (Lavi et al. 2005). In general, *P. halepensis* stands are more flammable than oaks. Dense pine forests are even more combustible than single trees because of the litter accumulation and the understory shrub species, of which many contain resins or flammable essential oils (Neeman et al. 2004). Parallel to the maturing of the planted pine stands, succession processes dominated the vegetation changes in other open areas. The mature vegetation communities dominating these areas are characterized by *Quercus* and *Pistachia* spp. Until the end of the twentieth century the woody vegetation cover has significantly increased in the region from an average cover of 13 to over 35% (Kadmon and Harari-Kremer 1999), which resulted in the accumulation

of fuel loads. Consequently, the afforestation and succession processes form a patchwork of areas characterized by different fuel loads and susceptibilities to wildfires. Compiling the database of forest fires that occurred during the recent history on the Carmel Mountain ridge enabled us to evaluate whether any patterns in their occurrences exists. Assessing the number of fires that occurred prior to 1978, the year from which we have details on the outlines of the fires, revealed that fire frequency more than doubled during the second time period, i.e., after 1978.

Pausas (2004), based on climatic data from 350 meteorological stations (1950–2000), indicated that climatic variables, including mean annual temperature, mean summer temperature and summer rainfall, were significantly cross-correlated with summer area burned for a lag time of 2 years, suggesting that a high amount of precipitation contributes to the increase of biomass and fuel load. In contrast, assessing the relationship between Mt. Carmel annual precipitation amounts and number of fires or total area burned annually yielded no correlation. However, the results do indicate that a relationship between human activities and fire patterns does exist.

Hence, we propose that the fire regime observed in the Carmel region is a result of increased human activities coupled with the maturation of the forest. Accumulation of fuels, and particularly of pine trees, rich with flammable resin provides the potential settings for large-scale fires. This is particularly evident by the fact that the proportion of pine stands burned by large fires was significantly higher than expected. In addition, the mature *P. halepensis* forest provided a suitable environment for *M. josephi* outbreaks, which accelerated drying of trees and additional fuel accumulation (Mendel et al. 1994). This process, which may last for several decades, increases the flammability of the stands and presumably the probability for extensive fire outbreaks. Further, the increased human activities associated with recreation, military training and increased urbanization in the periphery of the region provide increased opportunities for ignition of wildfires. The combination of these two factors may explain the increasing number of fires and increased areas consumed annually. In particular, the significantly higher number of fires occurring in the vicinity of roadsides found in this study supports this notion. Moreover, given this combination of processes, we expect that this trend will continue to influence the landscape in the future.

Conclusions

The present landscape structure of the Carmel ridge is a consequence of a delicate balance formed by several factors operating in the system. On the one hand succession processes result in rapid regeneration of the maquis forest.

This is complemented by the afforestation management practices conducted by the land stewardship agencies. This results, as described above, in the accumulation of fuel loads in the system. On the other hand, the increased anthropogenic activities result in an increasing number of fires. As has been observed, this resulted in an increasing number of large fires during the last couple of decades. If this trend continues, however, the land stewardship agencies ought to consider the ramifications of the changing fire regimes characterized by larger and more frequently burned areas. Repeated afforestation by tree species more susceptible to fire may result in fires propagating to areas revegetated by natural succession processes, or to repeated burning of the natural vegetation communities. This in turn may potentially result in altering the vegetation structure, loss of species and higher risks of land degradation.

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