Evaluating Post-Fire Forest Resilience Using GIS and Multi-Criteria Analysis: An Example from Cape Sounion National Park, Greece

Margarita Arianoutsou · Sotirios Koukoulas · Dimitrios Kazanis

Abstract Forest fires are one of the major causes of ecological disturbance in the mediterranean climate ecosystems of the world. Despite the fact that a lot of resources have been invested in fire prevention and suppression, the number of fires occurring in the Mediterranean Basin in the recent decades has continued to markedly increase. The understanding of the relationship between landscape and fire lies, among others, in the identification of the system's post-fire resilience. In our study, ecological and landscape data are integrated with decision-support techniques in a Geographic Information Systems (GIS) framework to evaluate the risk of losing post-fire resilience in *Pinus halepensis* forests, using Cape Sounion National Park, Central Greece, as a pilot case. The multi-criteria decision support approach has been used to synthesize both bio-indicators (woody cover, pine density, legume cover and relative species richness and annual colonizers) and geo-indicators (fire history, parent material, and slope inclination) in order to rank the landscape components. Judgments related to the significance of each factor were incorporated within the weights coefficients and then integrated into the multicriteria rule to map the risk index. Sensitivity analysis was very critical for assessing the contribution of each factor and the sensitivity to subjective weight judgments to the final output. The results of this study include a final ranking map of the risk of losing resilience, which is very useful in identifying the "risk hotspots", where post-fire management measures should be applied in priority.

Keywords Multi-criteria evaluation · GIS · Post-fire resilience · *Pinus halepensis* forests

Introduction

Mediterranean ecosystems are characterized by oscillation in the prevailing meteorological conditions, with dry hot summers (lasting between two to three months on the French and Italian coasts in the northern Mediterranean Basin to more than five-six months on the Libyan and Egyptian coasts to the south) and mild wet winters (Nahal 1981). These ecosystems are also characterized by the occurrence of frequent wildfires. Fire has long been considered as a natural phenomenon, largely incorporated in Mediterranean climate systems, having shaped their diversity (Cowling and others 1996), their function (Rundel 1981) and their distribution and evolution (Bond and others 2005). Fire regimes are critical in defining plant community responses. High fire frequency may prevent seeders from replenishing their seed banks (Zedler and others 1983; Daskalakou and Thanos 2004; Arianoutsou 2004), may deplete resprouters from their bud banks (Lloret and López-Soria 1993; Canadell and López-Soria 1998; Arianoutsou 1999) and may favour the establishment of alien species (e.g., Vilà and others 2001; Lambdon and others 2008).

The concept of resilience has been conceived by Holling (1973) and received much attention in the Mediterranean

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ecosystems in the 1980s (Westman 1978; Dell and others 1986). Renewed interest on the concept has emerged for two main reasons (Lavorel 1999; Arianoutsou 2007): (1) the accelerated loss of biodiversity and (2) the projected effects on disturbance regimes that climate change might bring.

Resilience is defined here in the context of multiple equilibriums and is measured by the amount of disturbance that the system can absorb before it changes its state by redefining its variables and processes that determine its function (Gunderson 2000). The two key elements for this assessment is the amplitude of changes brought about by disturbance—in this case fire—and the dynamics of post-fire recovery. In considering the prediction of ecosystem resilience, Westman (1978) has suggested to focus either on sensitive attributes of individual species or of community-level changes in species richness, composition etc which may be the basis for observing community-level components of resilience. The existence of efficient regeneration strategies that allow for rapid recovery from a fire has been considered the basis for high resilience of Mediterranean terrestrial ecosystems (Lavorel 1999). Classification of plant species in relation to these regeneration strategies—jointly with other attributes—has led to the organization of functional groups. Hence, the evaluation of resilience can be performed through the evaluation of values derived for several critical community components such as plant functional groups (e.g., Lavorel 1999; Kazanis and Arianoutsou 2004a). Although the mechanisms under these dynamics are phylogenetically established, environmental gradients and types of disturbance potentially contribute to their success across biomes (Pausas and others 2004; Vesk and Westoby 2004).

Mediterranean pine forests (i.e., *Pinus halepensis, P. brutia* and *P. pinaster*) constitute 16% of the total forest cover around the Mediterranean Basin (Barbero and others 1998). According to Quezel (2000) 2.5 million ha of the Mediterranean forests correspond to *P. halepensis* Mill. (Aleppo pine) forests and they are among the most affected by fire in the Mediterranean. For example, in Greece, where *P. halepensis* stands cover almost 9% of the forest area, for a period of 17 years (1980–1996) 11.15% of the overall number of fires and 16% of the total burned area corresponded to Aleppo pine forests (Dimitrakopoulos 2001). Because of this, detailed studies regarding post-fire regeneration of *P. halepensis* communities (e.g., Arianoutsou and Ne'eman 2000; Trabaud 2000; Pausas and others 1999, 2004; Kazanis and Arianoutsou 1996, 2002, 2004a; Baeza and others 2007; Pausas and others 2008) have been performed. These studies show that in most cases plant communities of *P. halepensis* are resilient to fire. However, *P. halepensis* forests are not always homogeneous across a landscape, as differences in the

underlying geological substrate or exposure may be reflected in the composition and the structure of the understorey vegetation (Trabaud and others 1985; Kutiel 2000; Kazanis 2005). Similarly, response to fire may differ among the various patches of the forested landscape, depending on the ability of the constituent plant species to regenerate after fire under the specific biotic and abiotic interactions occurring in the various patches (Hobbs and others 1984). Variability in fire and land use history strongly define the fine grained distribution of plant communities at different successional stages across the forested landscape thus influencing their response to another fire (Arianoutsou and others 2002; Pausas and others 2002; Lloret and Vilà 2003).

During the last decades, large fire events have been very common in the European Mediterranean region, consuming thousands of hectares of *P. halepensis* forests and woodlands. The countries that are affected most are Spain, Portugal, France, Italy and Greece. Although the area affected by fires varies considerably from year to year and from country to country, it could be argued that a trend of increasing fire frequency has been observed during the last years, in particular along the eastern Mediterranean Basin, with the year 2007 being the worst in terms of overall area burned for Greece and Italy (Camia and others 2008). Therefore, there is an increasing demand for reliable and fast evaluation of the post-fire plant community resilience, and decisions on sustainable management of burned areas. Given the aforementioned heterogeneity in forest structure across the landscapes and the limitations in human and financial resources, it is essential for the responsible management authorities to be able to identify areas with low resilience to fire, so as to apply management practices only to those parts that actually require them. In this respect, the knowledge of factors governing this system's property would permit the establishment of priority action zones immediately after a fire in order to mitigate its effects. To do this, it is essential to design an evaluation system that incorporates ecological knowledge on the mechanisms of the community post-fire recovery and can be applicable over larger units of the landscape affected by fire. For this purpose we examined the use of multicriteria evaluation in order to rank areas at risk of losing resilience within a Geographical Information Systems (GIS) framework.

Several attempts have been made to study the complexity of Mediterranean landscapes (Mouillot and others 2001; Pausas 2003 among others) and to model their interactions with fire (Mouillot and others 2003; Pausas and Ramos 2004, 2006), using simulation tools, including spatially-explicit models such as SIERRA, MELCA, FATELAND, BROLLA and LASS. Geographical Information Systems and Remote Sensing technologies have

often been used in studying wildfires (e.g., Amiro and others 2003; Roder and others 2008; Clemente and others 2009). However, they have focused mainly on fire risk assessment (e.g., Maselli and others 2000; Jaiswal and others 2002; Tàbara and others 2003; Hernandez-Leal and others 2006; Vasilakos and others 2007; Vadrevu and others 2010) or on the response after fire (e.g., Ricotta and others 1998; Díaz-Delgado and others 2002; Keramitsoglou and others 2004; Vafeidis and Drake 2005 among others).

Application of remote sensing and GIS tools has recently been used to locate priority intervention areas after wildfires in Mediterranean systems. For example, Ruiz-Galardo and others (2004) proposed a methodology based on remote sensing and GIS techniques, which permits speedy identification of erosional areas in a semi-automatic way and has been tested in a large burn scar in south-eastern Spain. Thon and others (2007) have proposed a combination of GIS and forest fire simulation in a virtual reality environment for environmental management. Vafeidis and others (2007) presented a method for the quantitative estimation and mapping of post-fire erosion and runoff, which can provide a basis for planning mitigation activities. Corona and others (2008) reviewed the benefits of the use of remote sensing techniques for an effective support to post-fire management (burned scar perimeter mapping, damage severity assessment, post-fire vegetation monitoring), Bisson and others (2008) have focused on the creation of an index (VRAF) for evaluating short to medium term (5 years) capability of vegetation recovery (community resilience) at a smaller spatial scale. However, working at a local scale enabled us to include indicators derived from field work that, as explained above, are essential criteria for the evaluation of post-fire resilience at landscape level. Other researchers have used this particular approach mainly for decisions related to land prioritization for planning purposes and for natural resource planning. Linkov and others (2006) give an overview of relative applications. In a similar context, this approach has been used by Smith and others (2003) for the assessment of drought related ecological risk. A fair amount of literature is available on the impacts of fire on Mediterranean plant communities as well as on their post-fire response. On the contrary, very few studies are available on how factors expressed at the landscape level affect these responses (Pausas and others 2004).

Modelling with knowledge-based rules has also been proposed as a promising tool for predicting community level responses (Arianoutsou 1998a; Legg and others 1998; Arianoutsou and others 2000; Oxley and others 2002; Vakalis and others 2004a, 2004b). The incorporation of such a knowledge-based database within a GIS is currently

being tested (Arianoutsou and others 2007; Arianoutsou and others unpubl. data).

In our research we focus on the early detection of the plant community resilience across the landscape level. We propose the adoption of a multi-criteria evaluation approach (MCE or MCDM: Multiple Criteria Decision Making) in order to incorporate the existing ecological knowledge aiming at providing an alternative methodology that is valuable for the prioritization and quantification of ecological expertise on post-fire ability for recovery of *P. halepensis* forest communities. Selected parameters used are bio-indicators (key plant species and plant cover), and geo-indicators (parent rock material and slope). The innovation of this research is that it brings together field data which are indicators of the plant community and landscape scale data for characterising the ability of the ecosystem to recover after a fire event. By using these indicators together we form a ranking index of the risk of losing resilience for a large area of a National Park and are able to prioritise for management purposes.

Study Area

This work is a pilot case study performed in Sounion National Park, located at the south-easternmost part of Central Greece, less than 80 km far from the capital of the country (Fig. 1). The area is hilly and used to be covered mainly by a dense, old growth *P. halepensis* (Aleppo pine) forest; due to its ecological and aesthetic value, the authorities declared the area as a National Park in 1974. The Park covers a total area of 3500 ha, 750 ha of which correspond to the strictly protected area. The altitude of the studied area varies between 30–320 m a.s.l. The long and diverse history of human influence and human induced disturbance together with the variety of geomorphological features explain the diversity of habitats and landscape heterogeneity within the Park. The climate of the Sounion National Park is dry Mediterranean, with an average annual precipitation of 310 mm. The area in question is among the driest areas of continental Greece.

Urbanization pressures along the peripheral zone of the Park as well as wildfires, usually acting in combination, are the main causes of degradation of the site. A large wildfire took place in the summer of 1985, when almost all the area covered by Aleppo pine was burned. Nevertheless, regeneration of the mature Aleppo pine forest took place rapidly leading to the recovery of the burned ecosystem (Kazanis and Arianoutsou 2004a; Kazanis 2005). In the summer of 2000, a new severe fire burned over the same area and destroyed approximately 1100 ha. Most of the year 2000 burned area falls within the limits of the year 1985 burned surface, whereas a couple of forest stands that had survived
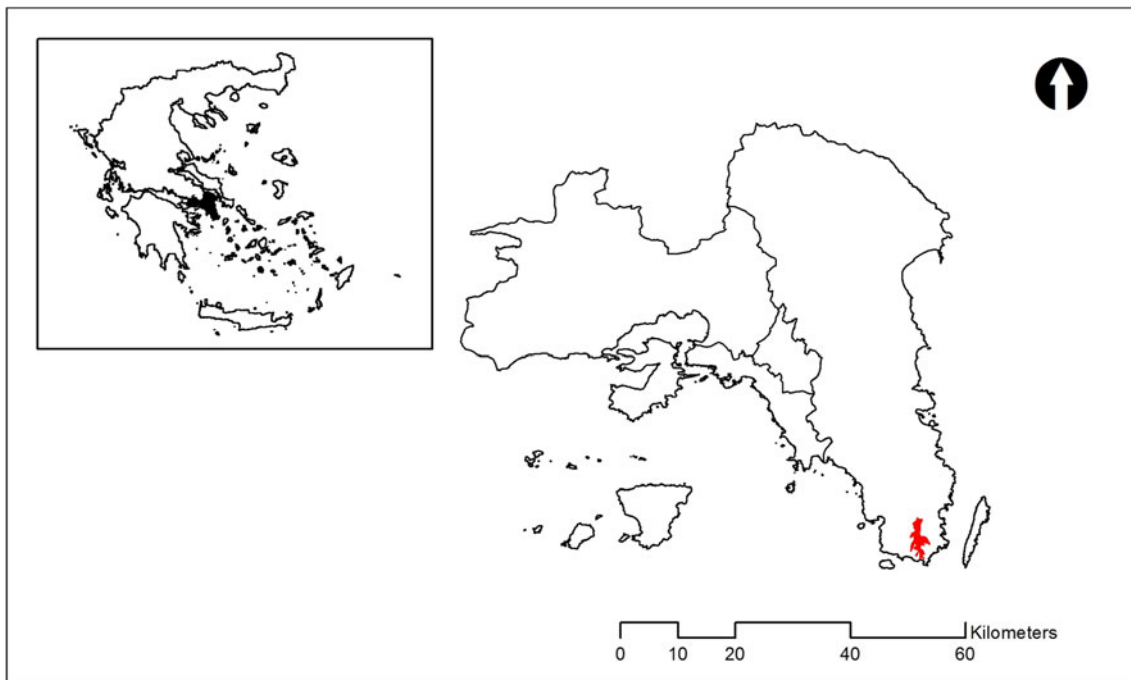
Fig. 1 The geographical area of Sounion National Park, Attica, Greece

the first fire event were burned during that incident. Our study, regarding post-fire resilience of the Aleppo pine forest, focused on the area burned in the year 2000.

Materials and Methods

Research Design

The first steps in supporting decisions for post-fire landscape management are related to the evaluation of landscape status. The purpose of this evaluation would be to formulate detailed information to be used either for conservation or for general management policies (restoration, mitigation actions, etc.) (Farina 2000).

Landscapes can be considered as dense, complex networks of interactions between environmental factors (forms and patterns, as well as processes) that encompass the properties of the environment (Kolassa and Pickett 1991; Philips 1997) and the biological communities that are supported by these factors. For the evaluation of such complex systems one should form abstraction layers of information that can be processed by computer. One way to evaluate a given landscape is to select suitable indicators (Farina 2000) and create their corresponding GIS layers. These can be:

(i)   process indicators (integrity, fragility, fragmentation, disturbances)
(ii) pattern indicators (landscape structure, here under a more general class: geo-indicators)

(iii) bio-indicators (key species, biodiversity, animal behaviour etc)

In this study, the selected parameters are bio-indicators (key plant species and vegetation cover), and geo-indicators (parent rock material, slope). The data used for our analysis can be categorised in these two groups based on their collection/creation. The first group of data involved geographical information at landscape scale and included a vegetation map, a fire history map, parent rock material and soils maps as well a Digital Terrain model (DTM) of the area.

The sampling scheme was based on these unique areas created from all available combinations of fire interval, parent rock material and slope inclination. The combination of these landscape level layers was used to create a map of patches which formed the sampling base for the rest of the factors. This scheme was necessary in order to have a full representation of all physiographic units present in the landscape studied.

For this purpose, the slope inclination layer was reclassified into three classes: low (0–5%), moderate (6–25%), and high (>25%). In our experience these classes represent adequately the three slope regimes. Ruiz-Galardo and others (2004) have used a similar classification in their work of identifying erosional areas in Catalonia, Spain. Within the twice burned area, five different cases of stands have been identified: those developing on schist, subdivided into those of low, moderate and high inclination slopes, and those developing on limestone subdivided into those of moderate and high inclination slopes. In the former case, that of the

stands developing on schist, the pre-fire plant community was over-dominated by *P. halepensis* (pine cover > 80%), with *Cistus* shrub species and woody legumes (*Genista acanthoclada*, *Calicotome villosa*, *Anthyllis hermaniae*) along the sparse gaps (Kazanis 2005).

The pre-fire situation was rather different at the stands developing on limestone. There, *P. halepensis* was again dominant, presenting lower cover values (~60%), due to the high presence of the evergreen sclerophyllous shrub species *Quercus coccifera* and *Pistacia lentiscus*. Once more, along the gaps, the presence of *Cistus* species and woody legumes was evident, together within the notable presence of the dwarf shrub *Coridothymus capitatus* (Kazanis 2005).

Within the area burned once, only two different cases of stands were available for sampling, both referring to stands developing on schist, subdivided into moderate and steep slopes. Before the fire, the understorey of these mature pine stands was characterized by the sparse presence of evergreen sclerophyllous shrubs and the low cover of woody species, such as woody legumes *G. acanthoclada* and *C. villosa*, *C. capitatus* and *Erica manipuliflora* (Kazanis 2005).

Table 1 presents the number of stands considered for sampling, for all the above mentioned combinations. These combinations formed the basis for the sampling scheme, as dictated by the heterogeneity of the area. More sampling sites were used in areas, which despite the above categorization, showed increased variability in their characteristics (bio-indicator scores).

Data Description

Geographical Information (Landscape Scale)

In this section we describe the layers of geographical information that were used along with the reasoning (where appropriate) concerning their suitability as criteria for evaluating the risk of resilience loss.

Vegetation Map   This layer was created from 1/10000 scale forest ortho-photomaps created by the Hellenic Ministry of Agriculture in the year 1998. The attribute table for this map contains information about the overstorey and understorey vegetation type, vegetation cover and volume of woody components. This layer was used to identify vegetation types existing before fire for designing the sampling scheme (see also above).

Fire History   This layer was digitized from maps provided by the Hellenic Forest Service. There are two classes, denoting fire frequency: area burned once and area burned twice. The first fire occurred in 1985 and the second in the summer of year 2000. All patches burned twice within 15 years were considered as low resilience patches. This is because this period of 15 years is not long enough to allow adequate development of the Aleppo pine canopy seed bank (Arianoutsou 1998a, 2004), which could ensure natural regeneration of the pine population.

Parent Rock Material   Two major classes of parent rock material for the area of interest were considered: limestone and schist. This layer was created from soil maps of scale 1/50000 provided by the Hellenic Forest Service. Parent rock material and slope inclination are largely responsible for the landscape heterogeneity of the area, which in turn is reflected in the potential of the various vegetation patches across the landscape to regenerate.

Soils developed over different parent rock materials may differ in their water retention capacity, rocks and rocky outcrops and occurrence, both related to regeneration capacity (Kazanis and Arianoutsou 2004b; Pausas and others 2004). Furthermore, different rock types usually support different types of Aleppo pine forest, each one with its own regeneration potential (Kazanis and Arianoutsou 2002, 2004b).

Area Topography (Digital Terrain Model—DTM)   This layer was produced from 20 m contours derived from a topographic map of 1/10000 scale. A DTM was subsequently created together with a slope layer (Slope inclination calculated as a percentage). This is another factor that has been associated with poor regeneration of pine forests. Tsitsoni (1997), working in *P. halepensis* forest in Northern Greece, suggested that Aleppo pine tends to regenerate more efficiently on moderate slopes or flat areas than on steep slopes. This result was attributed to higher water runoff levels on steep slopes that lead to an increased risk of seed loss.

Table 1 Number of sampled burned stands for the different available combinations of parent rock material, slope inclination and fire interval, in the Sounion National Park, Attica, Greece

Parent rock material	Slope inclination	Fire interval	Number of sampled stands
Schist	High	15 years	4
Schist	Moderate	15 years	3
Schist	Low	15 years	4
Limestone	High	15 years	4
Limestone	Moderate	15 years	3
Schist	High	>50 years	1[a]
Schist	Moderate	>50 years	1[a]

[a] The number of stands sampled in the mature communities (>50 years) was defined by the availability of the unburned area in each of the slope inclination categories identified

Field Sampling (Patch Scale)

All stands were sampled in spring 2002, during the second post-fire year. Within each stand, three 50 m-long transects were randomly established. Plant species richness was estimated by recording all species growing along the established transects. Furthermore, and in accordance with the selected bio-indicators the following measurements were made: (a) 'woody vegetation cover'; by means of point measurements, i.e., recording the presence or absence of woody species at every 50 cm point along the transect and calculating the percentage of points where woody species were present; (b) 'pine density'; by recording all pine individuals growing along the transects (linear density); (c) 'legume cover'; by recording the total cover of this group (point measurements); (d) legume contribution; by calculating the percentage of legume species against total species richness of the transect; (e) 'contribution of annual colonizers'; by calculating the percentage of colonizer species against total species richness of the transect. In this work, as colonizers we consider all species that do not possess an active post-fire regeneration mechanism. These plants have usually wind-dispersed seeds reaching

the burned area from unburned patches, they manage to germinate and their seedlings become established in the recovering communities. Each one of the proposed bio-indicators was subsequently characterized by a mean value for each one of the different combinations of fire history, parent rock material and slope inclination (Table 2). This mean value formed the basis for the creation of spatial layers of information, which were used subsequently as inputs to our model. Based on the sampled values of the bio-indicators and the base map, the following thematic layers (criteria) were created:

- Woody vegetation cover (%).
- Pine density (individuals/m).
- Legume cover (%).
- Legume contribution (%).
- Annual colonizers (%).

All selected bio-indicators are considered as components of community resilience as following: (a) 'woody vegetation cover'; the degree of which is related to the rate of vegetation recovery and hence the susceptibility of the land to be eroded or not, (b) 'Pine density', which is defining the vegetation physiognomy and hence the

Table 2 All available combinations of the parameters (fire interval, parent rock material and slope) defining each indicator and their values used in the Sounion National Park, Attica, Greece

Geo-indicators			Bioindicators				
Type of parent rock	Class of slope	Fire interval (years)	Woody cover (%)	Pine density (ind/m)	Legume cover (%)	Legume contribution (%)	Annual colonizers contribution (%)
Schist	Low	15	17.67	0.11	4.67	2.63	47.37
Schist	Low	15	11.67	0.13	0.33	2.33	34.88
Schist	Low	15	13.67	0.11	0.00	2.86	37.14
Mean values			14.34	0.12	1.67	2.61	39.80
Schist	Moderate	15	37.33	0.01	7.67	6.90	29.31
Schist	Moderate	15	34.00	0.01	5.67	5.36	28.57
Mean values			35.67	0.01	6.67	6.13	28.94
Schist	High	15	20.67	0.00	5.00	5.44	34.16
Schist	High	15	28.33	0.00	7.00	9.26	22.22
Schist	High	15	24.00	0.00	5.33	6.00	22.00
Mean values			24.33	0.00	5.78	6.90	26.13
Limestone	Moderate	15	33.67	0.00	1.00	7.55	30.19
Limestone	Moderate	15	21.00	0.00	1.33	5.96	25.49
Limestone	Moderate	15	23.33	0.00	1.67	5.25	25.53
Mean values			22.17	0.00	1.50	5.61	25.51
Limestone	High	15	4.67	0.00	7.33	4.87	34.15
Limestone	High	15	6.33	0.00	5.00	2.63	31.58
Mean values			5.50	0.00	6.17	3.75	32.87
Schist	Moderate	>50[a]	38.00	0.37	22.33	24.35	19.23
Schist	High	>50[a]	33.00	0.15	13.67	22.22	15.87

[a] The number of stands selected for sampling in the mature communities (>50 years) was defined by the availability of unburned area in each of the inclination categories identified

landscape mosaic configuration; (c) 'Legume species contribution'; which is related to N-fixation, a process clearly linked to ecosystem function and therefore is considered as a key functional group strongly related to community resilience (Arianoutsou 2001; Kazanis and Arianoutsou 2004a), and (d) 'contribution of annual colonizers', which reflects the susceptibility of the landscape to plant elements that do not belong to its constituent communities, thus being greater changed in identity.

Multi-Criteria Evaluation of the Landscape

We applied the multi-criteria evaluation method which is a systematic approach used to rank areas according to a set of criteria (the criteria used here are the indicators presented above in Table 2).

With this method a decision matrix is formed where the columns are the criteria and the rows are the areas under evaluation. Each cell (e.g., row1, column1) in this matrix received an evaluation score that refers to a particular criterion and area. The evaluation scores attributed to the criteria described before, were at a natural (not constructed) scale (as measured in the field in percentages and then rescaled to 0–10). Since our goal was to produce a layer of information indicating the areas at risk of losing resilience, some of these factors were classified as cost (slope, annual colonizers) which means that the highest value is the worst, and some as benefit factors (woody vegetation cover, Pine density, Legume cover and Legume species richness) with the highest value being the best. The scale for the benefit factors was reversed so that the value of 10 corresponds to high risk.

Different weightings were applied to the criteria adopted, utilising the ratio estimation method (Malczewski 1999a). In this method weights were given in the scale of 1–100 and then each value was divided by the lowest, representing in this way the "distance" of each factor to the less important factor. Normalized weights were used (by dividing each element by their sum) in order to keep the scale of the resultant map at the same levels (0–10) (as shown in Table 3).

The Simple Additive Weighting (SAW) multi-criteria rule used here enabled us to evaluate the losing of Resilience Risk (LRR) based on the following index:

$$\text{LRR} = \left(\sum_{i=1}^{n} C_i * a_i \right) * \text{Constraint factors}$$

where, C_i: the value of criterion i [where $i =$ (list of criteria in Table 3)]; α_i: the weight for criterion i (see Table 3); n: the number of criteria; Constraint factors: excluded areas (here areas for which no data are available).

There are, however, two main assumptions of the adopted multicriteria model that we need to consider: the first is linearity and the second is additivity (Malczewski 1999b). Linearity is usually a plausible assumption to make in the absence of contradictory evidence. Additivity is much more challenging when dealing with environmental indicators because interactions between the indicators often exist, causing a violation of this assumption. Extra care is therefore needed in the selection and formation of the indicators/criteria, keeping their number as small as possible in order to avoid interaction effects. Further discussions about multi-criteria methods and their applications can be found in Malczewski (1999a, b). Based on the above index a map with area rankings is produced. In order to increase the interpretability of the final map the risk scores were classified into three classes using the quantile division rule (ranking based on percentages).

There are several types of uncertainties involved into a multi-criteria analysis. There are uncertainties in data layers and uncertainties related to decision maker's preferences, which are attributed to criterion values, criterion weights and rating (Malczewski 1999a). The ranking classes of our final map are influenced by errors in the criterion maps and in the weights chosen. Errors in the criterion maps involve different types of errors; positional errors (e.g., in boundaries used), thematic errors for the thematic (categorical) maps and measurement errors for the continuous variables measured in the field. Each of these types of errors is measured in a different way (e.g., Root Mean Square Error for DTMs and percentage correct or kappa index for thematic maps) and their integrated assessment is a challenging issue.

Table 3 Weights estimation using the ratio estimation procedure. In the second column the criteria are ranked according to their importance, in the third column points are allocated in the scale 1–100, in the fourth column the weights are derived by dividing the points allocated with the minimum value and in the last column the standardised weights are reported

Factor/criterion	Ranking	Points allocated	Weights	Standardised weights
Slope inclination	4	65	6.5	0.17
Fire frequency	1	100	10	0.26
Pine density	2	80	8	0.21
Woody cover	3	70	7	0.18
Legume cover	5	50	5	0.13
Legume species	6	10	1	0.03
Colonizers	7	10	1	0.03
Sum			38.5	1

For the purposes of this study, where the final result was three classes of risk of losing resilience based on the resulting scores, we dealt mostly with the uncertainties introduced in scores set by the decision maker's preferences (weights). For the errors resulting from possible measurement errors and in order to alleviate the influence of these errors in the final ranking classes, we followed a simple approach by using only the mean values of what was measured.

In sensitivity analysis different numerical values (±5, 10) were assigned to the weight scores for successive runs of the model. The sensitivity analysis enabled us to evaluate if and how the outputs of each run were different and what it meant for the areas involved.

Results and Discussion

Results combining all parameters via the SAW rule are shown in Fig. 3. The quantile division rule was used to present the results into three (3) final classes of risk (medium 5–7.8, medium high 7.8–8.1 and high 8.1–10).

Before the fire, the studied area was covered by various physiognomic types of *P. halepensis* woodland and forests. As for the substrate, two major rock types could be distinguished within the periphery of the burned area, limestone and schist. The distribution of these two rock types looks like parallel zones alternating each other and extending from North to South (see Fig. 2). Limestone coincides with
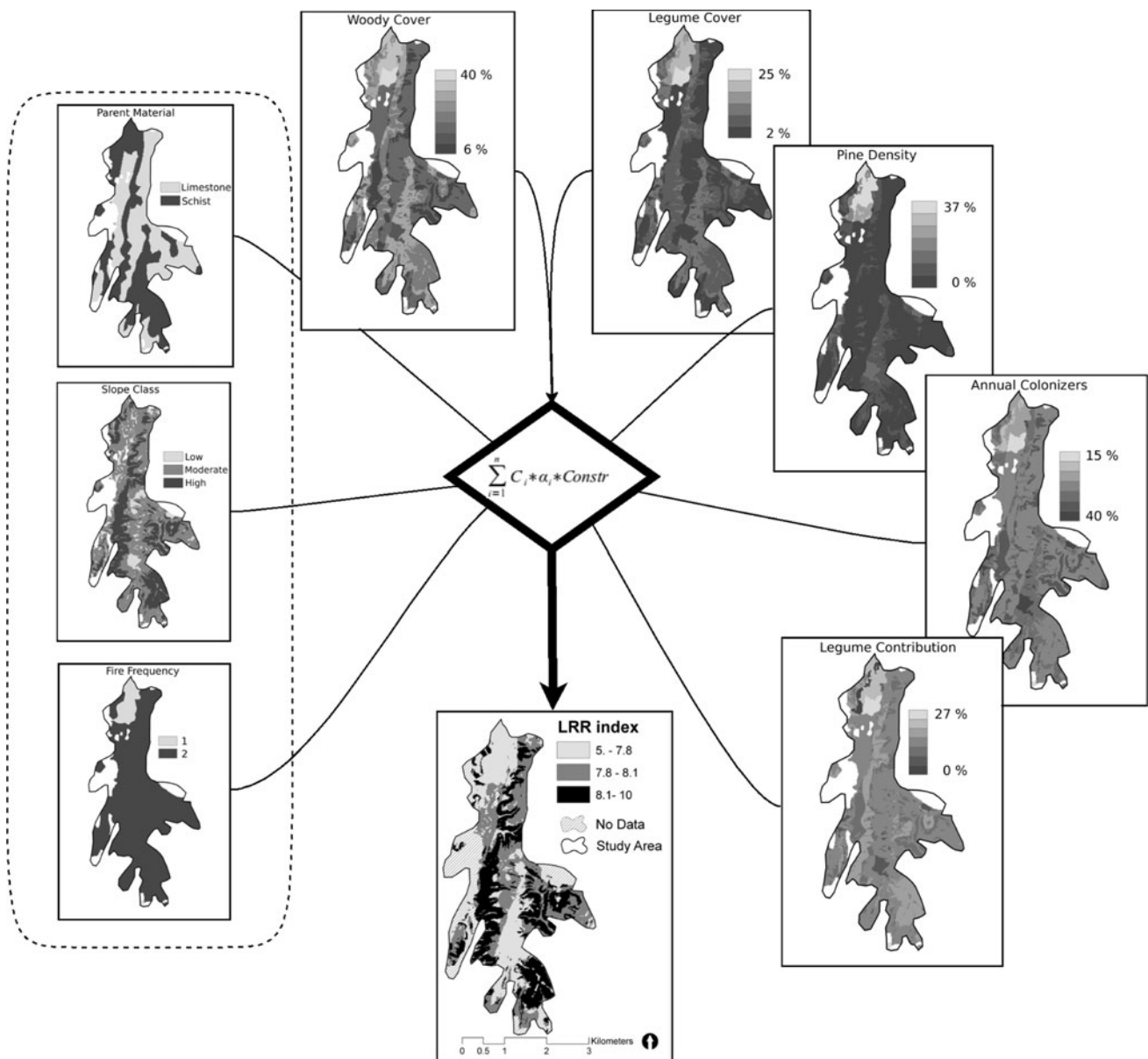

Fig. 2 The multicriteria evaluation process. On the *left panel* (*dotted line* frame) the geo-indicators are shown; the bio-indicators are shown above and on the right of the Simple Additive Weighting rule. The image on the *bottom* represents the final rankings of losing resilience risk (shown also in Fig. 3)

moderate and high inclination slopes, while schist is located on low, moderate and high inclination slopes.

After the summer 2000 fire no part of the study area presented high woody vegetation cover. This can be attributed primarily to the fire history of the site and secondarily to the parent rock type. In general, areas burned twice show moderate to low woody vegetation cover, especially on limestone rock. Slope acts as an additional limiting factor making vegetation cover even lower when slope is high. As for the substrate type, limestone, being a harder parent rock material than schist, is rather more slowly weathered and hence soil depth is shallower than in the case of schist. Consequently, the vegetation it supports is not that dense, although it can be quite rich in species. All these factors result to communities of high risk of losing resilience as shown in Figs. 3 and 4 (third class, with score above 8).

The results from the sensitivity analysis showed that the rankings did not change at small (±5) variations in the weights scores, while small changes occurred for larger variations (±10) at specific areas (see Table 4 and Fig. 4).

From Table 4 it can be seen that the weight scores have changed significantly only for the larger variations (±10). These are worth exploring further as small variations have no significant effects (Fig. 4).

These results show that our risk ranking holds and is producing the same results (with regard to class membership) when the weights are shifted by ± 5 units on the 0–100 scale. Larger changes in the weightings produce small changes in the final rankings except in the slope factor. As we can see from Fig. 4, the risk ranking is
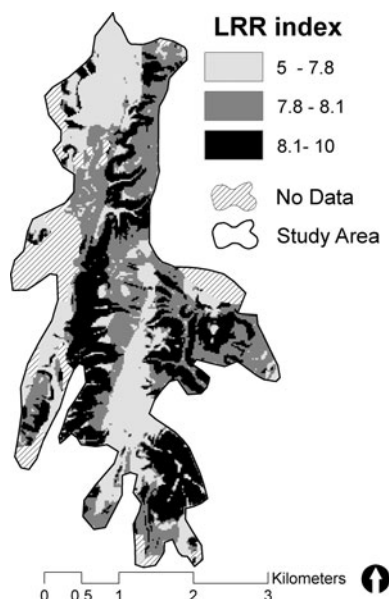

LRR index

5 - 7.8

7.8 - 8.1

8.1 - 10

No Data

Study Area

0 0.5 1   2   3 Kilometers

Fig. 3 Risk score of Losing Resilience—LRR (5: Medium −10: High)

sensitive to large changes of the weighting (importance) of the scale factor. We can also observe that the inclusion of fire history is critical (top right panel in Fig. 4).

As we can understand from the sensitivity analysis (Fig. 4), changes in the density of *P. halepensis* (the dominant tree species), alone do not increase the risk of losing resilience significantly. However, the change in pine density recorded is related to fire history. Pine density recorded in areas burned once is 37% of moderate slope and 15% in areas of high slope. In areas burned twice pine density does not exceed 15% and this only in areas with low slope values (Table 2). Two consecutive fire events within a 15-year interval (1985 and 2000) prohibit full recovery of the canopy seed bank of the dominant tree species. Arianoutsou (1998a) and Daskalakou and Thanos (2004) also report similar results. This, in turn, affects the availability of produced seed rain which is therefore low and consequently the number of emerging seedlings is rather small and scarce.

With regard to legume species and the model's low sensitivity to changes of its weight, we must note that at the time of sampling, the area studied was at its second post-fire year. Under a fire regime of a period >50 years considered as normal for the Mediterranean (Cowling and others 2004), this area should have high legume representation (Papavassiliou and Arianoutsou 1993, 1998). Yet, only in very few patches were legumes a significant component of the extant vegetation. These patches are all concentrated on the sites that were burned only once. When we look at the combined effect of legume cover and legume species richness, the majority of the patches created (in the GIS layer) could be characterized as 'low' to 'moderate' risk. This is an indication of rather limited nitrogen availability, due to low to medium legume representation. Patches overlying limestone seem to support fewer legume species than on schist, while slope seems to have less effect on their presence (Table 2, Figs. 2 and 3). Overall, the landscape process related to post-fire N replenishment appears to be rather adversely affected by fire frequency and rock type; thus the area is characterised as high risk in this respect.

With respect to the 'annual colonizers' bio-indicator, the majority of the area studied is in the 'red alert' situation. The relatively high (>20% of the site's flora) contribution of wind-dispersed (anemochorous) plant species of the Compositae, Gramineae and Umbelliferae families—considered as colonizers—implies that the system is rather highly disturbed. The recorded contribution of this flora component is unusually high for plant communities found in their second post-fire year of recovery under normal fire regimes (Kazanis and Arianoutsou, 1996, 2004a, b). The high contribution of such colonizing plants could be explained by the relative short fire interval, which has
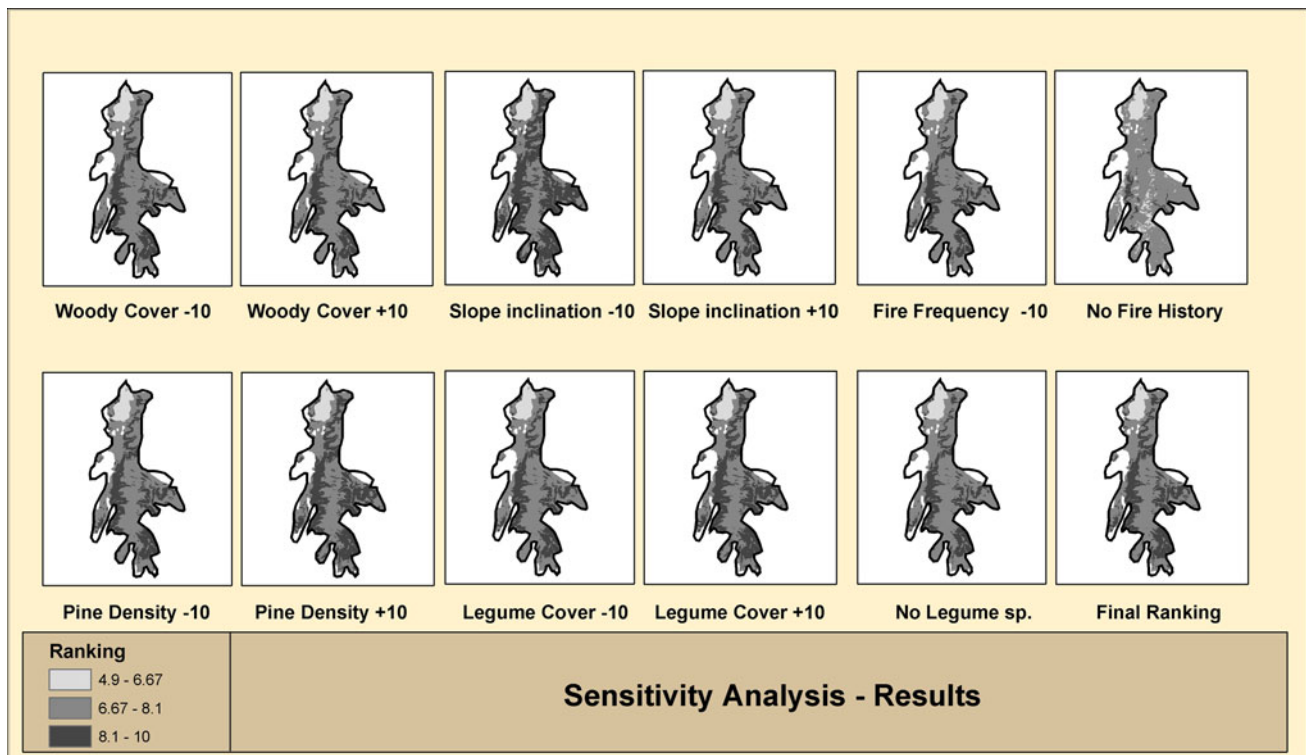
Fig. 4 Results of the sensitivity analysis

affected the woody plants and changed the normal community recovery patterns. The scarcity of woody elements in the vegetation and the decreased capability of the herbaceous plants to recover, because of the very short time interval, leave the ground open to intrusions from external wind-dispersed elements (D' Antonio and Vitousek 1992; Evans and others 2001). This situation will lead to a dramatic change in the structural components of the vegetation, often resulting in a more flammable system due to grass architecture and structure (Anderson 1982).

These indicators have been selected so as to represent fundamental features of community structure and function and are linked to the relevant features of the landscape (patterns and processes). Their fusion using a SAW method in the framework of a GIS has provided us with a complete ranking of the areas with risk of losing resilience. The advantage of using such methods is their simplicity and applicability in a spatial framework.

A possible pitfall regarding this methodology is the choice of weights and their estimation methods. Usually, these are subjective judgements made in a constructed scale by the scientists involved. A questionnaire survey is a good alternative that can alleviate the subjectiveness of the weights; however, this is often impractical. As a safeguard, a sensitivity analysis is often the solution to this problem. In our case, we did not have evidence of non-linearity and we have tried to limit the number of indicators to those absolutely necessary in order to avoid strong interaction effects. In the sensitivity analysis that was carried out, our results were not sensitive to small changes of the weight scores, indicating a suitable ranking of risk of the areas of losing resilience.

The advantage of using a multi-criteria analysis is that we can take into account all the criteria and produce a single index. The model developed has used indicators as criteria and is an improved version of similar knowledge-based strategies that have been used in studies of wildfire ecology and management (Pivello and Countinho 1996; Conedera and others 1997; Arianoutsou 1998b; 2004; Arianoutsou and others 2000, 2007; Rollins and others 2004; Bisson and others 2008). It is easily applicable to other regions of the Mediterranean Basin either with *P. halepensis* forests or with other vegetation types and the results are easily interpretable even by non-experts.

The results derived from this research have shown that this approach is potentially very useful and easily implemented for the management of Mediterranean landscapes. For instance, patches of plant communities having low resilience can be identified and specific measures can be immediately taken e.g. for preventing soil erosion when vegetation cover is minimum or design specific plantations where pine density is extremely low. Similar interventions can be made for the conservation of biodiversity in the area.

Table 4 Sensitivity analysis for the weights (±5, 10 points)

	Slope inclination	Fire Frequency	Pine Density	Woody cover	Legume cover	Legume species	Colonizers
Slope inclination							
+5	*0.18*	0.26	0.21	0.18	0.13	0.03	0.03
−5	*0.16*	0.26	0.21	0.18	0.13	0.03	0.03
+10	*0.19*	0.25	0.20	0.18	0.13	0.03	0.03
−10	*0.15*	0.27	0.21	0.19	0.13	0.03	0.03
Fire Frequency							
No fire frequency	0.22	*0.00*	0.28	0.26	0.17	0.03	0.03
−5	0.17	*0.25*	0.21	0.18	0.13	0.03	0.03
−10	0.17	*0.24*	0.21	0.19	0.13	0.03	0.03
Pine density							
+5	0.17	0.26	*0.22*	0.18	0.13	0.03	0.03
−5	0.17	0.26	*0.20*	0.18	0.13	0.03	0.03
+10	0.16	0.25	*0.23*	0.18	0.13	0.03	0.103
−10	0.17	0.27	*0.19*	0.19	0.13	0.03	0.03
Woody cover							
+5	0.17	0.26	0.21	*0.19*	0.13	0.03	0.03
−5	0.17	0.26	0.21	*0.17*	0.13	0.03	0.03
+10	0.16	0.25	0.20	*0.20*	0.13	0.03	0.03
−10	0.17	0.27	0.21	*0.16*	0.13	0.03	0.03
Legume cover							
+5	0.17	0.25	0.20	0.19	*0.14*	0.03	0.03
−5	0.17	0.26	0.21	0.19	*0.12*	0.03	0.03
+10	0.16	0.25	0.20	0.19	*0.15*	0.03	0.03
−10	0.17	0.26	0.21	0.20	*0.11*	0.03	0.03
No legume species	0.18	0.27	0.22	0.20	0.11	*0.00*	0.03
No colonizers	0.18	0.27	0.22	0.20	0.11	0.03	*0.00*

The rows represent the weights used for all criteria. The columns represent the change in the weights when the original scale is altered. Numbers in italics represent changes in the weight of the criterion being altered

Conclusions

Significant changes in the fire regime induced either by human factors or by climate change may have detrimental effects on landscapes and their resilience to fire disturbance. The use of proper indicators at a landscape—regional scale with spatial explicit models in a GIS framework can form a useful early warning system at the hands of both scientists and managers. Each indicator used, was weighted for its significance and then integrated into the multicriteria rule to map the risk of losing resilience index. Through sensitivity analysis we were able to assess the contribution of each factor and the effect of the weight judgments to the final output. The final ranking map has enabled the identification of the 'risk hotspots' where post-fire management measures should be applied in priority. Taking this approach a step further, it is possible to apply the methodology to an area at different time periods in order to monitor changes in resilience levels and take appropriate actions if necessary.

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