Assessing the impact of different landscape features on post-fire forest recovery with multitemporal remote sensing data: the case of Mount Taygetos (southern Greece)

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Abstract. Fires affecting large areas usually create a mosaic of recovering plant communities reflecting their pre-fire composition and local conditions of burning. However, post-fire recovery patterns may also reveal the effects of landscape heterogeneity on the natural regeneration process of plant communities. This study combines field data and remote sensing image interpretation techniques to assess the role of various landscape characteristics in the post-fire recovery process in a mountainous region of Greece burned by a severe wildfire. Remote sensing techniques were used to accurately map secluded, large burned areas. By introducing a temporal component, we explored the correlation between post-fire regeneration and underlying topography, soils and basement rock. Pre-fire forest cover was reduced by more than half 8 years after fire. Regarding the dominant pre-fire forest trees, \textit{Abies cephalonica} did not regenerate well after fire and most pre-fire stands were converted to grasslands and shrublands. In contrast, \textit{Pinus nigra} regenerated sufficiently to return to its pre-fire cover, especially in areas underlain by softer basement rock. The use of different time series of high-resolution images improved the quality of the results obtained, justifying their use despite their high cost.

Additional keywords: black pine, conifer forest, GEOBIA, geomorphology, multitemporal, random forest.

Introduction

Fire is an ancient, recurrent disturbance on planet Earth, especially in seasonally dry areas like the Mediterranean biome (Pausas and Keeley 2009). The occurrence of fire in the Mediterranean Basin is nearly entirely due to human ignitions, but its spread and control are strongly influenced by prevailing weather conditions (Moritz et al. 2005; Moreira et al. 2011; Peñuelas et al. 2017). Changes in fire regime have been documented in the western Mediterranean Basin, with a shift from fuel-limitation before the 1970s to climate limitation since that time (Pausas and Fernández-Muñoz 2012). Turco et al. (2016) reported that in most European Mediterranean countries both total annual burned area and annual number of fires have decreased since the 1980s, owing primarily to better fire prevention and management. Nevertheless, this trend has not reduced the ecosystem or societal effects of fires, which might be fewer but are often larger in size and more severe (San-Miguel-Ayanz et al. 2013). Large fires, i.e. fires that are larger than 500 ha (San-Miguel-Ayanz et al. 2013; Mitsopoulos and Mallinis 2017), are fairly new in the recent history of the Mediterranean Basin (Lloret and Mari 2001). Although they represent a small fraction of the total number of fires, large fires are responsible for a high
percentage of the total burned area (e.g. Diaz-Delgado et al. 2004; de Zea Bermudez et al. 2009). They tend to occur under specific meteorological conditions (e.g. high temperatures, prolonged drought and strong winds), and often exhibit extreme behaviour (e.g. higher intensities). Moreover, large extreme fires offer fewer suppression options, and, depending on their severity and rate of recurrence, may have more adverse effects on ecosystems (Diaz-Delgado and Pons 2001; Gill and Allan 2008; Pausas et al. 2008; de Zea Bermudez et al. 2009; Moreira et al. 2011).

Climate change is expected to further increase wildfire risk (Moriondo et al. 2006; Karali et al. 2014; Kalabokidis et al. 2015), with the interplay between ignitions, drought and fire-weather dynamics leading to potential shifts in fire frequency (Fyllas and Troumbis 2009). Greece is among the countries that are almost annually affected by numerous and large wildfires (European Commission 2017). Particularly extensive and destructive burning occurred in 2007 in the Peloponnese (south Greece) and 2018 in Attica. Both events killed dozens of people and the 2007 fires caused extensive losses of forested and arable land (Koutsias et al. 2012; Diakakis et al. 2017; personal observations).

Post-fire vegetation regeneration has been thoroughly studied in the Mediterranean Basin (e.g. Pausas et al. 1999; Silva and Rego 1999; Arianoutsou and Ne’eman 2000; Arnan et al. 2007; Catry et al. 2010). At the landscape level, multiple environmental factors control post-fire vegetation recovery. In the Mediterranean Basin, it has been found that interactions between the fire regime and plant species traits play a very important role in this process (Pausas et al. 2004). A strong and complex relationship between soil quality and plant recovery has also been found (e.g. López-Poma and Bautista 2014; González-De Vega et al. 2018; Moya et al. 2018). Vegetation type, elevation, slope and anomalies in post-fire precipitation are the principal variables defining the rate of plant recovery (Viana-Soto et al. 2017). These factors and soil composition are major drivers of water availability, which is key in seasonally dry landscapes (Rodríguez et al. 2008). In short, landscape characteristics are major factors in the process of vegetation recovery after wildfires.

The combined use of remote sensing (RS) and geographic information systems (GIS) can provide reliable and timely information to land and fire managers to assess fire effects at different spatial and temporal scales (Lentile et al. 2006), but also to identify vulnerable areas where intervention is needed (Meng et al. 2015) and aid in the design of restoration strategies (Duguy et al. 2012). The increased frequency of large fires has greatly raised the demand for such work and recent advances in RS data characteristics (spatial, spectral, radiometric and temporal resolutions) and the greater availability of data have made it progressively more viable. Thus, RS is now used in various aspects of fire science, e.g. for delineating fire events at various scales (Chuvieco et al. 2019) and for providing estimates on fire severity (Mallinis et al. 2018), but also as a cost-effective method (in comparison with field surveys) for monitoring post-fire vegetation recovery and analysing the role of the physical environment in vegetation dynamics (Poirazidis et al. 2012; Chu and Guo 2014; Nioti et al. 2015; Viana-Soto et al. 2017).

The aim of the current study was to assess the influences of different landscape features on post-fire forest recovery across a mountain range in the Peloponnese (south Greece) 8 years after the fire event. Multitemporal, very-high-spatial-resolution satellite images acquired before and after the 2007 fire were processed through an efficient object-based classification approach using a robust machine learning classifier for the detection of changes in vegetation types induced by fire. Finally, GIS analysis was used to discern which of the landscape characteristics most influenced vegetation recovery.

Materials and methods

Study area

The study area is located on Mount Taygetos, the highest (2407 m above sea level) and most extended mountain range in the region of the Peloponnese. Mount Taygetos is bound by two subparallel and tectonically active fault zones trending NW-SE that contribute to its high relief and elongated outline (Papnikolaou et al. 2013). The area is dominated by marbles (Mani unit) and limestones (Tripolis unit), especially at the highest altitudes of the mountain (Psonis 1986, 1990). Between the Mani (the basal formation) and Tripolis units, several series of schists are intercalated with each other (see supplementary material). Smaller outcrops of fysch formations (Pindos unit) are observed occasionally around the range (tectonically emplaced on top of almost everything else) surrounded by Tripolis carbonates (Bonneau 1984; Jolivet et al. 2010).

Soil types are dominated by regosols (developed over clastic substrates and carbonate outcrops) and leptosols (developed over clastic substrates of the study area) (Nakos 1979). In 2007, a large fire burned the mountain range in a heterogeneous fashion, probably because of the dissected landscape physiography, the prevailing meteorological conditions and the fire suppression tactics. As a result, although much of the forest area was burned at high severity, several forest patches of various sizes remained unburned within the burned area (Arianoutsou et al. 2010). The total area burned was 8807 ha (Christopoulou et al. 2013), of which 4500 ha were conifer forests and 3800 ha shrublands and deciduous forests. The remaining area was agricultural land.

Mount Taygetos is a protected area, part of the Natura 2000 network – a European network of nature conservation areas. Before the 2007 fire, the mountain was mostly covered by single-species forests of Pinus nigra J.F. Arnold subsp. nigra (black pine) and Abies cephalonica Loudon (the endemic Greek fir) as well as mixed forests of the two (mixed-conifer forests), while broad-leaved forests of deciduous oaks (Quercus spp.), chestnuts (Castanea sativa Mill.) and planes (Platanus orientalis L.) were also present. Non-forested areas of the mountain were mostly covered by shrublands with evergreen sclerophyllous species (maquis), short seasonal dimorphic shrubs (phrygana) and patches of grasses and ferns (grasslands). A high number of Greek endemic plant taxa, several of which are local endemics (Dafis et al. 1996), are reported for the mountain.

A recent dendrochronological study (Christopoulou et al. 2013) revealed that Mount Taygetos has experienced frequent surface fires during the last 165 years. The 2007 fire event was the most extensive and severe event recorded to date. Patterns of post-fire regeneration of the heavily affected P. nigra forest after the 2007 fire have been thoroughly studied (Christopoulou et al. 2014), while Arianoutsou et al. (2010) documented general patterns of vegetation regeneration after the same fire event.
Imagery and preprocessing

An RS approach based on comparative analysis of independently produced classifications from different dates was used for spatially assessing vegetation change and recovery. This approach involves independently produced classification results from each time interval of interest to detect changes in the desired classes (Coppin et al. 2004). Subsequently, a complete matrix of change can be obtained. Therefore, three different very-high-resolution (VHR) images were originally employed for pre-fire vegetation mapping (IKONOS image), burned area delineation (Quickbird image) and forest vegetation recovery assessment (WorldView-2 image) (Table 1).

Furthermore, in order to facilitate the pre-fire classification process and considering the limited spectral resolution of the IKONOS image, spectral information from an ASTER medium–high-spatial resolution image was used complementarily (Fig. 1).

All images were orthorectified using ground control points extracted from orthophotos, at 1:5000 scale, and a digital elevation model (DEM) generated from 20-m interval contour lines.

Image segmentation

The overall classification approach adopted in our study relied on Geographic Object-Based Image Analysis (GEOBIA) (Blaschke 2010) and included the generation of a two-level object hierarchy through image segmentation, followed by a machine-learning classification of the finer level of hierarchy. The upper level was derived through a per-field segmentation using existing digital vector data and the lower one through a region-growing segmentation algorithm (Mallinis et al. 2016).

In the case of the pre-fire image classification, a reference large-scale vector layer was used for delineating non-natural and natural vegetation areas. The latter were subjected to the region-growing segmentation algorithm, generating the lower level used for the discrimination of homogeneous polygons. These include Greek-fir dominated forests, black pine forests, mixed-coniferous forests, broadleaved forests, grasslands, maquis, phrygana and sparsely vegetated areas.

For fire mapping, the same reference vector layer was used for identifying areas with natural vegetation (i.e. non-agricultural and non-artificial areas). The finer homogeneous
polygons of the lowest level were then delineated for classifying burned and unburned areas.

In the case of the Worldview-3 image classification, the upper level was derived from a field-based segmentation relying on the burned area vector layer. The finest-scale polygon level was then generated for discriminating the different vegetation types, with the aid of ground-truth samples. As no regeneration was observed in the Greek-fir dominated forests, this vegetation category was removed from the analysis.

**Image classification**

For the classification of image objects, a random forest (RF), supervised non-parametric ensemble learning algorithm was used (Breiman 2001). Regarding the parameters that needed to be specified for the implementation of the algorithm, the number of classification trees grown (Ntree) for each classification was set to the default value of 500, while the optimal number of random variables to be tested in each tree (Mtry) was set as the square root of the number of input variables (Belgiu et al. 2016). The minimum size of the terminal nodes of the trees (nodesize) was set to 1, the default value of the ‘randomForest’ package within R statistical software for RF classification.

Features quantifying different aspects of the spectral (mean, ratio and standard deviation) and textural (co-occurrence contrast, dissimilarity and entropy) properties of the objects were used as explanatory variables for the discrimination of the classes of interest (see Supplementary material).

To validate the classification, the out-of-bag (OOB) error was used that utilises observations that are not part of the bootstrap sample used for constructing the RF model. After the initial GEOBIA classification, the classified maps were visually inspected and corrected for errors, following the automated extraction procedures, thereby increasing the accuracy of the subsequent modelling procedures.

**GIS analysis and field data**

Analogue soil sheet maps and geology maps (scale 1 : 50 000) were digitised to retrieve information regarding the basement rock (Nakos 1979; Psonis 1986, 1990), aiming to calculate erodibility from information in Nakos (1979), which is the only rock type to produce soil. For the study area, we estimated erodibility (Romkens 1985) and reflects the tendency for erosion, especially after the wildfire event. Erodibility is the vulnerability of the basement rock type to erosion (Romkens 1985) and reflects the tendency of a basement rock type to produce soil. For the study area, we estimated erodibility from information in Nakos (1979), which is the only relevant information available at the scale of the current analysis for Greece.

To quantify the effects of landscape characteristics (e.g. slope and aspect), data were extracted from the latest NASA Shuttle Radar Topography Mission DEM (SRTM Plus version 3.0), which offers worldwide coverage at a resolution of 1 arc sec (30 m). Geomorphology was quantified and classified by calculating and using topographic position index (TPI) values that represent the elevation difference between a specific point and the elevations of its neighbouring cells (Jenness 2006).

Ground-truth data for training remotely sensed vegetation classification were obtained from field measurements performed in June 2016. A field campaign was organised 8 years after the fire event, allowing enough time to detect any potential natural regeneration of *A. cephalonica* that might have taken place since the fire (Christopoulou et al. 2018). Twenty-five sampling plots of 10 × 10 m² were established in the forest vegetation types identified within the periphery of the 2007 fire event. The sampling plots were selected to cover all combinations of basement rock types and pre-fire vegetation. In each plot, field measurements consisted of estimating total vegetation cover and herbaceous and woody species cover, as well as seedlings and saplings density (individuals per m²) of dominant tree species to assess the level of species regeneration. Individuals bearing only the cotyledons were characterised as seedlings, whereas all other young ones were characterised as saplings (Christopoulou et al. 2014). Regeneration was classified into three classes (Retana et al. 2002; Ordoñez et al. 2006; Tavşanoğlu 2008; Christopoulou et al. 2014), based on the mean individual’s density per square metre: low < 0.1 m⁻²; medium up to 0.5 m⁻² and high > 1 m⁻².

**Statistical analysis**

To detect vegetation cover changes before and after the fire event, cross-tabulation analysis was performed in R statistical software (R Core Team 2017) using the gmodels package (Warnes et al. 2018) and contingency tables were produced. For this analysis, we used a total of 828 462 polygons of the eight different vegetation types detected within the study area. A chi-squared test was applied to test the null hypothesis of no effects, as well as to compare expected with observed values (Nioti et al. 2015). A logistic regression analysis was performed to determine the effects of landscape variables on the recovery of black pine forest with the binary response variable being ‘recovery of the original vegetation type either occurs or does not occur’ (Pueyo and Alados 2007). Predictor variables were aspect, basement rock, erodibility and geomorphology (Table 2), key landscape features known to influence post-fire regeneration and vegetation dynamics (Röder et al. 2008; Viana-Soto et al. 2017; Vidal-Macua et al. 2017). An intuitive variable classification of the response variable to 0 for non-recovery and to 1 for recovery was applied. For visualisation of the results,
we used the R packages `arm` (Gelman and Su 2016) and `effects` (Fox 2003).

Results
The results of the cross-validation procedure during RF classification model development (Fig. 2) confirmed the complex nature of the landscape under study. The OOB accuracy for the burned area mapping using the Quickbird image was 95.14%, while the lowest prediction accuracy was noted for the pre-fire forest type classification (73.95%). Finally, the results of the RF performance showed good classification accuracy for the post-fire classification of the Worldview-3 image (OOB accuracy 82.73%).

Changes in the distribution and percentage of total cover of different vegetation types 8 years after the 2007 fire event are shown in Figs 3 and 4 as well as in Table 3. The overall changes indicate a decrease in all forest vegetation types from 40% of the total cover to 18%. The most striking difference is the total lack

![Fig. 2. Out-of-bag (OOB) error for the three different Land Use Land Cover (LULC) classifications. The highest error was noted for the pre-fire classification using the IKONOS and ASTER images (26.05%), whereas lower error rates were found for post-fire classification of the Worldview-3 image (17.27%) and burned area mapping using the Quickbird image (4.86%).](image)

![Fig. 3. Natural vegetation before the 2007 fire (left), and recovery after an 8-year period (right).](image)
of *Abies cephalonica* regeneration, which is evidenced by the absence of both fir forest stands and mixed-conifer stands 8 years after the fire. Pre-fire Greek fir-dominated forests were converted mostly into grasslands and shrublands, while in some plots, the regeneration level of black pine was higher than that of Greek fir. The area of ground covered by black pine forests did not change substantially after fire (from 16.6 to 15%). This is because of the conversion of mixed-conifer forests or Greek fir-dominated forests into black pine forests due to the lack of regeneration of *A. cephalonica*. Nevertheless, the level of black pine regeneration was not the same everywhere, with higher densities recorded closer to unburned patches with mature black pine trees. However, there was a remarkable increase in the relative contribution of phrygana (from a percentage cover of 0.7 to 22.3%), with species such as *Genista acanthoclada*, *Sarcopoterium spinosum* and *Thymbra capitata* occupying areas previously covered mostly by grasslands and maquis.

Likewise, sparsely vegetated areas increased from 0.4 to 9.6% of the landscape, demonstrating recovery failure of various vegetation types, including mostly grasslands and Greek fir-dominated forests. In total, 8 years after fire, 72.6% of the burned area was covered either by grasslands or by shrubs, revealing a transition from forest to shrubby vegetation types (i.e. maquis and phrygana) and grasslands. More than 55% of the study area was affected by this transition. Results of Pearson’s chi-square test (665 264.8, d.f. = 35, *P* < 0.001) and differences between observed and expected values (Table 3) indicate that there is an association between vegetation type before and after the fire event.

At a second stage, we constrained our analysis to coniferous forests, representing the main forest type of the mountain. As no *A. cephalonica* regeneration was identified, additional statistical analyses were performed only for black pine and mixed-conifer forests. This reduced the initial number of analysis polygons to 49,026. For the same reason, mixed-conifer forests were aggregated to black pine forests and treated as a single category.

A summary of the logistic regression analysis results is given in Table 4. All four predictor variables are categorical (Table 2). We chose to include the interactions between aspect and erodibility as well as aspect and geomorphology as these were the most meaningful ones. In this analysis, aspect, basement rock type, erodibility and geomorphology were recognised as significant factors affecting the regeneration of black pine on Mount Taygetos. In addition, significant interactions between levels of aspect × erodibility and geomorphology × aspect were identified and are presented in Table 4. In general, eastern and south–south-western aspects had a lower regeneration probability compared with northern orientations (Fig. 5). Canyons and mountain tops had a higher regeneration probability in contrast to open and upper slopes. Overall, the interpretation for coefficients of categorical variables is somewhat different from that of numerical ones and may be understood with an example from Table 4. Having a background geomorphology of type 2 (i.e. canyons) vs type 1 (i.e. valleys) changes – increases because the coefficient is positive – the log odds of *Pinus nigra* recovery by 0.40. All coefficients for the effect of different types of the categorical variables on the outcome are presented in comparison with the base type of each variable.

**Discussion**

Eight years after Mount Taygetos wildfire, combined results of RS- and GIS-based analyses and field measurements indicate a widespread transition from forest to shrubby vegetation types, namely maquis and phrygana or to grasslands and sparsely vegetated areas. The nature of this transition depends on the dominant tree species before the fire event, as well as on the spatial configuration of the burned area. For both conifer species (*Pinus nigra* and *Abies cephalonica*), distance from unburned patches with mature trees that can contribute to the post-fire forest recovery through seed dispersal is of paramount importance after high-intensity crown fires (Ordoñez *et al.* 2006; Christopoulou *et al.* 2014, 2018; Raftoyannis and Spanos 2015). Black pine, in contrast to Greek fir, can withstand low-intensity surface fires, owing to its thick bark (Tapias *et al.* 2001, 2004; Pausas *et al.* 2008). Decreasing natural regeneration after wildfires has been recorded for conifer species in many temperate-zone forests (e.g. Stevens-Rumann *et al.* 2018) and is mostly attributed to reduced seed availability in the case of large stand-replacing fires (Harvey *et al.* 2016; Rother and Veblen 2016; Welch *et al.* 2016; Shive *et al.* 2018; Stevens-Rumann *et al.* 2018). The 2007 wildfire did not burn the landscape in a homogeneous way, resulting in the presence of unburned patches of various sizes within the periphery of the burned area. These patches could contribute to post-fire Greek fir recovery through seed dispersal to the burned areas and subsequent seed germination (Arianoutsou *et al.* 2010). In such cases, provided that the distance from the unburned mature Greek fir stands is less than 100 m, there is a chance of *A. cephalonica* regeneration (Christopoulou *et al.* 2018). Nevertheless, even in these cases, post-fire recovery of Greek fir is expected to be a lengthy process (Ganatsas *et al.* 2012; Christopoulou *et al.* 2018).
Another factor that may affect the total seed availability for the Greek fir is its masting behaviour, expressed with high inter-annual variability in the number of adult trees bearing cones, as well as in cones produced per tree and viable seeds per cone (Politi et al. 2011). The lack of suitable microhabitats for seedling establishment in the post-fire open habitat may further limit Greek fir post-fire recovery (Ganatsas et al. 2012; Raftoyannis and Spanos 2015; Christopoulou et al. 2018), as has also been found for other fire-sensitive conifer species (e.g. Stevens-Rumann et al. 2018). However, the faster growth rate

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Table 3. Contingency table of changes in vegetation types 8 years after the fire event
and better colonisation capacity of *P. nigra* in burned areas where unburned patches of both species are present at fairly small distances (Arianoutsou *et al.* 2010) allows us to claim that wildfires may lead to shifts in vegetation composition.

Focusing on black pine forests, it seems that geomorphology can greatly affect post-fire recovery. Erosion and subsequent soil loss are generally the dominant surface processes on landscapes (Bryan 2000). However, better recovery of *P. nigra* was recorded in canyons and on mountain tops and high ridges of the study area. This is in general agreement with previous studies of *P. nigra* (e.g. Sass *et al.* 2012). Seedlings and saplings of *P. nigra* established at higher elevations are subjected to

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**Table 4. Coefficients of the logistic regression model (dispersion parameter for binomial family taken to be 1) predicting *Pinus nigra* forest recovery as a function of the landscape predictor variables**

Statistically significant variables are indicated with bold *P* values. Only significant interactions are reported. See text for explanation.

<table>
<thead>
<tr>
<th>Estimate</th>
<th>s.e.</th>
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<th><em>P</em> value</th>
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<tr>
<td>Intercept</td>
<td>0.26</td>
<td>0.04</td>
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<tr>
<td>Canyons (Geomorphology 2)</td>
<td>0.40</td>
<td>0.06</td>
<td>6.42</td>
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<td>Open slopes (Geomorphology 3)</td>
<td>−0.16</td>
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<td>Upper slopes (Geomorphology 4)</td>
<td>−0.11</td>
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<td>Mountain tops, high ridges (Geomorphology 5)</td>
<td>0.46</td>
<td>0.06</td>
<td>7.09</td>
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<tr>
<td>E-NE slopes (Aspect 2)</td>
<td>−1.18</td>
<td>0.07</td>
<td>−17.46</td>
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<td>S-SW-W slopes (Aspect 3)</td>
<td>−0.74</td>
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<td>Flysch (Basement rock 2)</td>
<td>1.11</td>
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<td>Quaternary deposits (Basement rock 3)</td>
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<td>Low–medium erodibility (2)</td>
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<td>Geomorphology2: Aspect2</td>
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<td>4.20</td>
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<td>Geomorphology3: Aspect2</td>
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<td>Geomorphology2: Aspect3</td>
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<td>3.05</td>
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**Fig. 5.** Predicted probabilities for post-fire recovery across the different levels of the topographic and geomorphological variables, based on the logistic regression prediction. Note that interactions are not included in this graph. Aspect: 1, N slopes; 2, E-NE slopes; 3, S-SW-W slopes; Basement rock: 1, limestone; 2, flysch; 3, quaternary deposits; Erodibility: 1, low; 2, low–medium; 3, moderate; 4, high; and Geomorphology: 1, valleys; 2, canyons; 3, open slopes; 4, upper slopes, mesas; 5, mountain tops, high ridges.
lower drought stress because of the prevailing lower temperatures during the summer period. This has been reported for the same species in previous studies (Christopoulou et al. 2014) and for other pine species in the Mediterranean Basin (Viana-Soto et al. 2017) and elsewhere (Rother and Veblen 2016). Better post-fire recovery in canyons may be partly explained by the anemochorous seed dispersal mode of P. nigra, whose seeds have a low seed wind-loading index (Richardson et al. 1990) and may be transported appreciable distances by wind and deposited in the lower parts of the landscape (Thompson and Katul 2009). Seed movement by water and gravity may also explain this pattern. Moreover, in canyons, deeper soils and wetter conditions are expected, facilitating seed germination and subsequent seedling survival.

In terms of the correlation between post-fire recovery and basement rock, it appears that more favourable conditions were observed over the clastic sedimentary lithologies, such as flysch layers. Forest recovery was also higher in areas where the parent basement rock consisted of flysch or quaternary deposits, as the lower bulk density of the soils and the easier access of roots to lower layers allow access to resources such as water and nutrients. Sites with low–medium or moderate erodibility (classes 2 and 3), based on Nakos (1979), showed a higher recovery, indicating probably better soil conditions, but on highly erodible sites (class 4), the recovery probability was qualitatively lower, although the difference was not statistically significant. This can be attributed to the impermeability of clastic rock types (e.g. flysch, schist) and consequently the ability to retain water, especially in the near-surface layers. Limestone and other types of solid rocks make much less contribution to soil production and host shallower soil layers, especially when combined with steep slopes where the ability to retain locally produced soil is reduced. Conditions after a fire event can be even worse because vegetation cover is temporarily minimised and thus the retention of soil in situ is reduced (Pelletier 2017). Essentially, a fire event on a steep limestone slope could create a barren landscape with the basement rock exposed (Diakakis et al. 2017; Farangitakis et al. 2017). In such conditions, it is highly unfavourable to any post-fire regeneration taking place, especially for obligate seeders.

In relation to aspect, post-fire recovery was found to be higher on north-facing slopes, as has also been found elsewhere (Rother and Veblen 2016; Welch et al. 2016). North-facing slopes are generally moister, whereas eastern, south and south-western aspects are exposed to higher heat loads (McCune and Keon 2002), leading to more severe drought stress. These findings agree with Fyllas et al. (2008), who found that P. nigra was more abundant on north-facing slopes, whereas Pinus brutia prevailed on lower, drier and southern-oriented aspects. Although P. nigra can experience reduced regeneration under drier microenvironmental conditions (Fyllas et al. 2008), in the current study, it seems that the species is likely to increase its relative abundance compared with A. cephalonica. This confirms the suggestion made by Arianoutsou et al. (2010) that in burned areas where stands of the two species are found in quite close quarters, black pine could potentially invade sites previously dominated by fir.

The patches covered by short seasonal dimorphic shrubs (phrygana) most probably reflect the result of repeated fires that have happened in the study area during the last 165 years (Christopoulou et al. 2013), and which did not allow the recovery of the initial forest vegetation. The presence of phrygana may be attributed to the ability of those species to withstand fire and become more abundant in cases where the canopy tree cover fails to recover (Arianoutsou–Faraggitaki 1984).

With regard to our combined RS and GIS analyses, the highest OOB accuracy was obtained in our burned mapping (the Quickbird image classification) owing to the binary classification scheme and the profound changes in the spectral response between burned and unburned areas. This is due to the modification of the composition and moisture content of the aboveground vegetation and char and ash deposition after fire, resulting in substantial differences in the spectral profiles between adjacent burned and unburned areas, thus facilitating discrimination and classification (Mallinis and Koutsias 2012). However, the lower prediction accuracy of the pre-fire classification of the forest types in the area, although deemed satisfactory based on accuracy standards for vegetation mapping (Rudnicki et al. 2015), can be attributed to the fact that the pre-fire landscape in the area is complex, with an intermix of vegetation types with similar spectral signatures (i.e. Greek fir-dominated forests, mixed-conifer forests and black pine forests).

The higher accuracy of the post-fire classification compared with the pre-fire vegetation map is also likely related both to the refined spectral information (compared with other VHRSensors) recorded by the Worldview-3 sensor, which provides eight multispectral bands over the 400–900 nm spectral range and to the non-existence of A. cephalonica in the post-fire landscape.

Conclusions

Our study provides evidence that landscape characteristics are influencing post-fire vegetation recovery on Mount Taygetos. Such evidence can be of paramount importance for the evaluation of the resilience of different vegetation types, as well as for the identification of vulnerable sites within the burned area and of sites needing human-aided restoration. Future studies addressing similar questions coupled with fire severity information could contribute to the assessment of ecosystem vulnerability to changing fire regimes induced by global change and greatly support adaptive forest management (Lloret et al. 2002; Moreira et al. 2011; Duguy et al. 2012; Torres et al. 2017; Moya et al. 2018).

Remote sensing techniques have been extensively employed in studies related to fire effects on ecosystems and monitoring in various biomes at local, regional and global scales. Several methods have been developed, from the fairly common burned area mapping to more challenging tasks such as tracking forest successional stages and recovery patterns (Chu and Guo 2014). Despite the advantages that RS techniques have over traditional field sampling methods, more robust approaches and methods need to be further developed. Our use of GEOBIA combined with very high spatial resolution images proved to be very effective in the present study, as it provided spatially explicit and unbiased representation of pre- and post-fire forest patterns and improved the accuracy of forest recovery modelling. As has been suggested in other studies, time series of high-resolution images can enhance monitoring results of post-fire recovery (Vanderhoof et al. 2018), but their high cost remains a serious restriction for forest managers.
Conflicts of interest
The authors declare no conflicts of interest.

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References


