Monitoring vegetation regeneration after forest fires using satellite imagery

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Keywords: forest fires, vegetation regeneration, spectral mixture analysis, Landsat

ABSTRACT: This work describes the monitoring of forest regeneration in a large fire occurred in 1997 in south-east France using Landsat data. The main objective of the study was to analyse post-fire vegetation recovery at the test site as a temporal and spatial process. This implied the analysis of regrowth trajectories of different vegetation communities and the investigation of the spatial patterns of regeneration. The analysis of post-fire regeneration relied on a multitemporal time series of 11 Landsat images that were previously geometrically and atmospherically corrected. Spectral analysis revealed that vegetation regeneration was related to gradual spectral changes over time with different vegetation communities following different spectral pathways. Different regeneration pathways were identified for Quercus coccifera and Pinus halepensis plots which could be related to their post-fire regeneration strategy. In order to monitor regeneration for the entire time-series of available Landsat data (1997-2002), linear mixture modelling was used to unmix scene reflectance into normalized fractions of soil and vegetation. The technique of spectral unmixing was effective at separating the contribution of soil and vegetation spectra to a given pixel. The accuracy of the normalized vegetation fractions was evaluated using linear regression analysis. Estimates of fractional vegetation cover using spectral mixture showed high correlation with field-based estimates. The regression coefficient of R = 0.9638 indicated a strong positive correlation of the two variables with 92.89 % of the total variation explained by the linear regression model (R² = 0.9289).

1 INTRODUCTION

Every year there are more than 50,000 forest fires in Europe, affecting over 500,000 ha of forest and other woodland, the majority of which occur in the Mediterranean Region (European Commission 2002). Although fire is a natural process of the Mediterranean ecosystems (Chuvieco 1997, Trabaud et al. 1980), human influence has intensified its impact and altered natural fire-cycles (Naveh 1975), transforming the original landscape into degraded ecosystems with species developing adaptive responses which allow them to persist (Ferrandis et al. 2002). Spatial databases on forest fires are necessary to support fire management programs and evaluate the manifold implications of fire occurrence (Koutsias et al. 1999). In order to support the protection and reconstruction of the fire-affected ecosystem, information on the temporal and spatial dynamics of post-fire recovery is required. This knowledge is essential to establish post-fire vegetation management and to evaluate the necessity of reforestation programs to reduce the risk of landslides and soil erosion after the fire (Riaño et al. 2002). Earth observation techniques have been increasingly used over re-
cent years as a beneficial tool for monitoring various aspects of the fire process at different spatial and temporal scales (Shoshany 2000). Due to their synoptic, repetitive and consistent perspective, space borne satellite platforms constitute an important means to gather information on the impact of forest fires in a timely and cost-efficient manner.

2 OBJECTIVES AND STUDY AREA

This study is focused on the monitoring of vegetation recovery after the fire using remote sensing techniques and data collected from the Landsat series of satellites. In particular, this study aimed to analyse post-fire vegetation recovery as a temporal and spatial process. This implies the assessment of the swiftness of recovery, the analysis of re-growth trajectories of different vegetation communities and the investigation of the spatial patterns of regeneration. The effectiveness of different techniques in monitoring post-fire vegetation recovery accurately was also analysed, but only the results obtained using Spectral Mixture Analysis (SMA) will be presented in this paper.

The study area near the city of Marseille corresponds to the southernmost part of low western Provence. This study focuses on a 26 x 13 km area surrounding the boundaries of the two forest fires that took place from 25th until 27th July 1997. The larger of the two fires spread over an area of 3450 ha in the south facing slopes of the “Massif de l’Étoile” and the south-west facing slopes of the “Massif du Garlaban”. The smaller of the two fires affected an area of 465 ha between the village of Le Rove and the rocky coastline of the western bay of Marseille. Inside the burned area there were three main pre-fire vegetation classes according to the French national forest inventory:

1. Garrigue non boisée
2. Garrigue ou maquis boisée de pins
3. Futaie de pin d’alep

The first inventory class, non-forested garrigue, is the most degraded landscape type which mainly occupies the calcareous western slopes of “Massif de l’Étoile”. It was also widespread on the “Massif du Garlaban” and the south-western part of “Le Rove”. “Garrigue ou maquis boisée de pins” basically constitutes a more evolved, denser, and higher-grown transition stage between the non-forested garrigue and full-grown coniferous forest. On slopes where light, calcareous soils are still present, the evergreen shrubs are complemented by relatively widely spaced pines (mainly Pinus halepensis). “Futaie de pin d’alep” corresponds to full-grown coniferous forest dominated by Aleppo pine over the ages. Pine forest has primarily spread from the V-shaped valleys north of the village of “Plan-de-Cuques” up to the higher regions.

Table 1. Properties of utilized satellite data

<table>
<thead>
<tr>
<th>Path/Row</th>
<th>Acquisition Date</th>
<th>Landsat Sensor</th>
<th>Sun Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>196/30</td>
<td>13.04.1997</td>
<td>TM</td>
<td>48.387</td>
</tr>
<tr>
<td>196/30</td>
<td>03.08.1997</td>
<td>TM</td>
<td>55.091</td>
</tr>
<tr>
<td>196/30</td>
<td>21.07.1998</td>
<td>TM</td>
<td>58.468</td>
</tr>
<tr>
<td>196/30</td>
<td>22.06.1999</td>
<td>TM</td>
<td>61.356</td>
</tr>
<tr>
<td>196/30</td>
<td>10.09.1999</td>
<td>TM</td>
<td>46.232</td>
</tr>
<tr>
<td>196/30</td>
<td>19.08.2000</td>
<td>ETM+</td>
<td>53.839</td>
</tr>
<tr>
<td>196/30</td>
<td>06.10.2000</td>
<td>ETM+</td>
<td>38.635</td>
</tr>
<tr>
<td>196/30</td>
<td>21.07. 2001</td>
<td>ETM+</td>
<td>59.908</td>
</tr>
<tr>
<td>196/30</td>
<td>25.10.2001</td>
<td>ETM+</td>
<td>32.187</td>
</tr>
<tr>
<td>196/30</td>
<td>22.06. 2002</td>
<td>ETM+</td>
<td>62.857</td>
</tr>
<tr>
<td>196/30</td>
<td>26.09.2002</td>
<td>ETM+</td>
<td>42.014</td>
</tr>
</tbody>
</table>
A total of 11 Landsat quarter scenes were used. As a result of the satellite repeat coverage interval of 16 days and the unsuitability of several images in the Landsat archive due to cloud coverage, annual Landsat data was not always temporally matching. However, interannual variability of land cover is low because evergreen species (e.g. Quercus coccifera, Pinus halepensis) are predominant in the study area. Table 1 lists the main properties of the acquired Landsat quarter scenes that were geometrically and atmospherically corrected.

3 FIELD DATA

The fieldwork campaign had three main objectives:
• to take photographs of selected sample plots in order to give a visual impression of the regeneration for different vegetation species
• to gain information on the vegetation composition and characteristics of the area in order to define distinctive regeneration pathways for different vegetation types
• to estimate fractional vegetation cover (FVC)

Field-work was carried out from the 14th-16th May 2003 using a GPS unit, a compass, a laptop computer, and a high-resolution digital camera mounted on a tripod. The field campaign data was further used to define homogeneous areas of interest for the comparison of regeneration pathways of different vegetation types and, for correlation analysis with remote sensing derived information.

Three classes derived from forest inventory data were used for a stratification of the area in order to have representative samples for each pre-fire vegetation type and to make statistically meaningful comparisons among them. Proportionate sampling was selected to produce sample sizes that were directly related to the size of the classes. With the minimum sample size set to 0.075% of the total pixels of each class, a total of 45 sample points was generated for the burned area of 1997. The field work consisted in the localization of the central point of each sample area of 50 x 50 m by using GPS measurements. The following measurements were made for the central point and four sub-plots located 25 m in N, E, S and W direction from the central point:
• Fractional Vegetation Cover (%) by using a digital camera and visual estimation
• Height of tree/shrub-layer (m)
• Dominant Species (for complete sample plot)

The camera stand was aligned to cover a total area of 1.5 x 1.5 m for each sub-plot. The photos were visually interpreted using a simple thresholding technique and a calculation of the total area covered by vegetation. A comparison between visual estimates and the approximation derived from digital imagery showed a high level of agreement (Brogaard and Ólafsdóttir 1997).

4 SPECTRAL DYNAMICS OF REGENERATION

Trajectories of regeneration were defined from homogeneous field plots which allowed following the spectral dynamics of two dominant species of the study area: Kermes oak (Quercus coccifera) and Aleppo pine (Pinus halepensis). These species embody two different strategies of regeneration which are characteristic for the Mediterranean (Lloret and Vilà 1997). While Quercus coccifera has an extensive rhizomatous system which allows vigorous resprouting after disturbances, Pinus halepensis is an obligate seed regenerator and relies on seed germination from cones that burst open during the fire event (Naveh 1990).

Five plots per species were identified during field-work. Each plot of 50 x 50 m was related to the average of a matrix of 3 x 3 pixels to minimize the influence of geometric inaccuracies.

The visible bands show similar trajectories, although the change is particularly pronounced in TM3. Reflectance increases in all visible wavelengths until it reaches a peak after one year (Quer-
Quercus coccifera) and three years (Pinus halepensis) respectively (Figures 1 and 2). This increase can be explained by the gradual removal of charcoal and by the exposure of the soil layer. It seems that Quercus coccifera covers the soil more quickly in the first years after the fire because reflectance in these plots decreases earlier due to chlorophyll absorption. While reflection of TM1, TM2 and TM3 is already relatively stable in the Quercus coccifera plots two years after the fire, the plots dominated by regenerating Pinus halepensis are characterized by a gradual decrease in reflectance, probably caused by slow crown closure.

Figure 1. Spectral trajectory of Quercus coccifera plots in the visible wavelengths

Figure 2. Spectral trajectory of Pinus halepensis plots in the visible wavelengths

In the Quercus coccifera plots, near-infrared TM4 reflectance increased drastically one year after the fire. This can be explained by vegetation re-growth and contribution of bright soil background which is fully exposed after one year due to the removal of charcoal and residues of dead vegetation (Figure 3). Whereas TM4 reflectance stabilizes for these sample plots in the following years, Pinus halepensis is marked by a slower polynomial increase in near-infrared reflectance which seems to saturate after four years of regeneration (Figure 4). It is further noticeable for both plots that after one year of regeneration, TM4 reflectance is already considerably higher than before the fire. This observation suggests that TM4 reflectance increase cannot be linearly related to an increase in vegetation vigour as the exposed soil layer strongly influences reflectance in this band. In order to separate both effects, an interpretation of TM4 reflectance in combination with TM3 where leaf-chlorophyll strongly absorbs is necessary - the basic principle of vegetation indices. The two mid-infrared ranges are characterized by an increase in reflectance directly after the
fire. Since TM5 and TM7 are both sensitive to plant water content and soil moisture, this observation can be explained by two processes. Firstly, the combustion of vegetation reduces the absorption of the mid-infrared wavelengths through leaf tissue water content. Secondly, after the removal of combustive residues one year after the fire, the soil is completely exposed and solar radiation dries out the upper soil layer. This goes along with a further increase in mid-infrared reflectance one year after the fire. The increase is especially marked in the *Pinus halepensis* plot because more residues (e.g. burned bark) cover the soil and are less quickly removed after the fire. In contrast to TM5, where no consistent trend during the following years can be observed, TM7 decreases progressively as a function of time. The trend of TM7 reflectance values towards pre-fire levels can be related to increasing plant water content as a result of vegetation regeneration.

![Spectral Trajectories - Quercus coccifera](image1)

Figure 3. Spectral trajectory of Quercus coccifera plots in the near- to mid-infrared wavelengths

![Spectral Trajectories - Pinus halepensis](image2)

Figure 4. Spectral trajectory of Pinus halepensis plots in the near- to mid-infrared wavelengths

5 SPECTRAL MIXTURE ANALYSIS RESULTS

Methodologies to decompose spectral reflectance into its contributors, such as spectral mixture analysis (SMA), can accurately quantify vegetation abundance in multi- and hyperspectral imagery (Smith et al. 1990, Roberts et al. 1993, Riaño et al. 2002). Hence, it was decided to construct a spectral unmixing model and evaluate its accuracy to predict vegetation cover using linear regression analysis. In general, the performance of the unmixing model largely depends on the selection of spectral endmembers (Elmore et al. 2000). Common endmembers in studies of vegetation cover assessment are spectra of soil, green vegetation and shade. While hyperspectral imagery such as

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AVIRIS permit to use many endmembers, the dimensionality of multispectral data like Landsat TM/ETM+ limits a successful unmixing model to a maximum of four (Roberts 1993, Small 2001). Although a large number of endmembers can explain more spectral variation, leading to increased model fitness, too many endmembers can lead to an extremely sensitive mixture model (Wu and Murray 2003). As the robustness of the model was regarded as essential, three candidate endmembers were defined to represent pixel reflectance: soil, green vegetation and shade. The definition of appropriate spectral endmembers can be either done using image-based extraction techniques such as the minimum noise fraction (MNF) algorithm and pixel purity index (PPI) (Garcia et al. 2001), or using pure field-spectra from spectral libraries. Being unlikely that a Landsat pixel is fully covered by a unique spectral feature such as vegetation, it was decided to use reference endmembers from a spectral library compiled from field measurements in Mediterranean France (Lacaze et al. 1996). The iterative optimization of the selection process was aimed at minimizing RMSE and fractional error for the study area. While RMSE indicates to what extent the image spectra cannot be explained by the endmembers, the fractional error accounts for portions lying outside the range of 0 to 1 which indicates either non-linear mixing or inappropriate endmembers. At the end of the iterative process, a final spectral library was defined that best described the variability of the original image reflectance. Various studies justified that the use of a universal green vegetation endmember can provide accurate estimations for several biophysical variables even when being used in heterogeneous landscapes (Mcgwire et al. 2000). Accordingly, the spectrum of oak canopy (Quercus ilex) measured using a spectroradiometer from an observation tower was used to represent fractional vegetation cover. The soil endmember was represented using spectra from a limestone soil. A shade spectrum is commonly implemented into spectral unmixing models to account for both topographic and canopy shading. Although some authors used a shade endmember with zero reflectance in all bands (Mcgwire et al. 2000), a shade endmember defined from the darkest image pixel in a clear dark water body resulted in an increased model fit and was thus preferred. Subsequently, the final set of three endmembers was used in a partially constrained (unit sum constraint) linear spectral unmixing algorithm. The elimination of the shade endmember and renormalization of the remaining endmember to sum up 1 was done to reduce topographic sun illumination influences and account for higher shade abundances of forest canopy.

Estimates of fractional vegetation cover (FVC) from the fieldwork were compared with pixel values of the normalized vegetation endmember. The approach of using a pixel matrix has been widely accepted to reduce potential geo-location errors (Ahern et al. 1991, Puhr and Donoghue 2000). The average reflectance of a 3 x 3 pixel matrix from the most recent image (26.09.2002) was taken to be spectrally representative of the ground survey plot. In order to estimate the degree of the variables’ relation, simple linear regression analysis and a least-squares fitting algorithm were employed. The regression coefficient of $R = 0.9638$ indicated a strong positive correlation of the two variables with 92.89 % of the total variation explained by the linear regression model ($R^2 = 0.9289$). The slope and intercept of the fit showed that fractions of green vegetation derived from linear spectral unmixing directly related to measured fractional vegetation cover. The dynamic range included the complete range of vegetation cover prevalent at the study site, with estimates being highly accurate for lower and higher percentages of vegetation cover (Figure 5).

In order to monitor regeneration for the entire time-series of available Landsat data (1997-2002), the model was used to unmix scene reflectance into normalized fractions of soil and vegetation. The accurate pre-processing of the time-series to units of surface reflectance permitted to use the previously established model for all satellite scenes. The temporal evolution of fractional cover generally indicated strong regenerative capabilities of the vegetation communities present at the study site. Averages of fractional vegetation cover calculated for the entire burned area perimeter showed that vegetation already reaches 34 % ground coverage one year after the fire. The quick recovery of vegetation one year after the fire can be explained by the appearance of annual species and perennial herbs, which emerge few months after the fire, but slowly decrease when woody species start to appear (Trabaud and Lepart 1980, Pereiras and Casal 2002). In addition, resprouting shrubs which are adapted to burning contribute to the relatively quick increase in vegetation cover. The most dominating shrub present, Quercus coccifera, is characterized by high survival rates after
fire and its ability to vigorously resprout by means of an extensive rhizomatous system (Trabaud 1994). Increase of vegetation cover is especially strong in the first two years of regeneration. After two years, a first peak of vegetation cover can be observed (49 %). Trabaud and Lepart (1980) found that floristic richness in a comparable biome in France increased after the fire and reached a maximum between the 10th and 40th month. The relative decrease of therophytes after the following post-fire years can probably explain the peak since a change of life forms occurs. In the following years, only little change is observable and vegetation cover oscillates around 50 % of fractional vegetation cover for the entire burned area. Change detection using pre- and post-fire scenes showed that regeneration swiftness was not homogeneous over the entire burned area. Distinct spatial patterns with vegetation of similar regenerative capability were observed. In comparison to pre-fire conditions, vegetation cover was still up to 40 % lower in certain areas, while in other areas reached or surpassed pre-fire levels. A comparison of these patterns with forest inventory data revealed a strong correlation between pre-fire vegetation type and regeneration swiftness.

![Correlation SMA - Field Data](image)

Figure 5. Relationship between SMA and field based estimates of fractional vegetation cover

## 6 CONCLUSIONS

Spectral post-fire analysis revealed that regeneration is related to gradual spectral changes over time with different vegetation communities following different spectral pathways. Differences between *Quercus coccifera* and *Pinus halepensis* plots were related to their post-fire regeneration strategy. Pre-fire vegetation type was identified as a main factor influencing regeneration rates. Spectral mixture analysis, applied to separate the green vegetation endmember from background endmembers (i.e. shade and soil), was found to accurately estimate fractional vegetation cover. Since SMA considers the full spectral range to derive sub-pixel abundances of vegetation, the described technique has a high potential to quantitatively monitor post-fire vegetation recovery. In this context, the proposed method of linear spectral unmixing showed to be capable of deriving physically accurate estimates of fractional vegetation cover. This was confirmed by an analysis of
shade-normalized green vegetation fractions derived from all consecutive Landsat scenes. It is believed that a quantitative approach, where more emphasis is put on deriving biophysically meaningful units, could help in establishing remote sensing as an interdisciplinary tool to monitor post-fire vegetation dynamics. In addition, it would potentially reduce the problem of upscaling detailed fire-ecological studies to larger scale remote sensing based monitoring. In combination with ancillary spatial data such as soil information and terrain slope, accurate estimates on vegetation cover can be valuable for identifying areas of elevated risk of erosion or landslides after fires.

REFERENCES


