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Quantifying spatial and temporal vegetation recovery dynamics following a wildfire event in a Mediterranean landscape using EO data and GIS

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A B S T R A C T

Analysis of Earth Observation (EO) data, often combined with Geographical Information Systems (GIS), allows monitoring of changing land cover dynamics which may occur after a natural hazard such as a wildfire. In the present study, the vegetation recovery dynamics of one such area are evaluated by exploiting freely distributed EO data and GIS techniques. The relationships of re-growth dynamics to the topographical characteristics of the burn scar are also explored. As a case study, a typical Mediterranean ecosystem in which a wildfire occurred during 2007 is used. Vegetation recovery dynamics of the whole area under the burn scar were investigated based on chronosequence analysis of the normalized difference vegetation index (NDVI) derived from anniversary Landsat TM images. The spatio-temporal patterns of post-fire NDVI on each image date were statistically compared to the pre-fire pattern to determine the extent to which the pre-fire spatial pattern was re-established and the recovery rate. The relationships between NDVI as an expression of recovery rates and aspect were also statistically investigated and quantified using a series of statistical metrics. Results suggested a generally low to moderate vegetation recovery of the local ecosystem five years after the fire event, with the post-fire NDVI spatial pattern generally showing a gradual but systematic return to pre-fire conditions. Re-growth rates appeared to be somewhat higher in north-facing slopes in comparison to south facing ones, in common with other similar studies in Mediterranean type ecosystems. All in all, this study provides an important contribution to the understanding of Mediterranean landscape dynamics, and corroborates the usefulness particularly of NDVI in post-fire regeneration assessment via a well-established methodology which can also be transferable to other regions. It also provides further evidence that use of EO technology which combined with GIS techniques can offer an effective practical tool for mapping wildfire vegetation dynamics and ecosystem recovery after wildfire.

Introduction

Altering land cover dynamics is currently regarded as the single most important variable of global change affecting ecological systems (Otukei & Blaschke, 2010). Wildfires are considered as one of the most widespread ecological disturbances of natural ecosystems that dramatically affect land cover dynamics at a variety of spatial and temporal scales as a result of the complete or partial removal of vegetation cover (Lhermitte, Verbesselt, Verstraeten, Veraverbeke, & Coppin, 2011). In this context, knowledge of the spatio-temporal distribution of post-fire vegetation recovery dynamics is of key importance. Such information plays a significant role in various aspects of policy and decision-making as well as in the dynamics and structures of plant and animal communities of the affected ecosystems (Elvira & Hernando, 1989; Gouveia, DaCamara, & Trigo, 2010). Knowledge of vegetation recovery dynamics following a fire outbreak is essential to estimate the effects of the fire and to understand the forces driving changes in post-fire ecosystems (Casady, Leeuwen, & Marsh, 2009; Grissino-Mayer &

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Swetnam, 2000). Such information, if available in a consistent, repetitive and cost-effective manner, is also a crucial element of successful landscape management (Wittenberg, Malkinson, Beeri, Halutzy, & Tesler, 2007). It can assist in identifying areas needing intensive or special restoration programs aiming to reduce soil erosion and runoff, thus mitigating long-term site degradation (Gouveia et al., 2010; Keeley, 2000; Malak & Pausas, 2006). Given that future changes in climate could potentially lead to increases in fire frequency, severity and extend into ecosystems that include species that have not evolved to be able to easily regenerate (Politi, Arianoutsou, & Stamou, 2009), information on regeneration vegetation is of key importance.

The speed of vegetation recovery can control the extent of various environmental, social, economic and political impacts (Minchella, Del Frate, Capogna, Anselmi, & Manes, 2009). Indeed, the rate of vegetation biomass re-growth can vary significantly; some areas can show complete vegetation recovery after a few years while others are still not completely recovered decades after the fire. In the Mediterranean region in particular, where fire has been an important ecological factor for millennia (Mayor, Bautista, Llovet, & Bellot, 2007; Naveh, 1974), rates of post-fire recovery dynamics are usually spatially variable and contingent upon a number of factors. This is because of the complexity of landscape structure and the range of responses of such systems to the diverse types of fire regimes. At the landscape level, various studies have shown post-fire regeneration to be mainly dependent on the initial vegetation and site-specific climatic and terrain parameters (Pausas & Vallejo, 1999; Wittenberg et al., 2007). Climatic factors, such as heavy autumn rainfall, generally also lead to a higher potential for post-fire soil erosion (Millán, Estrela, & Caseller, 1995), which also affects vegetation re-growth dynamics (Pausas, Ribeiro, & Vallejo, 2004). Moreover, various studies have shown that in such environments, post-fire growth is frequently affected by topography and aspect. South-facing slopes experience higher insolation and evapotranspiration rates than north-facing slopes. This results in vegetation tending to grow back more quickly on north-facing slopes with more favourable moisture conditions (Fox, Maselli, & Carrega, 2008; Mouillot, Ratte, Joffre, Mouillot, & Rambal, 2005). Unfortunately, interactions between such parameters and plant regeneration are poorly known, especially at the scale of a single large fire. At this scale, use of Earth Observation (EO) technology has proved to be a suitable tool for monitoring plant regeneration after fire.

When combined with Geographic Information Systems (GIS) techniques, EO data have demonstrated promising potential in providing an effective set of tools for analysing and extracting spatial information related to wildfires (Chen, Chen, Liu, Li, & Tan, 2005; Chen et al., 2011; Durduran, 2010; Kalivas, Petropoulos, Athanasiou, & Kollias, 2013). This integration provides an excellent framework for data capture, storage, synthesis and analysis of acquired spatial data. Indeed, EO data can be combined with GIS and can provide an efficient approach for analysing and extracting spatial information to support decision making reliably and consistently (Chen et al., 2005; Gens, 2010). Both have been used extensively in a range of post-fire applications at different scales of observation; from burnt area mapping (Kokaly, Rockwell, Haire, & King, 2007; Petropoulos, Kontoes, & Keramitsoglou, 2011), to mapping changes in soil erosion after fire (Fox et al., 2008; Mayor et al., 2007; Quintano, Fernandez-Manso, Fernandez-Manso, & Shimabukuro, 2006) to evaluating post-fire ecosystem recovery (Segah, Tani, & Hirano, 2010). The recent advancements in EO technology have made it possible to evaluate patterns of vegetation recovery after wildfires at different spatial, spectral and temporal scales, and a variety of techniques have been developed for this purpose.

Some of the most widely used image analysis approaches employed to characterize the vegetation recovery include image classification (Jakubauskas, Lulla, & Mausel, 1990; Hall, Botkin, Strebel, Woods, & Goetz, 1991; Steyaert, Hall, & Loveland, 1997; Stueve, Cerney, Rochefort, & Kurt, 2009; Viedma, Meliá, Segarra, & García-Haro, 1997; White, Ryan, Key, & Running, 1996), the use of spectral vegetation indices (Chen et al., 2011; Diaz-Delgado et al., 2003; Hope, Tague, & Clark, 2007; Lhermitte et al., 2011) and Spectral Mixture Analysis (Smith et al., 2007; Solans Vila & Barbosa, 2010; Veraverbeke et al., 2012). Out of the wide range of techniques available, spectral indices have been used most extensively (Veraverbeke, Verstraeten, Lhermitte, & Goossens, 2010). Their use has largely been based on the hypothesis that the ratio of red (R) to near infrared (NIR) reflectance for green vegetation changes when the foliage containing chlorophyll is destroyed by the fire. Subsequently, the use of a spectral index that is sensitive to the R and NIR regions of the electromagnetic spectrum can be used to identify and potentially quantify vegetation change. The most widely used index for studying regeneration processes is the Normalized Difference Vegetation Index (NDVI, Rouse, Haas, Schell, & Deering, 1973). NDVI combines the reflectance in the R and NIR spectral region and is a measure of the green vegetation amount. A significant number of studies have utilized this index to monitor post-fire vegetation dynamics, some conducted in regions with a Mediterranean climate (Roder, Hill, Duguy, Alloza, & Vallejo, 2008; Solans Vila & Barbosa, 2010; Veraverbeke et al., 2010). Also, although a wide range of EO data have been exploited in such studies, it is evident from a review of the literature that imagery from the Landsat series of platforms has been one of the most widely exploited.

Landsat is the only freely available multispectral satellite high spatial resolution sensor providing a synoptic coverage of the Earth extending back to 1972. Therefore, the value of data from this satellite radiometer is unique and they have been extensively used to monitor the spatial and temporal variations in post-fire vegetation conditions and landscape-scale trends in vegetation dynamics (Chen et al., 2011; Hope et al., 2007; Wittenberg et al., 2007). Landsat spatial resolution allows the detection of both large and small fires and its large sensor field of view allows the observation of several burnt areas in one image. The sensor also has an NIR band which is useful for evaluating vegetation recovery processes (Pereira et al., 1999). Furthermore, its shortwave infrared (SWIR) channels allow highlighting of the internal variability of burnt areas that can be linked to the spatial patterns of damage severity and fire intensity (Bisson, Fornaciai, Coli, Mazzarini, & Pareschi, 2008; Justice, Malingreau, & Setzer, 1993).

Yet, while remote sensing is currently being applied to estimate the vegetation recovery dynamics in different ecosystems, information on the relationships between post-fire recovery and topographic factors is scarce (e.g. Sunee, Hussin, & de Gier, 2001), particularly so in the Mediterranean. This is despite the importance of this issue, as for example identification, at the landscape level, of areas with low recovery dynamics could improve land management and help prioritizing post-fire restoration actions in the fire-affected areas. Results from relevant studies published so far suggest that vegetation recovery dynamics of south-facing slopes can be very different from that of north-facing ones (e.g. Fox et al., 2008; Hope et al., 2007; Wittenberg et al., 2007).

In this context, the main aim of this study has been to assess vegetation recovery dynamics following a fire event using multi-temporal analysis of Landsat Thematic Mapper (TM) images and GIS techniques for a typical Mediterranean site located in Greece for which a wildfire occurred in 2007. The specific objectives were: first to determine the spatio-temporal patterns of vegetation re-growth dynamics established within the burn scar monitored by the NDVI response and second to analyse the influence of topographical parameters on these dynamics. In this preliminary study, we attempted to fit regression models to the dynamics of the