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Indicator-based assessment of post-fire recovery dynamics using satellite NDVI time-series

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A B S T R A C T

Fire disturbance severely modifies ecosystem structure and functioning, and therefore predicting post-fire responses is pivotal to improve land management. Indicators that efficiently link post-fire recovery with a timely decision on landscape management can play a key role in the governance of fire risk. We describe a framework to evaluate post-fire recovery based on remotely-sensed measures of relative vegetation recovery, calculated from satellite NDVI time-series. Three indicators are proposed: the novel Cumulative Relative Recovery Index (CRRI), measuring the (mid-long term) extent and completeness of recovery; the Recovery Trend Index (RTI), measuring the steepness of the mid-term post-fire recovery trend; and the Half Recovery Time index (HRT), a measure of the short-term recovery rate. We used Random Forest (RF) models to predict the observed recovery patterns and ranked the predictive importance of several candidate explanatory factors. The performance of RF models ranged from good (CRRI, RTI) to moderate (HRT). Three sets of predictive variables consistently ranked higher: fire traits, landscape composition, and post-fire climatic conditions. The relative contribution of individual variables was different across recovery indicators. These results show that proposed indicators seem to capture different facets of the post-fire recovery process. The short-term recovery indicator (HRT) was linked to landscape composition and post-fire climate. Thus, HRT expresses the speed of initial recovery, related to differences in fire-response traits of vegetation and to climatic conditions immediately following fire. The mid-term recovery indicator (RTI) was mainly influenced by fire traits and post-fire climatic conditions. This indicator captures multiple interacting effects that shape the recovery process related to fire severity, vegetation type and post-fire conditions. Finally, the long-term recovery indicator (CRRI) was clearly more influenced by fire attributes related to severity than by vegetation type and structure or by post-fire climatic conditions. Overall, our results suggest that a combination of biotic processes (driven by plant life-history traits) and abiotic filters (e.g., post-fire climate) determine the early post-fire recovery process. Conversely, the mid to long-term recovery response (expressing its completeness) is driven by the depletion of resilience capacity and by the amount of change in vegetation structure and functioning modulated by spatial differences in fire severity. Our results strongly suggest that an indicator-based approach grounded on satellite time-series of vegetation indices can effectively cover various facets of post-fire recovery. This will improve the monitoring and prediction of post-fire recovery dynamics, with valuable applications in fire hazard management and post-fire ecosystem restoration and monitoring.

1. Introduction

The field of fire ecology has evolved to include an ever broader range of concepts and techniques (Keeley et al., 2011). Traditionally, fire research emphasised the relation between wildfire patterns and structural features of the landscape, such as land cover categories (Bajocco and Ricotta, 2008; Nunes et al., 2005) or vegetation types (Gumming, 2001; Krivtsov et al., 2009). This focus has been shifting towards the links of fire with various functional characteristics of vegetation, such as productivity dynamics or fuel phenology, in order to early detect or even anticipate ecosystem changes (Alcaraz-Segura et al., 2008; Angelis et al., 2012). This functional approach can be particularly useful in areas of the globe under a Mediterranean climate, with a marked seasonality of wildfire occurrence (Bajocco and Ricotta, 2008; Beven and Germann, 2013; Helman et al., 2015; Pausas, 2004) and a strong relation between the seasonal timing of vegetation and wildfire regimes (Bajocco et al., 2010).

Changes in ecosystem and landscape functioning induced by fire

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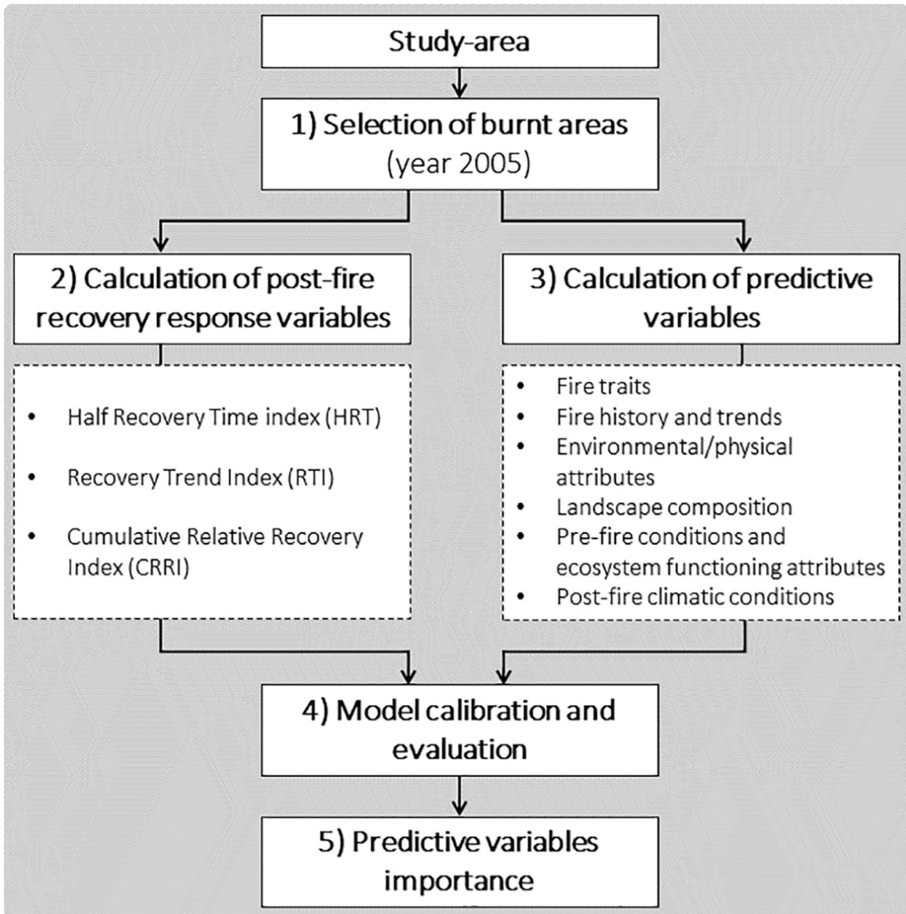

Fig. 1. Diagram representation of the general workflow adopted for the analysis of post-fire vegetation recovery.

disturbance have been reported from studies based on satellite imagery and remote sensing methods. Those changes include drastic decreases of photosynthetic activity (e.g. Gouveia et al., 2010; Tonbul et al., 2016), shifts in vegetation phenology (e.g. Angelis et al., 2012), changes in structure and function in forest landscapes (Cavallero et al., 2015), or feedbacks between surface temperature and climate change in burnt boreal forests (Rogers et al., 2012). Moreover, remote sensing of vegetation offers comprehensive spatiotemporal information about properties and condition of fuel type (Angelis et al., 2012; Schneider et al., 2008).

Remotely-sensed vegetation indices have also been used to analyse post-fire recovery. Díaz-Delgado et al. (2002) used the Normalized Difference Vegetation Index (NDVI) from Landsat imagery to monitor vegetation recovery after successive fires; they successfully correlated fire recurrence with resilience and with the contribution of different plant life strategies to that same resilience. van Leeuwen et al. (2010) used a remotely-sensed NDVI time-series to extract land surface phenological attributes (including the start and end of the growing season, the base and peak values, and the integrated seasonal NDVI), to monitor post-fire vegetation response. Di-Mauro et al. (2014) used MODIS-derived vegetation indices to analyse post-fire resilience and shifts in the start and end of the growing season, in broadleaf forest and prairies. The results from these and other studies suggest that satellite time-series of vegetation functioning data may support a valuable toolkit for efficiently monitoring post-fire responses. For example, remotely-sensed observations such as those obtained from the MODIS sensors provide comprehensive spatial coverage and enough temporal resolution (8 or 16-days composites of daily images) to update vegetation condition in a more efficient, timely and operational manner than traditional aerial photography (Oswald et al., 1999) or in-field surveillance (Riaño et al., 2002). These characteristics highlight the importance of developing remotely-sensed indicators for monitoring post-fire vegetation recovery. Indeed, satellite products have been particularly useful for investigating not only fire disturbances but also post-fire recovery (White et al., 2017). However, in spite of the accumulated evidence of the added-value of remote sensing to multiple aspects of fire ecology, there is still a lack of satellite-based indicator sets that can adequately describe different facets of post-fire vegetation recovery, namely concerning its rate and completeness. In this regard, three types of functional attributes potentially useful for tracking post-fire recovery can be extracted as yearly measures from NDVI time-series: productivity (annual mean), seasonality (annual range) and phenology (date of the maximum value) (Alcaraz et al., 2006). These three types of attributes describe the height and shape of the annual NDVI curve, and previous studies have shown they have biological significance (e.g., Alcaraz-Segura et al., 2017; Pettorelli et al., 2005).

Here we explored the usefulness of a high-temporal resolution satellite (MODIS) products to assess pre- and post-fire vegetation functioning dynamics. Specifically, we aimed to identify and rank the main drivers of the post-fire vegetation recovery process. Building on the Essential Variables narrative (e.g., Pettorelli et al., 2016), we explored a limited set of satellite-based indices to analyse post-fire recovery and its drivers in northern Portugal, a wildfire hotspot in Europe (EFFIS, 2015). First, we analysed pre- and post-fire NDVI profiles of a set of areas burnt in 2005, a focal year characterized by extreme wildfire occurrence (Marques et al., 2011). For each recovery indicator, we developed a predictive model to analyse how it is affected by fire severity, fire spatial attributes, fire history, physical environment, post-fire climatic conditions, landscape composition, and pre-fire vegetation functioning. Our final goal was to select a core set of indicators based