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**DOMINGOS XAVIER VIEGAS**
**LUÍS MÁRIO RIBEIRO**

# A satellite-based multi-dimensional approach to identify potential post-fire regime shifts in ecosystem functioning

Bruno Marcos*[1,2]; João Gonçalves[1,2,3]; Domingo Alcaraz-Segura[4,5,6]; Mário Cunha[7,8]; João P. Honrado[1,2,9]

[1]*CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Campus de Vairão, Universidade do Porto, 4485-661 Vairão, Portugal, {bruno.marcos, joao.goncalves}@cibio.up.pt*
[2]*BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Campus de Vairão, 4485-661 Vairão, Portugal*
[3]*proMetheus – Research Unit in Materials, Energy and Environment for Sustainability, Instituto Politécnico de Viana do Castelo (IPVC), Avenida do Atlântico, n.º 644, 4900-348 Viana do Castelo, Portugal*
[4]*iecolab. Interuniversity Institute for Earth System Research (IISTA), University of Granada, Av. del Mediterráneo, 18006 Granada, Spain*
[5]*Dept. of Botany, Faculty of Sciences, University of Granada, Av. Fuentenueva, 18071 Granada, Spain, {dalcaraz@ugr.es}*
[6]*Andalusian Center for the Assessment and Monitoring of Global Change (CAESCG), Universidad de Almería, Crta. San Urbano, 04120 Almería, Spain*
[7]*Departamento de Geociências, Ambiente e Ordenamento do Território, Faculdade de Ciências, Universidade do Porto, 4099-002 Porto, Portugal, {mccunha@fc.up.pt}*
[8]*Institute for Systems and Computer Engineering, Technology and Science (INESC TEC), Campus da Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, Porto 4200-465, Portugal*
[9]*Departamento de Biologia, Faculdade de Ciências, Universidade do Porto, 4099-002 Porto, Portugal, {jhonrado.fc.up.pt}*

**Corresponding author*

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**Abstract**

Wildfires can profoundly impact many aspects of matter flows and energy budgets in ecosystems. Exacerbated by projected shifts in climate, land use, and forest management, changes in fire regimes can lead to decreased ecosystem resilience, regime shifts, and ecosystem collapse. Thorough assessments of ecosystem resilience to wildfires are thus critical to bridge gaps between science, policy, and management. To that end, approaches based on ecosystem functioning offer an integrative view of ecosystem responses to wildfire-induced changes and provide quicker, quantifiable responses to disturbances that are more directly connected to ecosystem services. In that regard, satellite remote sensing can be employed to easily and frequently monitor multiple dimensions of ecosystem functioning over large areas and across time, and to evaluate ecosystem functioning resilience to wildfires. This study describes an approach for identifying potential regime shifts based on satellite-based surrogates of four key dimensions of ecosystem functioning: primary production, water content, albedo, and sensible heat. To that end, we classified the trajectories after wildfires in 2005, in NW Iberian Peninsula, for the 2000–2018 period, into five main types, using two metrics of medium-to-long term spectral post-fire recovery. Then, we derived a synthetic indicator to analyse the overall "strength-of-evidence" of potential regime shifts across dimensions. Potential regime shifts were identified for each dimension of ecosystem functioning considered, with the main effects associated with the sudden removal of vegetation. For primary production, regime shifts may be linked to changes in land cover and use, as well as management. Changes in the concentrations of impervious and radiation-absorbing materials following wildfires may be responsible for regime shifts in water content and albedo, with loss of canopy moisture due to fire-related damage leading to vegetation mortality during post-fire recovery. On the other hand, regime shifts in sensible heat were less frequent, since wildfires tend to have transient effects on this dimension of ecosystem functioning. Overall, our results show that our approach successfully captured different patterns of post-fire recovery and resilience across multiple dimensions of ecosystem functioning. We argue that our approach can provide an enhanced characterization of ecosystem resilience to wildfires, and support the identification of potential regime shifts after such disturbances, ultimately upholding promising implications for post-fire ecosystem management.

## 1. Introduction

Fire is an integral part of many ecosystems worldwide, playing a key role in their structure, composition, and functioning. However, wildfires can pose a major threat to a wide range of environmental, social, and economic assets (Adámek et al., 2016; San-Miguel-Ayanz et al., 2013). Changes in fire regimes can reduce the ability of ecosystems to recover and persist in the face of disturbances, eroding ecosystem resilience, which can lead to ecosystem collapse, with subsequent impacts on human societies (Folke et al., 2004; Johnstone et al., 2010; Scheffer et al., 2015). Moreover, wildfire disturbances can trigger sudden regime shifts in ecosystems, leading to critical transitions from one dynamic equilibrium to an alternative stable state (Boettiger et al., 2013; Scheffer et al., 2012). Furthermore, fire activity is projected to increase in the next decades, exacerbated by shifts in global climate, land use and forest management (Bowman et al., 2009; Tedim et al., 2013). Therefore, conserving fire-resilient ecosystems is a key priority (Willis et al., 2018).

Thorough assessments of ecosystem state and resilience to wildfires are thus critical to bridge gaps between science, policy, and management, with more comprehensive indicators needed for a better understanding of post-fire processes (Baho et al., 2017; Gouveia et al., 2010; van Leeuwen et al., 2010). To that end, approaches based on ecosystem functioning offer an integrative view of ecosystem responses to wildfire-induced changes, since fire can cause rapid modifications in key aspects of matter and energy flows in ecosystems (B. Marcos et al., 2021; Petropoulos et al., 2009). Furthermore, ecosystem functioning provides quicker, quantifiable responses to disturbances than structure or composition, and are more directly connected to ecosystem services (Alcaraz-Segura et al., 2008). Satellite remote sensing (SRS) has been increasingly employed for a wide range of applications related to both fire and ecosystem functioning, making it a major asset for risk assessment and governance, and post-fire restoration and management (Keeley, 2009; Parks et al., 2019; Smith et al., 2014). Having unlocked our understanding of global fire activity, satellite remote sensing has contributed to advancing wildfire science and management (Szpakowski & Jensen, 2019), allowing us to overcome scale-dependent limitations (Benali et al., 2016). Indeed, multiple aspects of ecosystem functioning — such as carbon and water dynamics, as well as energy budgets — can be easily and frequently monitored over large areas through SRS, due to their strong relation to biophysical properties and ecosystem processes (Villarreal et al., 2018). Nevertheless, multi-dimensional satellite-based assessments of ecosystem functioning resilience to wildfires are still scarce (Frazier et al., 2013). Moreover, the utility of SRS to evaluate ecosystem functioning resilience, and to anticipate potential regime shifts — through the translation of spectral indices into meaningful, informative ecosystem variables — is still largely under-explored (B. Marcos et al., 2021).

In this study, we propose an approach for identifying potential regime shifts based on satellite-based surrogates of four key dimensions of ecosystem functioning, related to the carbon, water and energy exchanges: primary production, water content, albedo, and sensible heat. For each one of those four dimensions of ecosystem functioning, we classified the post-fire trajectories into five main types, using two metrics of medium-to-long term spectral recovery. Finally, we derived a synthetic indicator of "strength-of-evidence" of overall regime shifts across dimensions. We discussed the potential and added value of the proposed approach to improve satellite-based characterization of ecosystem resilience to wildfire disturbances, and to identify potential regime shifts after those disturbances, over multiple dimensions of ecosystem functioning.

## 2. Materials and Methods

### 2.1. Study area

To illustrate our approach, we analysed all areas that burned in 2005 in the northwest Iberian Peninsula (NW-IP). This is an area with high wildfire activity, in the last decades — both in terms of ignitions and burned area —, despite the enormous investments in fire suppression (Catry et al., 2009; Moreira et al., 2020). Furthermore, the year 2005 coincided with severe drought, with over 340,000 ha burned in this area (Bastos et al., 2011). The NW-IP features diverse environmental characteristics, with strong environmental gradients, a major climatic and biogeographic transition, diverse land cover classes and land uses, and vegetation types. Moreover, historical land uses and management made this area a highly fire-prone landscape.

### 2.2. Satellite data preprocessing

Firstly, we identified the areas that burned in 2005, within the study area, with a contiguous area above 100 ha (i.e., "big fires"; following (B. Marcos et al., 2019)), using the MCD64A1 product (Giglio et al., 2018) from the

Moderate Resolution Imaging Spectroradiometer (MODIS). Then, to inform on the four ecosystem functioning dimensions of primary production, water content, and surface albedo, we used time-series of the three Tasselled Cap Transformation (TCT) features of "Greenness" (TCTG), "Wetness" (TCTW), and "Brightness" (TCTB), as well as land surface temperature (LST), respectively. The three TCT features are sensor-specific linear combinations of bands in the visible, near-infrared, and short-wave infrared regions of the electromagnetic spectrum that maximize the association with biophysical parameters such as the amount of photosynthetically active vegetation, water content and soil moisture, and albedo (Lobser & Cohen, 2007; Mildrexler et al., 2009). The LST is a calibrated measure of the thermal emissivity of the land surface. We extracted these satellite image time-series (SITS) from the MODIS MOD09A1 (Vermote, 2015) and MOD11A2 (Wan et al., 2004) products, for the years ranging from 2000 to 2018, with a frequency of 46 images per year (i.e., one image for each 8-day period), at 500m spatial resolution.

Spurious values in each of the four SITS were corrected using a filtering procedure based on the Hampel identifier (Hampel, 1971, 1974). Time-series were seasonally adjusted using Seasonal and Trend decomposition using Loess (STL; (Cleveland et al., 1990; Hyndman & Athanasopoulos, 2018)), to establish pre-fire conditions, by defining reference intervals corresponding to one median absolute deviation around the median, from all values in the three years brfore the date of the fire occurrence. On the other hand, the trend component was used to compute moving-window medians (i.e., incremental steps in the post-fire trajectories).

All data was processed and analysed using software packages within the R statistical programming environment (Busetto & Ranghetti, 2016; Hijmans, 2020; R Core Team, 2019), and the Python programming language (Gillies et al., 2013).

### 2.3. Extraction of resilience indicators

To support the identification of potential post-fire regime shifts in ecosystem functioning, we first determined — for each pixel and each of the four dimensions of ecosystem functioning — the date of the first directionality inflexion in the trend component curve ($t_{INF}$) after the date of the wildfire occurrence ($t_{FIRE}$). This moment represents the first major change of directionality — from divergent to convergent with the pre-fire conditions — in the post-fire trajectory, which can be regarded as an approximation of the date of the start of recovery.

Then, we computed two related but independent "return time"-type metrics related to post-fire (spectral) recovery at medium-to-long term:

- "Return-to-Reference Time" (RRT) — the duration of the period between $t_{FIRE}$ and the first moment in the post-fire recovery when the post-fire trajectory returns to within the pre-fire reference interval — $t_{REF}$; and
- "Return-to-Equilibrium Time" (RET) — the duration of the period between $t_{FIRE}$ and the moment in the post-fire recovery when the trajectory is stabilized (according to a predefined threshold value for the change rate) — $t_{EQ}$.

The RRT metric provides an estimate of the amount of time needed to return to the pre-fire conditions (if and when applicable), whereas RET provides an approximate measure of the amount of time needed to achieve a stable state after a fire (if and when applicable) — which can be different from the pre-fire conditions.

### 2.4. Identification of potential regime shifts

Based on different combinations of the outcomes of the RRT and RET metrics, we classified the post-fire trajectories of each of the four dimensions of ecosystem functioning into four main types of medium-to-long term spectral recovery (Fig. 1):

- "Return to pre-fire" — equilibrium reached within pre-fire reference interval;
- "Under-recovery" — equilibrium reached outside pre-fire reference interval, but pre-fire reference interval not crossed;
- "Over-recovery" — equilibrium reached outside pre-fire reference interval after pre-fire reference interval was crossed;
- "No equilibrium" — pre-fire reference interval crossed, but no equilibrium achieved; and

- "(not detected)" — no recovery detected because either: (i) $t_{REF}$ and $t_{EQ}$ not successfully found; or (ii) inflexion point not found, or not within the pre-fire reference interval.

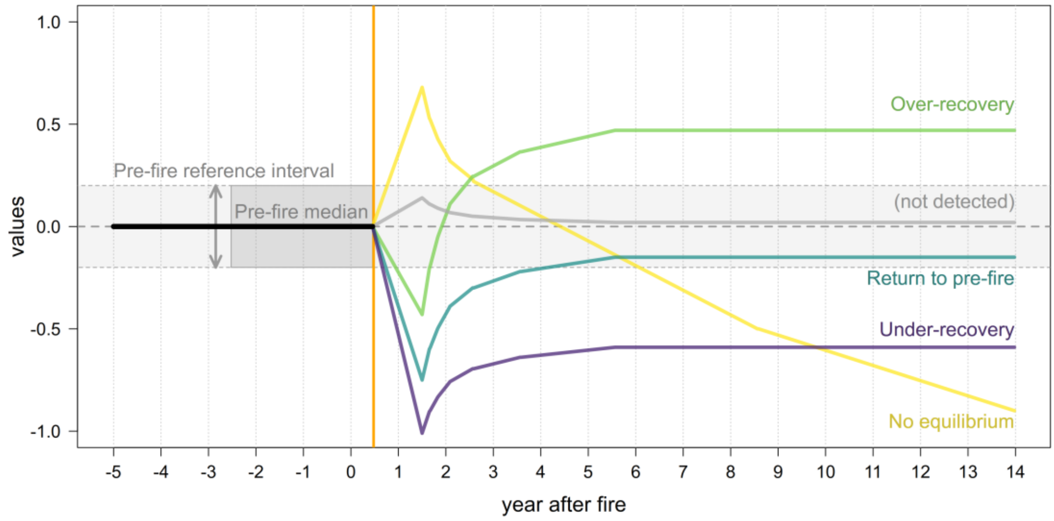


***Figure 1 – Illustration of the different classes obtained from the post-fire resilience classification, based on the two independent metrics of "Time to Return-to-Reference" (RRT) and "Time to Return-to-Equilibrium" (RET), respectively measuring the time needed after the wildfire to return to pre-fire conditions, and to achieve a stable state.***

Finally, we mapped the percentage of the four dimensions of ecosystem functioning with potential regime shifts (i.e. that were classified as either "Under-recovery" or "Over-recovery"), as a synthetic, multi-dimensional indicator of the overall "Strength-of-Evidence" for potential post-fire regime shifts in ecosystem functioning.

## 3. Results and Discussion

Overall, most burned pixels in NW-IP were classified as either "Return to pre-fire" or "(not detected)", within each dimension of ecosystem functioning (Fig. 2) — except for albedo ("Albedo"). This suggests an overall high resilience capacity of ecosystems in the study area. Furthermore, the percentage of the "(not detected)" class was highest for sensible heat ("Heat"), corresponding mainly to areas located either near or adjacent to the periphery of the burned patches (Fig. 3). These results, allied to the low percentages of the "Under-recovery" and "Over-recovery" classes, point to the effects of wildfires on Heat being mostly transient (E. Marcos et al., 2018; Quintano et al., 2015). On the other hand, the main effects on primary production ("Productivity"), water content ("Water"), and Albedo can be linked to the sudden removal of vegetation (Veraverbeke et al., 2012).

Regarding potential regime shifts, considerable portions of the analysed burned areas were classified as either "Over-recovery" — with the highest percentage for Productivity and Albedo —, or "Under-recovery" — with the highest percentage for Water and Albedo. Regime shifts in Productivity may translate land cover conversions, particularly when associated with land abandonment (Silva et al., 2011), invasions by exotic plant species (Nunes et al., 2020), or direct human interventions (Silva et al., 2011). Regime shifts in Water can be associated with the loss of moisture in canopy foliage due to fire-related damage — which can sometimes persist for up one year after the fire —, leading to vegetation mortality (Beringer et al., 2003; Senf & Seidl, 2020; Viana-Soto et al., 2020). Also, the increased concentrations of quantities of impervious materials (such as ashes, char, and soot) after a fire can clog soil pores, leading to decreased water retention capacity, and increased post-fire water repellency, surface runoff, and soil erosion rates (Bodí et al., 2014; Hubbert et al., 2012; Ramanathan & Carmichael, 2008). These materials can also be responsible for the observed regime shifts in Albedo, since they absorb visible solar radiation, translating into a darkening effect immediately after the fire that tends to dissipate before the regeneration of vegetation, leading to a temporary brightening effect one to two years after fire (Lentile et al., 2006; Quintano et al., 2019; Ramanathan & Carmichael, 2008; Saha et al., 2019). Whichever the specific driver responsible for regime shifts in each particular case, these qualitative changes can denote a depletion in the resilience capacity of ecosystems, with potentially severe consequences (Gatebe et al., 2014; Saha et al., 2017).

Finally, the “No equilibrium” class may translate either incomplete recovery or unforeseen interferences on the detection of post-fire inflexion points. Nonetheless, the percentages obtained for this class were low across dimensions.

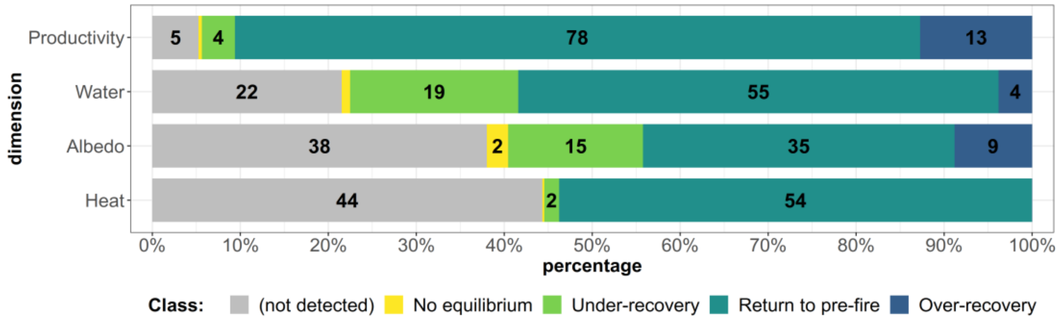


***Figure 2 – Relative frequencies obtained for each post-fire resilience class, for each of the four dimensions of ecosystem functioning considered — primary production, water content, albedo, and sensible heat —, across all patches burned in 2005 in NW Iberian Peninsula, up until 2018. Numbers in bold are only shown for percentages above 1%.***

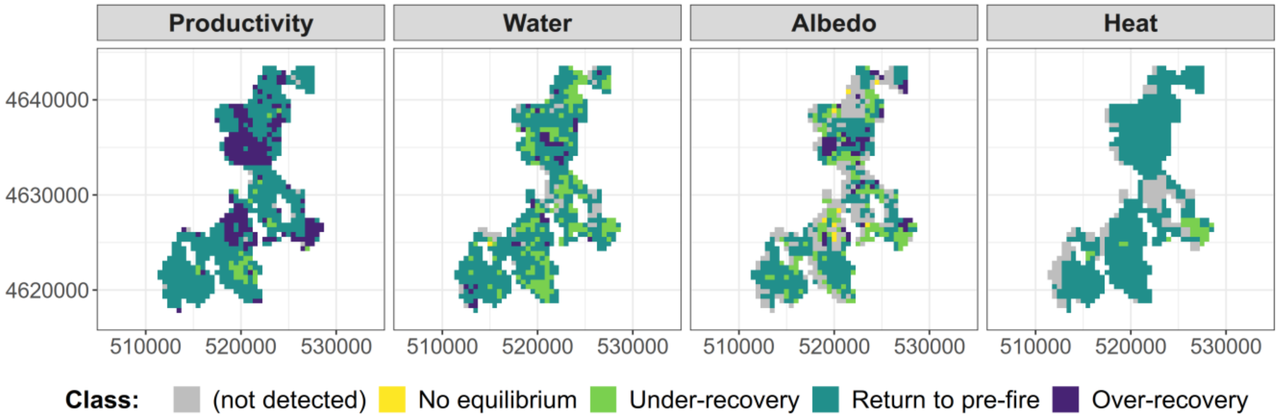


***Figure 3 – Post-fire recovery and resilience classification map for a selected burned area, for each of the four dimensions of ecosystem functioning considered — primary production, water content, albedo, and sensible heat.***

Maps of the overall “Strength-of-Evidence” of regime shifts, across the four dimensions of ecosystem functioning (Fig. 4), clearly show areas overall more likely to have experienced regime shifts in ecosystem functioning, with particular “hot-spots” being observable in darker colours.

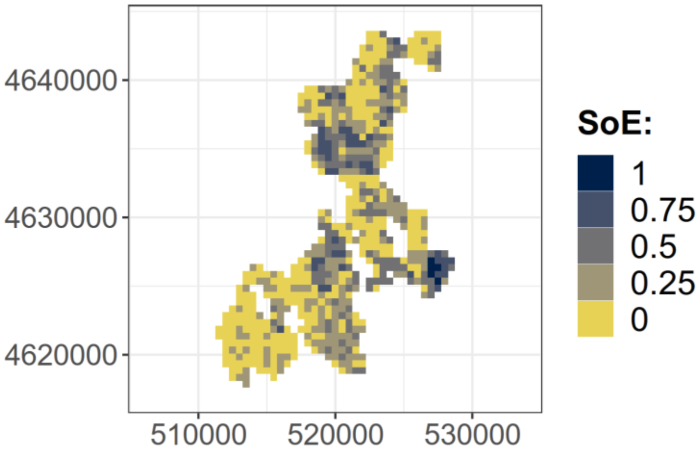


***Figure 4 – Maps of “Strength-of-Evidence” for regime shifts across the four dimensions of ecosystem functioning considered — primary productivity, vegetation water content, albedo, and sensible heat —, for a selected burned area.***

## 4. Conclusions and future outlook

In this study, we described an approach for characterizing ecosystem resilience to wildfires, across multiple dimensions of ecosystem functioning, as well as for identifying and mapping potential post-fire regime shifts, using metrics extracted from SITS. Furthermore, the proposed approach can be applied in a wide range of geographic and environmental contexts, using data from different satellite-sensor platforms. Together, the results obtained allowed us to highlight the added value and the potential of the proposed approach. Potential applications include regional-scale, spatially explicit prioritizations for management or conservation purposes, and as a precursor analysis to more detailed, local-scale assessments, investigating specific patterns. Potential future improvements include accounting for the duality in post-fire trajectories of albedo, as well as validating the obtained results through field-collected data such as spectral readings, and aerial ("drone") imagery. Overall, our approach successfully captures different patterns associated with key features of the post-fire processes in ecosystem functioning, pointing to a high degree of complementarity between different dimensions, and highlighting the added value of such multi-dimensional. We argue that such frameworks can provide an enhanced characterization of post-fire ecosystem resilience, ultimately upholding potential implications for post-fire ecosystem management.

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