Monitoring and extracting relevant parameters of wild fire spread using remote sensing data.

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Abstract. Wildfires are important elements of ecosystems that can have significant environmental and socio-economic impacts. The spatio-temporal dynamics of single events are very complex and have been studied mostly through the application of models and by reconstruction using multiple data sources. Both are time consuming approaches with high associated uncertainties and laborious applicability to other case studies. In this study we propose to reconstruct the fire events and extract relevant parameters using solely remote sensing data for a large time span and spatial region. We combined a burnt areas dataset with MODIS active-fire detections to reconstruct the fire events. The structure of fire spread was described using graphs which were used to calculate the main fire routes. Using the circular statistics each route's mean fire spread direction was calculated. The approach showed promising results providing a valuable reconstruction of the fire events and retrieval of important parameters related to the propagation of single fire events. The methodology can be easily applied to other regions of the globe since it depends on a very limited amount of input data and is based on the morphological spread structure of each fire event. The more conventional approaches, such as fire spread modeling, would greatly benefit of the integration of information extract from remote sensing data.

Palavras-chave: fire spread direction, MODIS, graphs, major fire routes, principais caminhos de propagação, direcção de propagação de fogo.

1. Introduction

Wildfires are an important element of ecosystems that can have significant risk to people and properties and can impose important socio-economic and environmental impacts (e.g. Stepanov and Smith, 2012). Wildfire spread is a very complex phenomenon which depends on three key factors which constitute the fire environment: fuel, topography and weather conditions (Countryman, 1972). Knowing the dynamics and development of wildfires has relevant implications on the identification of its main drivers of fire propagation (e.g. Loboda and Csiszar, 2007). It is particularly relevant for research purposes, but especially for managers and fire fighters helping the fire fighting strategies.

Wildfire spread has been studied mainly by laboratorial experiments (e.g. Bilgili and Saglam, 2003), fire spread modeling (e.g. Arca et al. 2007) and fire spread reconstruction (Cruz et al. 2012). All these approaches are valuable but also have important limitations. Laboratorial experiments lack the ability to describe larger scale events. Fire spread modeling requires large amounts of data and have high associated uncertainties. Additionally, their assessment is usually done by comparing the simulated and observed static burnt perimeter and sometimes by comparing simulations with data collected through witness interviews (e.g. Arca et al. 2007). Fire spread reconstruction is very time consuming and require large amounts of data, some of them highly subjective, such as, witness interviews. In sum, fire spread studies usually have low support on objective data, sometimes lack of data integration over the whole wild fire event and are limited to small temporal and spatial scale.

Although wildfires have been frequently studied using of remotely sensed data, mainly through the use of burned area products, it has been less used to study the spatio-temporal of dynamics of fire events have been less studied (Loboda and Csiszar, 2007). The synoptic capabilities and ability to capture relevant information covering the entire spatial and temporal extent of each fire event render remote sensing unique potentialities. Loboda and Csiszar (2007) used MODIS (Moderate Resolution Imaging Spectroradiometer) active-fire data to reconstruct the fire spread of large events in Russia, focusing their study on the rates of fire spread.

In this study we propose to study the spatio-temporal dynamics of the major wild fire events that occurred in Portugal from 2001 to 2009 using solely remote sensing data. The objective was to develop tools based on the fire spread structure that can be easily applied to other regions of the globe and other temporal periods with limited amount of data. We propose to extract relevant information about the fire spread dynamics of single events, such as, the fire dates and duration, ignition and extinction points, major fire routes and correspondent mean spread directions.

2. Data and Methodology

2.1 - Study Area and Fire Regime

The study was performed in continental Portugal located in south western Europe. Climate in Portugal is mostly Mediterranean, with hot, dry summers and mild, wet winters. Portugal is a region prone to fire due to its environmental characteristics (Oliveira et al. 2012).

Portugal has been in the last three decades the country with the highest absolute number of fires and the highest burnt area per area of forest of all the southern Europe countries. Recently, 2003 and 2005 were the years with highest burnt area of the last 30 years (Pereira et al. 2006).

2.2 - Remote Sensing Data

The burnt areas database from the National Forestry Authority (AFN) contains the burnt perimeters of all the fires that occurred between 1975-2009 in the entire Portuguese territory (Pereira and Santos, 2003). The database was derived from high resolution satellite imagery acquired in the end of the fire season and several studies have used it (e.g. Nunes et al. 2005; Oliveira et al. 2012). Regarding the period of this study, the data from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM) and AWIFS were used to derive burnt areas with 30m spatial resolution. The fire perimeter maps were derived with a semi-automatic procedure, starting with supervised image classification and complemented through manual editing of the classification results. Additionally, to isolate each fire event and its respective burnt perimeter, the contiguous burnt areas were separated by analyzing daily quick looks of the MODIS Rapid Response System.

In this study the burnt area maps were downscaled to a 90m resolution grid. For each pixel, the fraction of high resolution burnt pixels was defined and all pixels with more than 10% burnt fraction were classified as burnt. For the pixels with multiple burnt areas the fire event with the largest fraction was assigned.

The MODIS active-fire product detects fires that are burning at the time of overpass using infrared data (Giglio, et al. 2003). The spatial resolution at nadir is approximately 1km. The

MCD14ML product (collection 5) includes observations acquired during both, Terra and Aqua, day and night overpasses resulting in a maximum of four different acquisition periods per day. Each active-fire is represented by its geographical position (center of pixel), acquisition date and sensor, confidence value and the estimated fire radiative power (FRP).

Due to the different temporal availability of the MODIS active-fire and the burnt areas database, the study period was between 2001 and 2009.

2.3 - Fire Dating

A fire event must be constrained in space and time, thus, the first step was to identify the start and end date of the fire event. For that purpose the active-fires and burnt areas data sets were combined and matched.

Regarding the spatial constraints, given that both data sets had very different spatial resolutions, all the active-fires were kept if a part of their 1km pixel overlapped the burnt area. Many of the methodological steps described hereafter also had to take into account the scale heterogeneity arising from using data sets with very different spatial resolutions.

Regarding the temporal constraints, since the fire season in Portugal is concentrated between June and September (Oliveira et al. 2012, Pereira et al. 2006), the yearly temporal distribution of active-fires within a burnt perimeter was analyzed. The periods containing active-fires were clustered assuming that a single fire event could not have a period without acquisitions higher than 2.5 days to allow for missed observations due to cloud cover and undetected burning. Loboda and Csiszar (2007) used a similar approach to define active-fire clusters setting a threshold of 4 days which could be even more relaxed. Additionally, we assumed that in order to assign fire dates to a burnt area the temporal cluster had to contain at least 90% of the total active-fires acquired during the year over a specific burnt perimeter. Lower percentages potentially indicated the presence of different events distributed in time over the same burnt area. The fire starting and ending dates were determined by assigning the date and hour of the first and last active-fire respectively acquired in the valid temporal cluster.

2.4 - Defining a Fire Spread Network

The MODIS active-fires were aggregated into day and nighttime periods for each separate day by averaging their acquisition hour. All burnt areas smaller than 1000ha were discarded to increase the similarity in the spatial scales of the two main data sets used. Additionally, only fires with more than 4 active fires acquired at least in two different periods were kept. Although only 3% of the fires were considered for the remaining study these accounted for 60% of the total burnt between 2001 and 2009. After the above mentioned pre processing steps were performed, the dates of the active-fires' acquisitions were spatially smoothed using the k-nearest neighbor (KNN) algorithm.

The fire spread structure has both spatial and temporal dimensions and was represented by a graph (G_{ST}). A graph is a mathematical conceptual model that represents a structure in the abstract and is formed by a set of nodes (V) connected by a set of edges (E) (e.g. Dale and Fortin, 2010). The active-fires were defined as nodes and each active-fire acquired at a given time (t) was connected to an active-fire acquired at the posterior time (t_{+1}). The directed edge connecting V_t to V_{t+1} had its weight equal to the fire spread distance considering that propagation was made solely inside the burnt area. The spread distance was defined by the shortest path along the burnt area connecting V_t to V_{t+1} using the Dijkstra's algorithm (Dijkstra, 1959).

The main assumption contained in G_{ST} was that a given active-fire observed at a given time ($V_{i\,t}$) spreads and potentially originates an active-fire in the consecutive time frame ($V_{i\,t+1}$) if both are connected by an edge. The spread structure of a wildfire can be complex, therefore, connecting all V_t to V_{t+1} can yield a unrealistic fire spread network i.e. not all active fires are potentially connected just because they were acquired consecutively in time. This is particularly relevant when a main fire event i) is divided into several sub-events that are some extent independent; ii) is composed by independent events and/or iii) has re-ignitions. To define a network that reflects the spatio-temporal dynamics of fire spread in a more realistic fashion, improbable edges were removed from G_{ST} using empirically defined maximum spread distance thresholds that depended of the average burnt rate of the entire event (ha day^{-1}). Along with G_{ST} a merely spatial graph was created (G_s) representing the morphology of the entire network.

2.5 – Main Fire Routes and Fire Spread Direction

The main fire routes reflect the preferred and most significant paths in which the fire spread throughout the final burnt perimeter. It is an important piece of information to understand the main drivers of fire spread and to evaluate fire fighting management in a post-fire situation.

The fire spread network has the spatial and temporal structure of wild fire propagation from its ignition (V_s) to its extinction nodes (V_e). The ignition nodes, acquired in the same period, were aggregated into ignition areas (V'_s) using a hierarchical divisive clustering algorithm (DIANA-DIvisive ANAlysis; Kaufman and Rousseeuw, 1990). The dissimilarity matrix was defined by the distances between the ignition nodes. The ignition areas were defined when the largest dissimilarity was below the previously defined empirical distance threshold (see 2.4). Extinction areas (V'_e) were defined using the same method.

For each combination of ignition-extinction areas, in which there was a path connecting both, the shortest path between both was calculated and defined as a fire route. It was considered that the importance for each fire route was directly proportional to its total spread distance. The route importance was defined by normalizing all fire routes' spread distances by the maximum spread distance, varying between 0 and 1, corresponding to least and the most important fire routes respectively. The major fire routes were considered the ones in which their importance was above 0.25.

Each pair of connected active-fires forms a spread vector with a given length and direction. For each major fire route the mean resultant fire spread direction was calculated using the distribution of spread vectors according to equation 2.8 in Fisher (1993). The resultant fire spread length (in km) was considered to be the total fire spread distance of each major fire route.

Circular statistical measures were calculated, using the Circular Statistics Toolbox for MatLab (Berens, 2009), to assess if the mean direction was representative of the bulk of the distribution. The confidence intervals for both resultant and unitary means, at a 95% degree of confidence, were calculated using a non-parametric method (see eq. 4.22 in Fisher, 1993). Additionally, circular variance was also calculated as an indicator of high dispersion around the mean (Fisher, 1993). The fires with confidence amplitude higher than 60° or with circular variance above 0.80 were considered not to have a clear and representative mean direction.

3. Results and Discussion

The methodology presented in this study was applied to 200 fires in Portugal in the 2001-2009 period. We use a case study, a fire that burned around 25000 ha in 2005 for about 5days, to show the main outcomes of the application of this methodology. The combined use of satellite derived burnt perimeters and active-fires provides a good synoptic picture of the spatio-temporal distribution of wild fire spread dynamics (Figure 1). The points of starting ignition in day 200 and the complex spatio-temporal structure of wild spread, with at least three different branches (or fire runs) are clear in Figure 1.

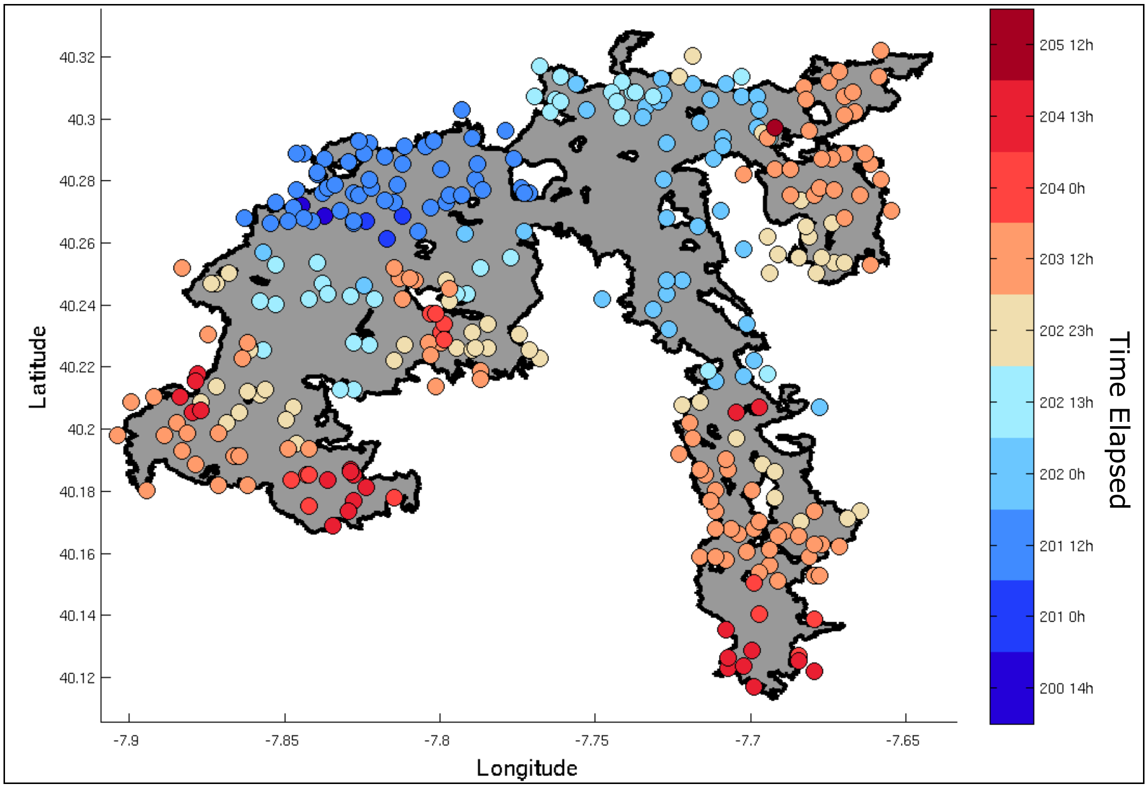

Figure 1 – Overview of wild fire spread for a case study using MODIS active-fire data.

The gray area is the burnt perimeter. The circles represent the active-fires and the colorbar indicates the day-of-year and hour of acquisition.

The use of satellite data within the fire spread context can provide valuable information to managers and scientists because it provide objective spatial and temporal information about wild fire spread, using observations instead of the commonly used model simulations or information subjectively collected by population or fire fighters. The data is synoptic, covers the entire burnt perimeter and can be used to calibrate and validated in an objective and quantitative fashion the commonly used fire spread models. Additionally, it can also be used to understand the main drivers of wild fire spread at a landscape level reducing the uncertainties associated with the use of fire spread models.

The major fire routes capture well the “backbone” of the wild fire spread in the case study presented (Figure 2a). The structure of spread directions is clearly depicted in Figure 2b considering the major routes that had a clear mean direction. The fire had three major branches: the most important that spread to NE with a total spread distance of about 20km; another that spread in the contrary direction (i.e. SW) and another that spread to South, both with a total spread distance of about 15km. The importance of the last branch was underestimated because the application of the empirical cut-off distance threshold caused a separation of its major fire routes with the starting ignition. This was due to a data gap in the northern part of the beginning of the fire routes that spread southwards.

The definition and representation of major fire spread routes can provide important information, when combined with weather data, about how the fire spread strategies could have been employed more effectively. In this case study the NE and S branches covered more than 70% of total burnt area that potentially could have been minimized by allocating suppression means E\NE of the main ignition area in day 200. Future work will focus on simplifying the number of main fire routes, since some of them had very similar spatio-temporal dynamics.

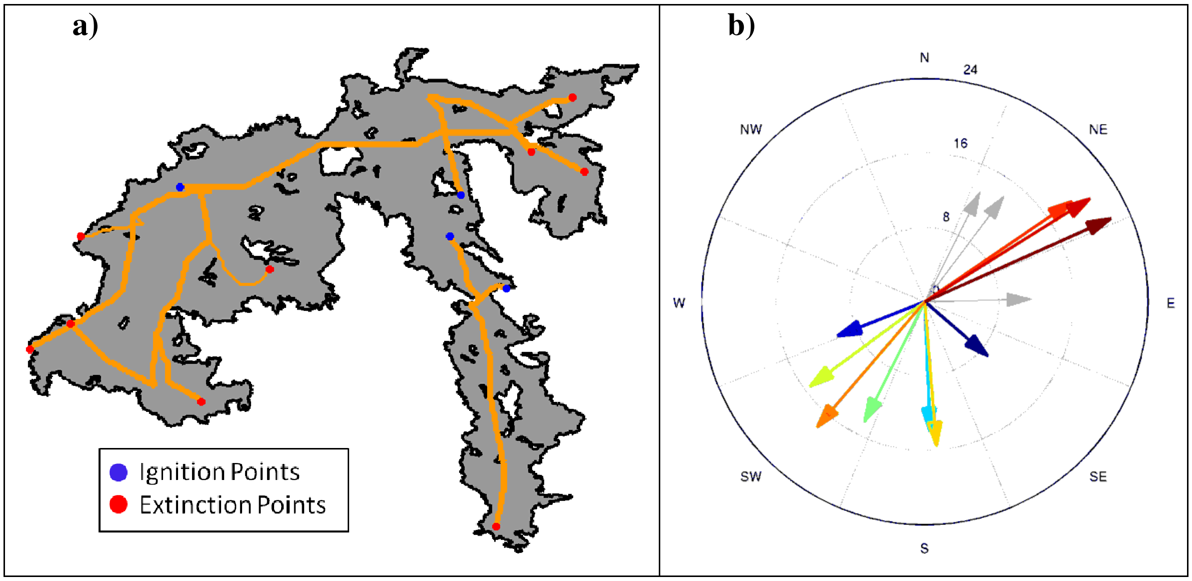

Figure 2 – Major fire routes (a) and the correspondent mean fire spread directions (b)

a) The more important major fire routes are represented with thicker lines and the blue and red circles represent the ignition and extinction points of each major fire route; b) each colored arrow represents the mean direction of each major fire route; the gray arrows do not have a representative mean direction and; the length of each arrow represents the total fire spread distance (in km).

Besides the fire dates, ignition points, the major fire routes and their mean spread direction, the use of satellite data can provide information regarding important fire spread related variables, such as, spread rate and the fire radiative power (i.e. energy released). Additionally, by comparing these variables with land use, fuel and weather data, satellite data can provide a good overview of their importance in driving fire spread behavior.

This methodology can be applied to any region of the globe from 2001 onwards, given that a burnt area dataset is available. Contamination from clouds and smoke and the existence of large and very fast fires are the main limitations of the application of this methodology to other regions of the globe. Additionally, the application to small fires (i.e. below 1000ha) is limited; however, the large wild fires are the ones with highest ecological and economic impact, thus, the study of such events would surely benefit with the information provided by satellite data.

4. Conclusions

The methodology presented in this work shows great potential to reconstruct the spatio-temporal dynamics of large wildfires using solely remote sensing data. The low amount of input data needed render this work the great capability of being extrapolated to any region of the globe. This will surely improve our knowledge about the dynamics of single fire events and can be easily integrated with more standard approaches, such as, the reconstruction of wildfires based on multiple data sources and fire spread modeling. Regarding the latter, model calibration and validation can largely benefit from the integration of remote sensing data.

The promising results show that remote sensing data can be used for the study of the dynamics of single events. The extraction of relevant parameters, such as, fire start and end dates, duration, ignition and extinction points, major fire routes and spread direction can help us increase our knowledge about the chief drivers of fire propagation. In the future, spread rate and fire radiative power can also be extracted and enable us to have a more complete overview of each single fire event.

5. References

Arca, B., Duce P., Laconi, M., Pellizzaro, G., Salis, M., Spano, D. Evaluation of FARSITE simulator in Mediterranean maquis. **International Journal of Wildland Fire**, n.16, p. 563–572, 2007.

Berens, P.. CircStat: A MATLAB Toolbox for Circular Statistics. **Journal of Statistical Software**, v.31, n. 10, p. 1-21, 2009.

Bilgili, E., Saglam, B. Fire behavior in maquis fuels in Turkey. **Forest Ecology and Management**, n.184, p. 201-207. 2003.

Countryman, C.M. **The fire environment concept.** Pacific Southwest Forest and Range Experiment Station. 1972.

Cruz, M.G., Sullivan A.L., Gould J.S., Sims N.C., Bannister A.J., Hollis J.J., Hurley R.J., Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. **Forest Ecology and Management**, in press. 2012.

Dale, M.R.T., Fortin, M.-J. From Graphs to Spatial Graphs. **Annu. Rev. Ecol. Evol. Syst.,** n. 41, p. 21-38, 2010.

Dijkstra, E. W. A note on two problems in connexion with graphs. **Numerische Mathematik**, n. 1, p. 269–271. 1959.

Fisher, N.I. **Statistical Analysis of Circular Data**. Revised edition. Cambridge University Press. 1995.

Giglio, L., Descloitre, J., Justice, C.O., Kaufman, Y.J.. An Enhanced Contextual Fire Detection Algorithm for MODIS. **Remote Sensing of Environment**, n. 87, p. 273–282. 2003.

Kaufman, L. and Rousseeuw, P.. **Finding Groups in Data—An Introduction to Cluster Analysis.** Wiley Series in Probability and Mathematical Statistics. New York: John Wiley & Sons, Inc. 1990.

Loboda, T.V., Csiszar, I.A. Reconstruction of fire spread within wildland fire events in Northern Eurasia from the MODIS active fire product. **Global and Planetary Change**, n. 56, p. 258-273. 2007

MODIS Rapid Response System. Available in: http://rapidfire.sci.gsfc.nasa.gov. Accessed in March 2012.

Nunes, M.C.S., Vasconcelos, M.J.P., Pereira, J.M.C., Dasgupta, N., Alldredge, R.J., Rego, F.C. Land cover type and fire in Portugal: do fires burn land cover selectively? **Landscape Ecology**, n. 20, p. 661–673. 2005.

Oliveira, S. L., Pereira, J.M.C, Carreiras, J.M.B.. Fire frequency analysis in Portugal (1975–2005), using Landsat-based burnt area maps. **International Journal of Wildland Fire**, v. 21, n.1, 48-60. 2012.

Pereira, J.M.C., Santos, M.T.N. **Fire risk and Burned Area Mapping in Portugal.** *Direcção-Geral das Florestas, Lisbon, Portugal*. 2003.

Pereira, J.M.C., Carreiras, J.M.B., Silva, J.M.N., Vasconcelos, M.J.. Alguns conceitos básico sobre os Fogos Rurais em Portugal. In Pereira, J.S., Pereira, J.M.C., Regro, F.C., Silva, J.M.N., Silva, T.P. (Eds.), **Incêndios Florestais em Portugal – Caracterização, Impactes e Prevenção.** ISA press (1st edition). 2006.