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Mapping fire severity levels of burned areas in Galicia (NW Spain) by Landsat images and the dNBR index: Preliminary results about the influence of topographical, meteorological and fuel factors on the highest severity level

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Abstract

Fire severity assessment and mapping are essential for prioritizing post-fire emergency rehabilitation actions. The present study, carried out in Galicia (one of the regions most severely impacted by wildfire in the Iberian Peninsula), focused on 36 wildfires affecting areas of more than 200 ha during the period 2006-2016. The aims of the study were i) to map the severity in these wildfires by using the differenced Normalized Burn Ratio (dNBR) index, and ii) to explore how the highest levels of fire severity and canopy damage are related to topographical, meteorological and forest fuel variables. Pre and post-fire Landsat images (Path 204 and Row 31), provided by the European Space Agency (ESA), were radiometrically and topographically corrected. The dNBR index was calculated for each wildfire, and the values obtained were used to establish four classes of fire severity and four levels of canopy damage. A total of 23 topographical, meteorological and fuel variables were also determined in order to characterize each wildfire. The non-parametric Random Forests method was used to relate the burned area (%) corresponding to the highest levels of fire severity and crown fire damage to the various environmental variables. The variables that best differentiated the most severely burned areas were in both cases wind speed and percentage of burned area with slope ranging from 30 to 45%.

Keywords: Fire severity, Landsat, dNBR, fire mapping, crown damage, EGIF

1. Introduction

The total number of wildfires, number of large wildfires (>500 ha) and the total area burned are higher in Galicia than in other regions of Spain, representing respectively 42%, 24% and 25% of the overall values for the whole of the country (MAPAMA 2012). Moreover, current forecasts for the fire regime indicate that the wildfire problem will be exacerbated by climate change (Moreno 2005, Arellano 2008, Vega *et al.* 2009), with increased frequency, extent, intensity and severity of wildfires. Fire severity has been broadly defined as the level of damage or disturbance caused by fire in an ecosystem or any of its components (Key and Benson 2006).

Fire severity assessment and mapping are essential tasks in post-fire emergency rehabilitation planning. These processes enable prioritization of the responses by focusing on the areas most affected by fire with the aim of minimizing the impacts and shortening the recovery time of the ecosystems affected (Robichaud *et al.* 2000, Miller and Yool 2002, Chuvieco *et al.* 2006).

Satellite spectral indices are useful for obtaining information on fire severity at landscape scale (Hudak *et al.* 2007; Parsons *et al.* 2010). These indexes also enable analysis of spatial patterns of different levels of damage caused by fire and identification of the most important factors influencing these patterns. Advantages of the use of remote sensing indices include the ability to assess fire severity in inaccessible sites or sites where field work is very expensive, because of the topographical conditions or the presence of very dense vegetation. However, the indexes can be limited by cloudy conditions, low spatial resolution and their poor representation of lower strata of the tree canopy and the soil (Hudak *et al.* 2007, Meng and Meentemeyer 2011). The differenced Normalized Burn Ratio or dNBR (Key and Benson 2006), obtained from Landsat images, is the index most widely used in many countries to estimate fire severity. Specifically, in the region of Galicia, fire severity evaluation and annual mapping of the most important fires is carried out using the dNBR index. This task is the first step in designing emergency actions aimed at reducing the hydrological and erosive risks associated with wildfire (Vega *et al.* 2013) and that are included in the regional Plan for Preventing and Fighting Forest fires (PLADIGA; Xunta de Galicia, 2017).

In a study relating values of the dNBR index to the fire severity and the levels of canopy damage observed in wildfires that occurred in Galicia in the 2013 fire season, Arellano (2014) proposed four specific classes of fire severity and four classes of canopy damage for the region. The present study used these classifications to characterize the wildfires that occurred during the period 2006-2016 in one of the areas most affected by wildfire in Galicia. The aims of the study were i) to map the levels of fire severity associated with the wildfires by using the dNBR index; and ii) to explore the most important variables (topographical, meteorological and forest fuels) influencing the highest levels of fire severity and canopy damage.

2. Material and methods

The study area is the XIV Forest District (Verín-Viana), a mountain region covering an area of 175,296 hectares in the south of the province of Ourense (Galicia, NW Spain). The region borders to the north and west with respectively the XIII Forest District (Valdeorras –Trives) and the XV Forest District (A Limia), to the east with the region of Castilla-León (Spain) and to the south with the region of Tras-Os-Montes Alto Douro (Portugal).

The study considered wildfires affecting an area of more than 200 hectares that occurred during the 11-year period between 2006 and 2016 (a total of 36 wildfires). The burned areas were selected from the database of the Spanish General Statistics on Forest Fires (EGIF), provided by the Ministry of Agriculture and Fisheries, Food and Environment (MAPAMA).

The perimeters and severity classes were mapped using a collection of pre and post-fire Landsat images (Path 204 and Row 31) that covered the entire area and study period. Some of the Landsat 5 TM, 7 ETM and 8 OLI images were downloaded from the European Space Agency website (ESA, https://earth.esa.int/web/guest/eoli), while others were provided by the Galician Institute of Territorial studies (IET). Scenes were radiometrically corrected by digital levels (ND), according to Chander *et al.* (2009), into top of atmosphere (TOA) reflectance. The topographic correction was also applied according to the Minnaert Correction with slope method (Riaño *et al.* 2003).

The fire severity class was assigned for each pixel by calculating the dNBR index (Key and Benson 2006) and applying the classification thresholds previously established by Arellano (2014). These thresholds are based on the existing relationship between the Composite Burning Index (CBI, Key and Benson 2006) and the dNBR for several wildfires that occurred in Galicia in 2013: unburned ($dNBR<12.3$); low ($12.3\leq dNBR<262.4$); moderate ($262.4\leq dNBR<577.2$) and high ($577.2\leq dNBR$). Likewise, a level of canopy damage was assigned to each tree-covered pixel according to Arellano (2014) and Arellano *et al.* (2017). The four levels of canopy damage considered are shown in Table 1.

Table 1 - Description of canopy damage levels and dNBR thresholds

Level of canopy damage	**Description**	**dNBR**
Green	Area covered by trees in which the crown remained green after fire >50%	282.9
Green-scorched	Area covered by trees with scorched crown after fire: 50-90%. The rest of the area, up to 100%, occupied by trees in which the crown remained green.	282.9-443.2
Scorched-consumed	Area covered by trees with scorched crown after fire: 50-100%. The rest of the area, up to 100%, occupied by trees with the crown consumed.	443.2-626.6
Consumed	Area covered by trees with the crown consumed >50%	≥626.6

The values of the dNBR index statistics (mean, standard deviation, minimum, median and maximum) were calculated for each wildfire. The proportion of burned area was also calculated for each fire severity class and each level of canopy damage in each wildfire.

Topographical, meteorological and fuel-related data were compiled for each wildfire. The digital elevation model (DEM), with a spatial resolution of 25 m, was downloaded from the Spanish Geographic Institute (IGN) website (http://www.ign.es/web/ign/portal) and used to generate slope and aspect cartography for each burned area. Five levels of slope (0-10%, 10-20%, 20-30%, 30-45%, >45%) and the four cardinal directions (N, S, E and W) were considered. Descriptive statistics on altitude and slope (mean, maximum, minimum, median and standard deviation) were computed. Meteorological databases were downloaded from the Meteogalicia website (http://www.meteogalicia.gal) and used to determine the following variables at the start of each wildfire: temperature (ºC), relative humidity (%), wind speed (km/h), wind direction (º), wind gust speed (km/h) and wind gust direction (º). Data from seven different meteorological stations in the Xunta de Galicia network that are close to the burned areas were used. Finally, the Spanish Forest Map (MARM 2011) was used to classify the burned areas into four different categories according to the fuel type (tree-covered land, scrubland, agricultural land and riparian forest land) and to estimate the proportion of each class in each area affected by wildfire.

A total of 23 variables were compiled for each wildfire. The non-parametric Random Forests method was then used to relate the proportion of the total burned area affected by the high fire severity class and the proportion of the total burned area affected by the most severe level of canopy damage, with the respective topographical, meteorological and fuel characteristics.

The study only considered the highest levels of both fire severity and canopy damage as these are the variables of most interest in relation to making decisions about the areas where recovery activities should be carried out.

The randomForest package developed for R (R Core Team 2013) by Liaw and Wiener (2012) was used to fit 500 regression trees for each variable analysed. For fitting each regression tree, 2/3 of the total fires were selected at random and 8 of the total descriptor variables were selected at random.

Finally, the relative importance of each descriptive variable was estimated by normalizing the values of the Increment of Node Purity statistic to a maximum value of 100. The importance of a variable in the classification process increases with the value of this statistic.

3. Results and discussion

The locations and perimeters of the wildfires are shown in Figure 1.

The average values of elevation, slope, temperature, relative humidity, wind and gust speed of the 36 wildfires were respectively 957 m, 22%, 23 ºC, 34%, 13 km/h and 24 km/h. The combination of the most frequent wind direction (SE) with the predominant orientation (E) promoted wildfire spread in the study area. In general, the percentage of burned shrub area exceeded that of tree-covered burned area. Considering all of the wildfires, the average percentage values of the different dNBR severity classes were as follows: unburned = 3%; low = 12%; moderate = 39% and high = 46%. For the levels of canopy damage, the average percentages were as follows: green = 25%, green-scorched = 17%, scorched-consumed = 21% and consumed = 37%. These values indicate the high level of impact of the wildfires in the study area.

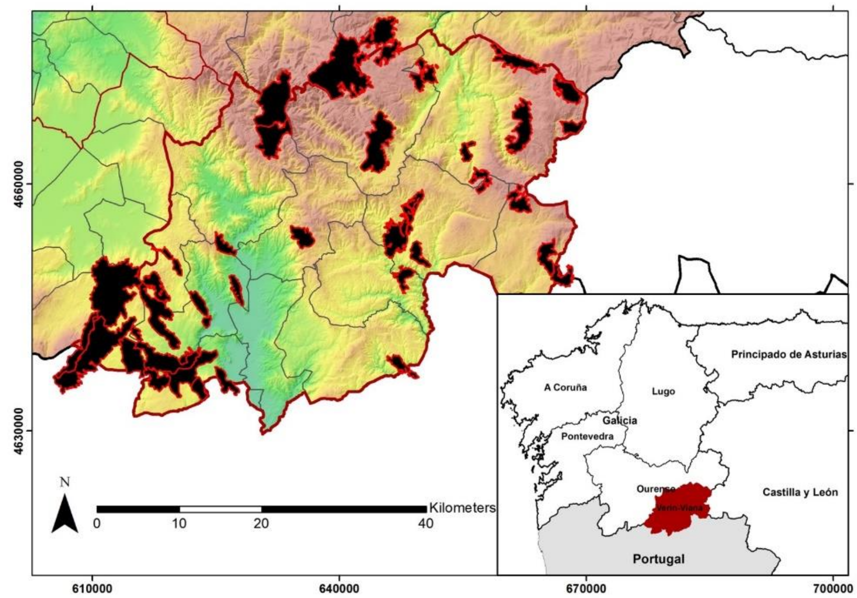

Figure 1 - Location and perimeter of the wildfires studied

The spatial distribution of dNBR severity classes in two of the wildfires (by way of example) is shown below (Figure 2).

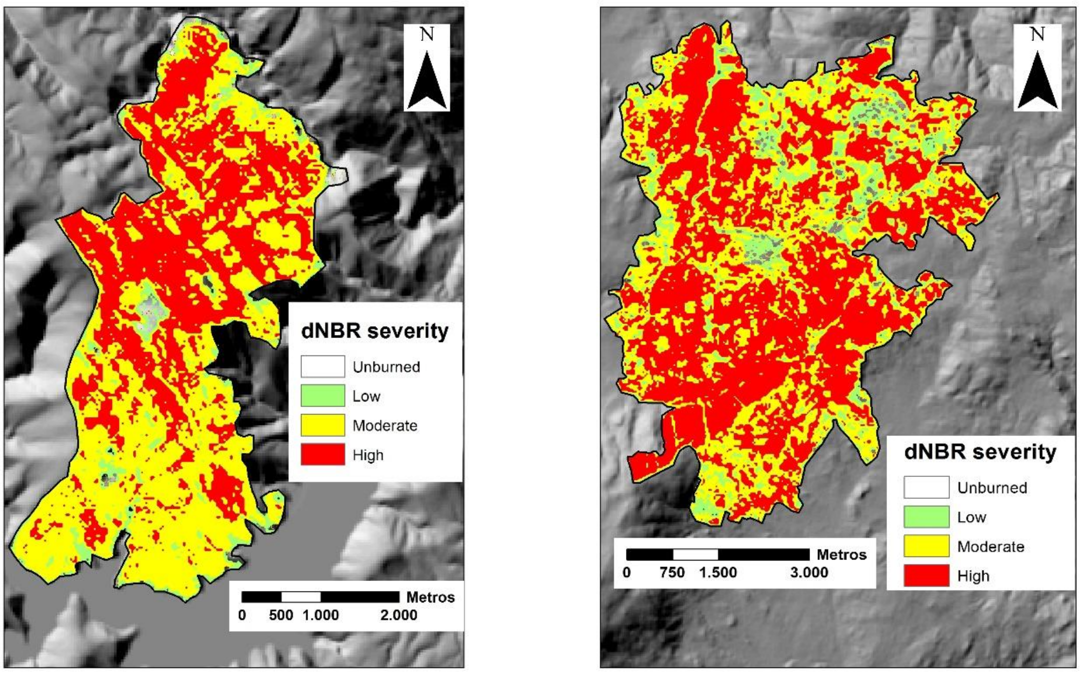

Figure 2 - dNBR Fire severity map: San Mamede de Hedrada Fire 2011 (left) and Lucenza Fire 2015 (right)

Box plots were constructed of the distribution of the mean values of dNBR obtained for each fire, grouped by year (Figure 3). The mean values exceeded the threshold of dNBR of 577.2, corresponding to the highest level of fire severity, in only three years (2008, 2015 and 2016). Interestingly, the average dNBR values were highest in shrubby habitats, followed by tree-covered land and were lowest in riparian forest and agricultural land.

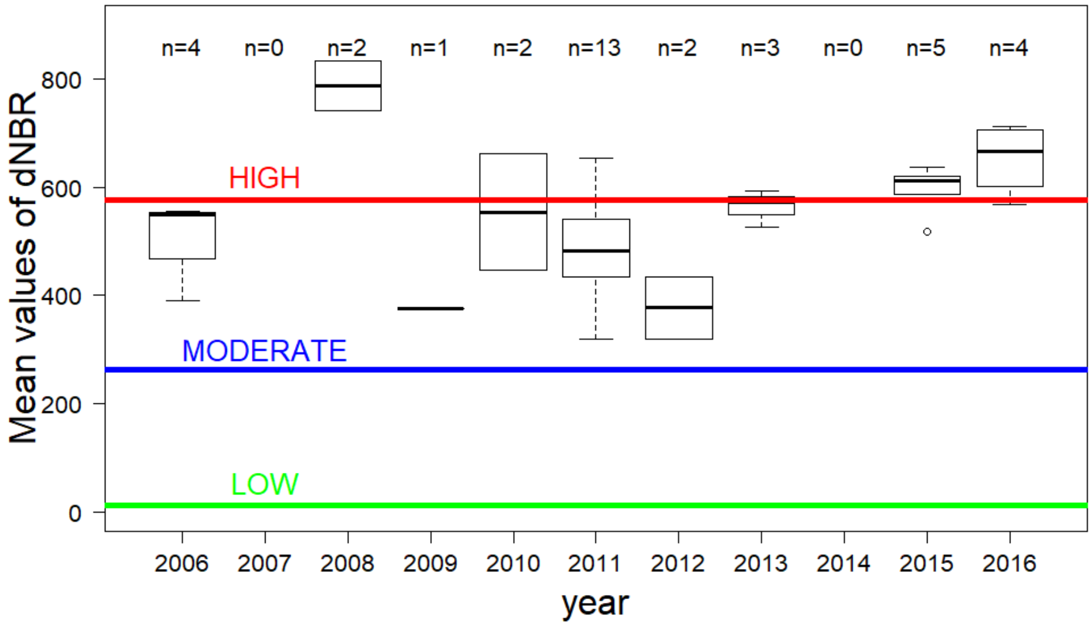

Figure 3 - Box plots of the distribution of averages values of dNBR throughout the study period

The relative importance of the main features explaining the percentage of burned area classified as high fire severity class and the classified with the highest level of canopy damage ("crown consumed", equivalent to crown fire) are shown in Figures 4 and 5. The two features that best differentiated the areas affected by high fire severity class and the level of crown fire were the wind speed and the burned area percentage with slope, ranging from 30 to 45%, coinciding for both random forests.

These results are consistent with those of Fernández Alonso *et al.* (2017), who reported that wind speed was also the most important variable explaining the spatial pattern of crown fire in several wildfires in Galicia. Other studies (Lentile *et al.* 2006, Holden *et al.* 2009, Lecina-Diaz *et al.* 2014) have also demonstrated the relationship between slope and -extreme fire severity. Overall, the results confirm the well-known overwhelming importance of wind and slope angle in wildland fire behaviour (Rothermel 1983) and particularly in high intensity fires (Werth *et al.* 2016). Other variables that proved important in explaining high levels of fire severity were the southern orientation and the wind direction, underlying the probable influence of lower dead fuel moisture content and the alignment of wind and slope as factors contributing to strengthening the intensity of fire. Finally, the maximum slope and the temperature at at the start of the wildfire were also important for predicting the crown fire. The latter is probably related to dead fuel moisture.

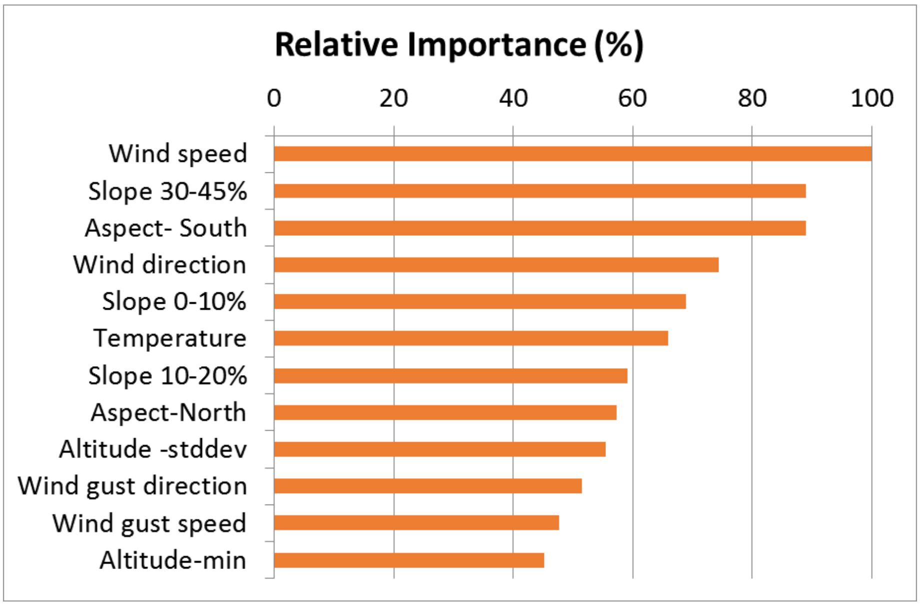

Figure 4 - Relative importance of each variable as determined by the Random Forests method used to explain the proportion of the highest level of fire severity

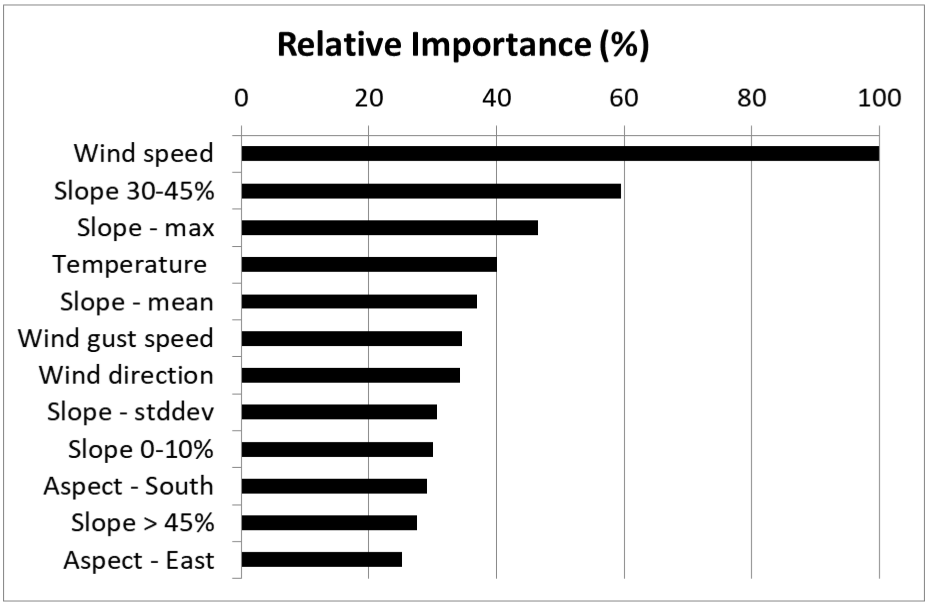

Figure 5 - Relative importance of each variable as determined by the Random Forests method used to explain the proportions of crown consumed

4. Conclusions

Mapping burned areas and fire severity in all wildfires of more than 200 hectares that occurred in the Verín-Viana Forest District over a period of 11 years is a fundamental starting point for new studies such as the analysis of the fire recurrence in the area, the location of strategic management areas and characterization of wildfires according to the main variables involved in their spread.

The dNBR index is capable of discriminating different levels of canopy damage caused by fire. These levels can be used as the basis for proposing rehabilitation actions in burned areas and for prioritizing these actions in areas affected by crown fires. However, dNBR severity thresholds must be calibrated for a longer period than used in this study. Identification of levels of fire damage in scrubland, in addition to wooded areas, would also be of interest.

The meteorological information used could also be improved. Including average variables, at least during the first hours of wildfire development, instead of specific information on the start time, would be useful. Use of the WindNinja (Forthofer 2007) software, which simulates the spatial distribution of winds by taking into account the physiography would enable studies to be carried out at much more detailed (pixel) level.

Future studies should also aim to characterize the fuel more comprehensively. The use of historical orthophotos and LIDAR data, when possible, would enable estimation of fuel related variables that may be important for predicting fire severity.

5. Acknowledgements

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