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Assessment of the influence of biophysical properties related to fuel conditions on fire severity using remote sensing techniques: a case study on a large fire in NW Spain

Paula García-Llamas [A,D], *Susana Suárez-Seoane* [A], *Angela Taboada* [A], *Victor Fernández-García* [A], *José M. Fernández-Guisuraga* [A], *Alfonso Fernández-Manso* [B], *Carmen Quintano* [C], *Elena Marcos* [A] and *Leonor Calvo* [A]

[A]Biodiversity and Environmental Management Department, Faculty of Biological and Environmental Sciences, University of León, 24071 León, Spain.
[B]Agrarian Science and Engineering Department, University of León, Avenida Astorga s/n, 24400 Ponferrada, Spain.
[C]Electronic Technology Department, Sustainable Forest Management Research Institute, University of Valladolid, Spanish National Institute for Agriculture and Food Research and Technology (INIA), C/ Paseo del Cauce, 59, 47011 Valladolid, Spain.
[D]Corresponding author. Email: pgarcl@unileon.es

Abstract. This study analyses the suitability of remote sensing data from different sources (Landsat 7 ETM+, MODIS and Meteosat) in evaluating the effect of fuel conditions on fire severity, using a megafire (11 891 ha) that occurred in a Mediterranean pine forest ecosystem (NW Spain) between 19 and 22 August 2012. Fire severity was measured via the delta Normalized Burn Ratio index. Fuel conditions were evaluated through biophysical variables of: (i) the Visible Atmospherically Resistant Index and mean actual evapotranspiration, as proxies of potential live fuel amount; and (ii) Land Surface Temperature and water deficit, as proxies of fuel moisture content. Relationships between fuel conditions and fire severity were evaluated using Random Forest models. Biophysical variables explained 40% of the variance. The Visible Atmospherically Resistant Index was the most important predictor, being positively associated with fire severity. Evapotranspiration also positively influenced severity, although its importance was conditioned by the data source. Live fuel amount, rather than fuel moisture content, primarily affected fire severity. Nevertheless, an increase in water deficit and land surface temperature was generally associated with greater fire severity. This study highlights that fuel conditions largely determine fire severity, providing useful information for defining pre-fire actions aimed at reducing fire effects.

Additional keywords: evapotranspiration, fire effects, Landsat, Meteosat, MODIS, VARI index.

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Introduction

In the European Mediterranean region, fire is a major disturbance (Oliveira *et al.* 2012) with significant ecological and socioeconomic impacts on forest ecosystems (Pausas *et al.* 2008). It is well established that a major determinant of the magnitude of the ecological impact and effects of wildfires is fire severity (Harris and Taylor 2017), as it can alter vegetation composition, structure and regeneration dynamics (Wang and Kemball 2003; González-De Vega *et al.* 2018), as well as contribute to increasing soil degradation (Heydari *et al.* 2017). Fire severity refers to the change between pre- and post-fire conditions (Key 2006; Meng *et al.* 2017; Fernández-García *et al.* 2018*a*), and is operationally represented as both aboveground and belowground consumption of organic matter (Keeley 2009). It has been commonly evaluated through field methods, (e.g. the Composite Burn Index – CBI – and the GeoCBI index); but also using remotely sensed spectral indices validated with field-measured metrics, as a timely and cost-effective alternative to field methods (Fang *et al.* 2018). Properties of fire regimes, such as the severity and size of fires, are expected to increase in the future in the Mediterranean region, likely owing to land use and climate change, and forest management policies (González-De Vega *et al.* 2016), which may lead to drastic shifts in fire activity and seasonality. Therefore, modelling potential fire severity and understanding its main drivers of control are emerging as a priority for improving pre-fire forest management strategies (Estes *et al.* 2017; García-Llamas *et al.* 2019).

Among the environmental factors that influence fire severity, there is increasing evidence that fuel is a major controlling factor (Kraaij *et al.* 2018; García-Llamas *et al.* 2019). In forest ecosystems, fuel characteristics, such as fuel moisture and structure, may affect fire spread, progression and behaviour (Harris and Taylor 2017), which largely determine fire severity levels. Furthermore, fuel composition and loading influence heat flux during combustion, which ultimately may affect the spatial patterns of fire severity (Fang *et al.* 2018). Nevertheless, how fuel characteristics are specifically related to fire severity is still not fully understood. Whereas studies by Lentile *et al.* (2006) and Lydersen *et al.* (2017) have shown clear relationships between fuels and fire severity, others, such as Bessie and Johnson (1995) and Estes *et al.* (2017), have suggested that fuels have a less important role on fire severity than other environmental factors (e.g. weather conditions and topography).

Fuel characteristics, such as fuel amount or spatial structure, can be modified through management treatments (Lee *et al.* 2018). As a consequence, knowledge of the role played by fuel in fire severity is critical for prioritising effective pre- and post-fire management strategies. Fire management strategies require, however, the development of reliable and accurate information that helps and supports decision-making processes (Chuvieco and Kasischke 2007).

Recent advances in remote sensing techniques have provided major opportunities to obtain valuable information for scientists and decision-makers related to fuel characteristics for fire severity modelling in a cost-effective way. For example, satellite remote sensing offers great potential for (i) mapping fuel models (Riaño *et al.* 2002; Van Wagtendonk and Root 2003); (ii) estimating live fuel moisture content from vegetation indices (Myoung *et al.* 2018); and (iii) measuring potential biomass production, the balance between moisture availability, fuel dryness and vegetation drought stress from remotely sensed evapotranspiration products (Kane *et al.* 2015; Fang *et al.* 2018). Information from remote sensing systems offers several advantages as it is spatially comprehensive and can be periodically updated (Chuvieco and Kasischke 2007), thus enabling the assessment of spatial and temporal variation in fuel characteristics and their effect on fire severity. For example, the Landsat satellite has been widely used for monitoring and modelling fuel characteristics, because it provides one of the longest moderate-spatial-resolution imagery collections (Banskota *et al.* 2014). Moderate-Resolution Imaging Spectroradiometer (MODIS) vegetation products have also been commonly used in fire studies across the globe, owing to their near-global spatial coverage and high temporal resolution (Uyeda *et al.* 2015; Fang *et al.* 2018). Additionally, characteristics of newer satellites, such as the high-temporal-resolution of Meteosat Second Generation (MSG; (Amraoui *et al.* 2013), are arousing interest in the fire research field. Nevertheless, despite its advantages, the operational use of remote sensing data in assessing the role of fuels in fire severity still presents some challenges associated with the current status of satellite sensor technology (Chuvieco and Kasischke 2007) and the availability of the spectral, spatial or temporal resolution required for operational performance (Meng and Zhao 2017).

In the present study, we aim to examine the suitability of different remote sensing sources [Landsat 7 Enhanced Thematic Mapper Plus (ETM+), MODIS and Meteosat] to evaluate how biophysical properties are related to fuel conditions and how they can predict fire severity. Further, we provide recommendations at management level for defining actions to reduce fire effects. As a case study, we used a megafire that occurred in 2012 in NW Spain that affected 11 891 ha of a Mediterranean ecosystem dominated by *Pinus pinaster* Aiton.

Methods

Study site

This study was conducted in the Sierra del Teleno mountain range (NW Spain; Fig. 1) where 11 891 ha burned in August 2012 (between 19 and 22). The orography is heterogeneous with altitude ranging from 2188 to 840 m above sea level (asl) and 10% average slope. Soils are of acidic origin, developed over siliceous lithology (i.e. quartzite, conglomerate, sandstone and slate) with low organic matter content (Fernández-García *et al.* 2018*b*). The climate in this area is Mediterranean. Mean annual temperature is 10°C, with 2–3 months of drought in summer and a mean annual precipitation of 650 to 900 mm (20 years' averaged values covering 1950–99; Ninyerola *et al.* 2005). During the week preceding the fire and during the fire itself, there was a heatwave that increased the fire risk (Quintano *et al.* 2015). The Sierra del Teleno mountain range has frequently been affected by wildfires, mainly associated to dry spring–summer lightning storms and anthropogenic causes (Santamaría 2015). Small fires have commonly burned the area during winter, spring and autumn, whereas large fires mainly occur during the summer season (July–September; Santamaría 2015). The area affected by the fire was dominated by a mature natural maritime pine (*Pinus pinaster* Ait.) forest, with a tree density in mature stands of 765 plants ha^{-1}. The shrubby understorey community is mostly dominated by *Erica australis* L. and *Pterospartum tridentatum* (L.) Willk. Maritime pine populations in this area are highly adapted to intense crown fires, with more than 95% of mature trees bearing serotinous cones (Tapias *et al.* 2004). Nevertheless, short fire return intervals (the average fire-free interval has been estimated at 15 years) may prevent *P. pinaster* from reaching reproductive maturity, thus undermining population resilience (Taboada *et al.* 2018). The fire under consideration was an extreme convective crown fire that completely destroyed the understorey and consumed the majority of tree crowns (40% of the surface burned at high severity levels; Quintano *et al.* 2015). Such extreme fire severity characteristics justified the selection of this fire event as a case study.

Fire severity

Fire severity data were estimated from two Landsat 7 ETM+ images obtained on 20 September 2011 (pre-fire image) and 20 September 2012 (post-fire image) from the United States Geological Survey (USGS) Earth Explorer server (http://earthexplorer.usgs.gov/, accessed 26 September 2018). Image selection was conducted considering the availability of cloud-free images closest to the date of the fire, aiming to avoid phenological changes in the vegetation (Lecina-Diaz *et al.* 2014). We applied the *FLAASH* algorithm (Berk *et al.* 1999; Matthew *et al.* 2003) to conduct atmospheric correction of the

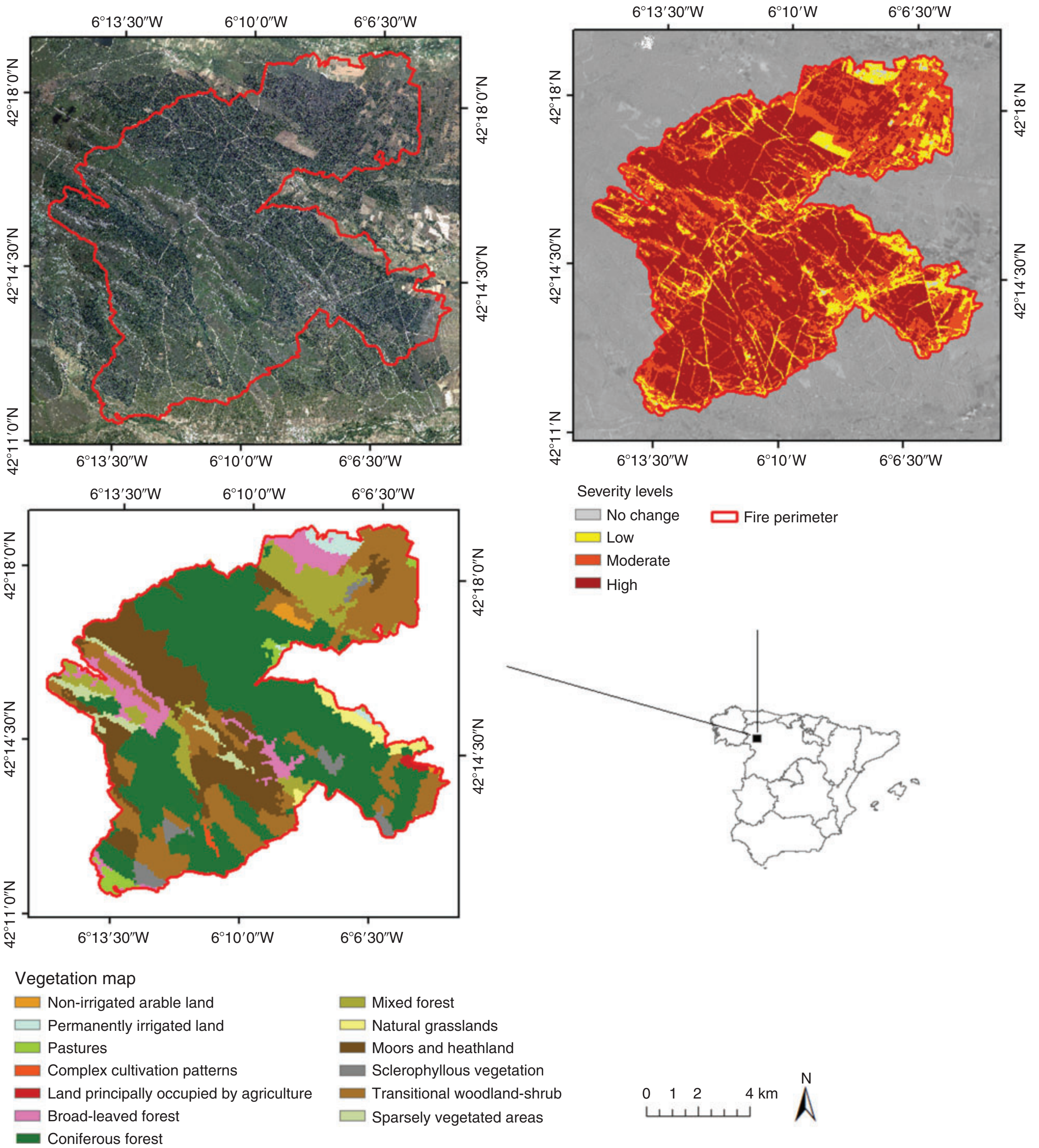

Fig. 1. Location map of the study area (Sierra del Teleno, NW Spain) including a pre-fire vegetation map of the burned area produced using: (*a*) an orthophotograph (from 2011) from the Spanish National Plan for Aerial Orthophotography (http://centrodedescargas.cnig.es/CentroDescargas/index.jsp#, accessed 24 October 2018); (*b*) the Coordination of Information on the Environment (CORINE) land-cover database available for 2012; and (*c*) a fire severity map obtained using classified delta Normalized Burn Ratio (dNBR) values derived from Landsat 7 Enhanced Thematic Mapper Plus (ETM+) post-burn imagery (20 September 2012) with breakpoints defined based on the Composite Burn Index (CBI) values: low severity, 45.898 ≥ dNBR < 413.185; moderate severity, 413.185 ≥ dNBR < 732.565; high severity, ≥732.565 (from Fernández-García *et al.* 2018*b*).

images, which enabled us to obtain a bottom of atmosphere (BOA) reflectance product.

Fire severity was calculated via the delta Normalized Burn Ratio (dNBR; Key and Benson 2006; Eqn 1), an index widely used for estimating fire severity in forest systems (Soverel *et al.* 2010; Whitman *et al.* 2018).

$$\text{dNBR} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}} \quad (1)$$

where the near-infrared (NIR) and the short-wave infrared (SWIR) bands used for calculation were the NIR (B4) and the SWIR-2 (B7) bands of Landsat 7 ETM+. The dNBR values in unburned areas were normalised to zero by subtracting the average dNBR in unburned areas outside the fire from those within the fire perimeter to account for interannual phenological differences between pre- and post-fire images (Miller *et al.* 2009).

The dNBR values were validated using the CBI index, which was estimated 3 months after fire following the protocol described by Fernández-García *et al.* (2018*a*), which is a modification of the CBI protocol developed by Key and Benson (2006). CBI values ranged between 0 (unburned) and 3 (high severity) according to the burn severity scale of Key and Benson (2006). They were obtained averaging the scores assigned to several variables of five vertical strata, in 54 plots of 30 × 30 m randomly distributed across the study area. The correlation value between the spectral index and CBI was 0.88. See Fernández-García *et al.* (2018*a*) for further details on the dNBR validation.

In the present study, we used continuous dNBR values as the response variable in further analysis. Nevertheless, for easier interpretation, we also show dNBR as classified fire severity using breakpoints defined based on the CBI values: low severity, $45.898 \geq \text{dNBR} < 413.185$; moderate severity, $413.185 \geq \text{dNBR} < 732.565$; high severity, ≥ 732.565; as in Fernández-García *et al.* (2018*b*) (Fig. 1).

Biophysical properties related to fuel conditions

The biophysical properties related to fuel conditions were characterised by including metrics related to fuel loads and moisture content. We estimated the potential live fuel amount on the basis of two variables: (i) the Visible Atmospherically Resistant Index (VARI), and (ii) the mean actual evapotranspiration (AET). The VARI is an index based on the red, green and blue visible bands (Eqn 2; Gitelson *et al.* 2002) that is related to the live vegetation fraction and net primary production (Gitelson *et al.* 2002; Maguigan *et al.* 2016). It was derived from a Landsat 7 ETM+ image (30-m spatial resolution) obtained on 20 September 2011 (the pre-fire image applied for calculating fire severity; see the *Fire severity* section for further details on image pre-processing).

$$\text{VARI} = \frac{R_{\text{green}} - R_{\text{red}}}{R_{\text{green}} + R_{\text{red}} - R_{\text{blue}}} \quad (2)$$

where R_{band}, band = green, red and blue, is the BOA reflectance for each band.

AET is related to potential biomass production and, thus, to fuel amount (Kane *et al.* 2015). It was calculated by averaging information acquired between June and August 2012 from two different remote sensing data sources: (i) an MSG (Schmetz *et al.* 2002; Romaguera *et al.* 2012) evapotranspiration product at 10-day intervals and 3-km spatial resolution, provided by the Environmental Analysis & Remote Sensing (EARS) enterprise; (ii) the MOD16A2 global evapotranspiration product at 8-day intervals and 500-m spatial resolution from MODIS (https://modis.gsfc.nasa.gov/data/dataprod/mod16.php, accessed 6 February 2019). We selected summer months because it is the season when large fires mainly occur in the area (Santamaría 2015), and it is well established that a main factor in fire ignition and propagation is the presence of fuel ready for burning (Gouveia *et al.* 2012; Russo *et al.* 2017), especially in crown convective fires.

Variables accounting for fuel moisture content included the land surface temperature (LST) and water deficit, which were derived from the MODIS satellite. We estimated these variables for the week before the fire because both the high temperatures and the low relative humidity of the heatwave episode during the week preceding the fire likely exacerbated the effects of summer drought and, thus, fuel desiccation and flammability (van Mantgem *et al.* 2013). The LST, which is expected to increase in drier vegetation (Dasgupta *et al.* 2005), was computed by averaging daily information from the MODIS 1-km LST product. Water deficit, at 500-m spatial resolution, was estimated as the difference between Potential Evapotranspiration (PET) and the AET (Kane *et al.* 2015). PET and AET were obtained from the MOD16A2 global evapotranspiration product at 8-day intervals.

Statistical analysis

In order to explore the relationship between the response variable (fire severity) and the predictors (biophysical variables related to fuel conditions), we applied the random forest (RF) machine learning algorithm (Breiman 2001), using the 'randomForest' package (Liaw and Wiener 2002) for *R* (R Core Team 2017) and a random sampling set of 1000 pixels (1% of pixels from the image) to build the models.

To avoid multicollinearity problems among the predictors, we previously checked Pearson's bivariate correlations, the correlation values reached being lower than 0.60 (Table 1).

The predictive power of RF was estimated through the internal out-of-bag error rates (Kane *et al.* 2015). Furthermore, in order to obtain stable results, the parameter of *ntree* (i.e. the number of trees to run) was set to 500 and the *mtry* parameter (i.e. the number of input predictors tested at each split) was established through initial tuning experiments. The decrease in the accuracy criterion (% IncMSE) was used to determine the relative importance of predictors in the variance explained in models. RF models were run 50 times and the average was provided as the final result, aiming to obtain stable model outputs and to minimise stochastic errors. Additionally, we obtained partial dependence plots for each predictor.

Results

RF models accounted for ~40% of the fire severity variance. Regarding the individual contribution of each predictor in explaining fire severity, biophysical properties associated with the potential amount of live fuel were relatively more important

Table 1. Pearson's correlation coefficients (*r*) between pairs of predictors (biophysical variables related to fuel conditions)
AET_{MODIS}, actual evapotranspiration obtained from the MOD16A2 global evapotranspiration product; AET_{MSG}, actual evapotranspiration obtained from the Meteosat Second Generation; LST, land surface temperature; VARI, Visible Atmospherically Resistant Index

	VARI index	AET_{MODIS}	AET_{MSG}	Water deficit	LST
VARI index	1.00	0.00	−0.01	0.00	−0.11
AET_{MODIS}	0.00	1.00	−0.60	0.53	−0.21
AET_{MSG}	−0.01	−0.60	1.00	−0.61	0.35
Water deficit	0.00	0.53	−0.61	1.00	−0.43
LST	−0.11	−0.21	0.35	−0.43	1.00

than those associated with fuel moisture content (Fig. 2). In detail, the VARI emerged as the most important predictor influencing fire severity (Fig. 2). Overall, high values of the VARI were related to an increment in fire severity levels, thus indicating higher fire severity in areas of great availability of live fuel (Fig. 3*a*). Additionally, the importance of AET in RF models changed between remote sensing data sources of different spatial resolution (Fig. 2). Particularly, AET obtained from MSG was the second most influential predictor explaining fire severity. Nevertheless, AET derived from MODIS had less influence on fire severity, even less than biophysical properties related to fuel moisture content (i.e. water deficit) (Fig. 2). Regardless of the remote sensing data source, higher AET values were correlated with higher fire severity levels, but just towards a threshold (2.5 and 2.9 mm for AET from MSG and MODIS respectively; Fig. 3*b, d*). Increasing water deficit was generally associated with greater fire severity levels (Fig. 3*c*). Furthermore, LST was weakly related to fire severity (Fig. 2) and exhibited a negative influence on fire severity (Fig. 3*e*).

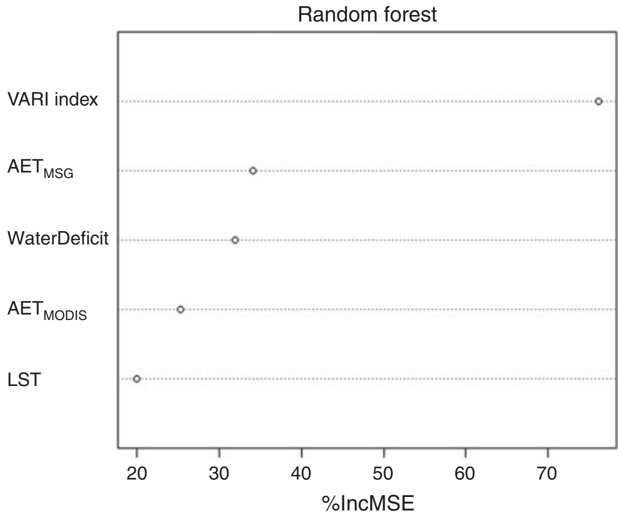

Fig. 2. Relative importance, measured as % IncMSE, of variables from random forest models explaining fire severity. AET_{MSG}, actual evapotranspiration from Meteosat Second Generation satellite; AET_{MODIS}, actual evapotranspiration obtained from the Moderate-Resolution Imaging Spectroradiometer (MODIS); LST, land surface temperature; VARI, Visible Atmospherically Resistant Index.

Discussion

Influence of fuel on fire severity

The results of this study confirm previous findings demonstrating the role of fuel conditions, obtained from different remote sensing data sources, as major controlling factors of fire severity patterns (Lentile *et al.* 2006; Gouveia *et al.* 2012; Kraaij *et al.* 2018). Nevertheless, in Mediterranean pine forest dominated by *Pinus pinaster*, results showed that fuel characteristics were not equally related to fire severity. The amount of live fuel, measured through the VARI, appeared to be the most important factor, positively affecting fire severity. Positive correlations between higher levels of fire severity and the presence of dense live vegetation loads have also been reported in other areas dominated by pine forests (Schoennagel *et al.* 2004; Arkle *et al.* 2012). In this context, the chemical properties of *P. pinaster*, such as high resin content, together with the structural characteristics of needles, tend to increase live biomass flammability and the energy released during combustion (Calvo *et al.* 2003), therefore contributing to higher fire severity levels. Additionally, recurrent fires in some zones of the study site have contributed to high post-fire regeneration stand densities (Calvo *et al.* 2013; Taboada *et al.* 2017), and resprouter shrub species (e.g. *Erica australis* L. and *Pterospartum tridentatum* (L.) Willk.) of high pyrogenicity (Calvo *et al.* 2008), which have been found to trigger high fire severity levels (García-Llamas *et al.* 2019).

The importance of live fuel on fire severity was also evinced by the overall positive effect of AET on fire severity, likely owing to the association of this parameter with vegetation productivity and, thus, with mounts of live fuel (Kane *et al.* 2015). Nevertheless, the impact of AET on fire severity changed substantially depending on the remote sensing data source used for analysis. AET obtained from MSG was the second most important predictor of fire severity, but the AET product from MODIS showed less importance than fuel moisture predictors (i.e. water deficit). The difference in spatial resolution between remote sensing-derived AET products may justify this inconsistency in AET importance, thus indicating that resolution may affect the predictability of fire severity models (Harris and Taylor 2017; Fang *et al.* 2018). In this context, it is well known that different spatial processes could operate at different scales and, hence, conclusions at one scale may not be applicable at another (Suárez-Seoane and Baudry 2002; Wu and Li 2009). Consequently, spatial resolution discrepancies between data sources may constrain the accuracy of models and lead to conflicting conclusions, thus limiting the development of remote sensing applications (Wu and Li 2009;

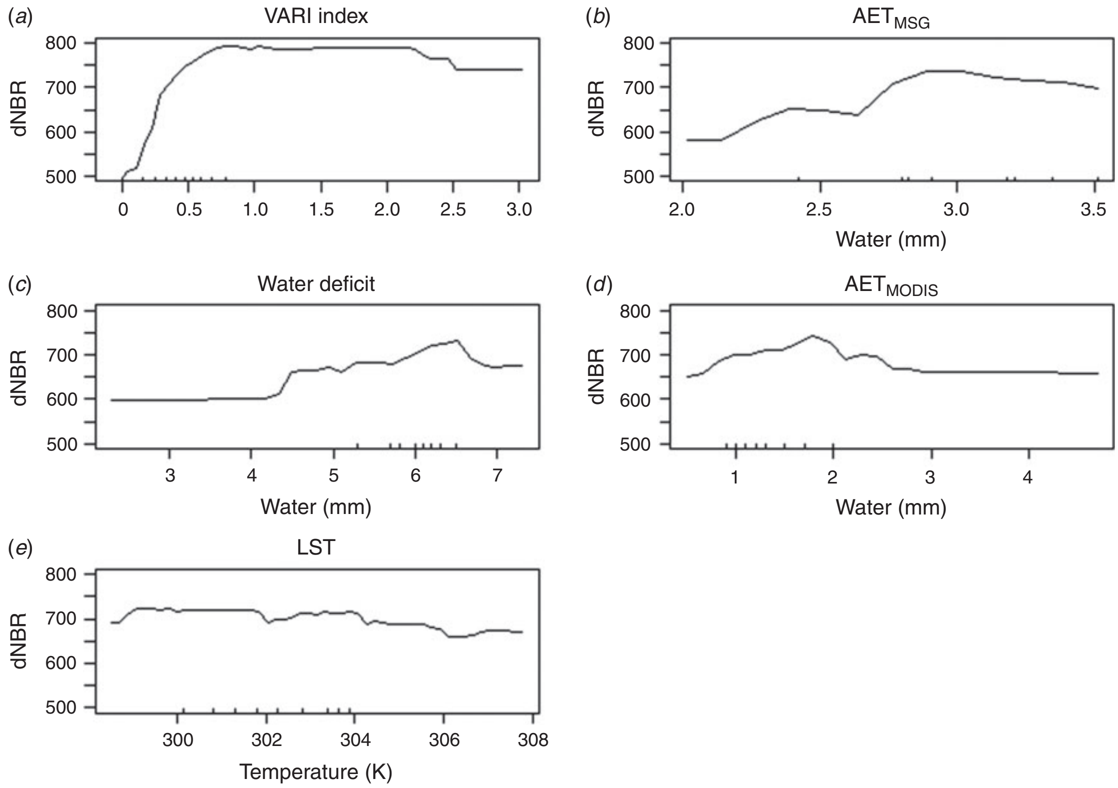

Fig. 3. Partial dependence plots showing the relationship between fire severity, measured as the delta Normalized Burn Ratio (dNBR) and each of the predictors included in Random Forest models: (*a*) Visible Atmospherically Resistant Index (VARI); (*b*) actual evapotranspiration from Meteosat Second Generation satellite (AET_{MSG}); (*c*) water deficit; (*d*) actual evapotranspiration from the Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite (AET_{MODIS}); (*e*) land surface temperature (LST).

García-Llamas *et al.* 2016). As a result, although the capacity of remote sensing techniques to provide information at multiple resolutions may be advantageous (Lentile *et al.* 2006), their utility for assessing the role of fuel on fire severity may be hampered by mismatches between the resolution of the data source and the scale at which fuel characteristics and fire severity correlate.

High fire severity levels have proved to be largely determined by fuel moisture content (Ferguson *et al.* 2002). Our results indicated that high-severity fires were more likely under greater hydric stress conditions (i.e. higher water deficit and LST values). This result may be explained by the fact that dry conditions tend to favour the consumption of greater amounts of fuel, as well as higher levels of energy released during combustion (Dillon *et al.* 2011). Nevertheless, although summers in the Mediterranean Iberian Peninsula are typically dry enough to promote fuel desiccation that permits ignition, the abundance of live biomass loads for combustion, rather than fuel moisture, has been noted as the primary limiting factor of fire severity (Pausas and Paula 2012; Lecina-Diaz *et al.* 2014), as also observed in our study. One reason could be that dry conditions limit vegetation growth, and thus fuel accumulation and continuity, leading to a decrease in the risk of crown fire spread (Alvarez *et al.* 2012) and fire severity. Additionally, these results could also be related to scale issues, in a way that the spatial resolution of moisture predictors may not properly match the scale at which fire severity patterns and fuel moisture content characteristics correlate.

Management recommendations

Our findings evinced how high live fuel accumulations may increase susceptibility to high-severity fire events in Mediterranean *P. pinaster* forest ecosystems. Under this assumption, pre-fire management strategies aiming at reducing high live fuel loads would be essential to reduce the likelihood of severe fires. Effective pre-fire fuel treatments should prioritise the reduction of canopy bulk density through silvicultural treatments, aiming at hampering crown fire spread, and decreasing fire intensity, as well as convective heat transfer into the canopy, thus reducing fire severity (Lininger 2006). Additionally, creating open and sparse stands and retaining large trees, which reduce fuel continuity, is also recommended, aiming to increase the resilience of the system (Agee and Skinner 2005). In this way, studies by Gallegos Pérula *et al.* (2003) and Kim *et al.* (2016) showed how an open forest structure was correlated with a decrease in fire severity. Nevertheless, it is necessary to consider that fuel reduction treatments need to be balanced against the development of fire-prone understorey vegetation. In this context, stand opening may enhance the development of fire-prone shrubby understorey (Fernandes and Rigolot 2007) and the desiccation of live and dead fuels (Peterson *et al.* 2003), which would make periodic surface fuel treatments necessary.

Conclusions

The results of this study highlight that, in severe crown convective fires in *Pinus pinaster* Mediterranean forest, the accumulation of live vegetation available to be burned plays a relatively more important role in determining high levels of fire severity than fuel moisture conditions. In addressing the role of fuel characteristics in fire severity, the VARI from Landsat 7 ETM+ and the AET product from MSG may be valuable tools for determining the amount of live fuel susceptible to influencing fire severity. However, we further highlight the importance of proper selection of the remote data sources at an operational spatial resolution that may be suitable for the predictability of fire severity models. Our analysis provides information that can be helpful for environmental managers when defining strategies aimed at reducing fire severity and its ecological effects during the pre- and post-fire decision-making process. These strategies should prioritise the reduction of live fuel accumulation and the enhancement of a more open canopy through the modification of forest stands and structure.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

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