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Exploring the use of spectral indices to assess alterations in soil properties in pine stands affected by crown fire in Spain

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Abstract

Background: Forest fires have increased in extent and intensity in the Mediterranean area in recent years, threatening forest ecosystems through loss of vegetation, changes in soil properties, and increased soil erosion rates, particularly in severely burned areas. However, establishing the relationships between burn severity and soil properties that determine infiltration remain challenging. Determining where soil burn severity evaluation should be carried out is critical for planning urgent measures to mitigate post-fire soil erosion. Although previous research has indicated that spectral indices are suitable for assessing fire severity, most of the classifications used consider combined effects in vegetation and soil. Moreover, the relationship between spectral indices and soil burn severity has scarcely been explored until now.

Results: We selected three pine stands in Spain for study immediately after being burned by wildfires. We analyzed various soil properties (soil saturated hydraulic conductivity, mean weight diameter of soil aggregates, and soil organic carbon) in relation to six levels of soil burn severity in all three stands. In addition, we established 25 field plots in the burned areas. We computed ten spectral indices for each plot by using Sentinel-2 satellite data. The soil burn severity categories indicated the degree of degradation of important soil properties related to soil erosion susceptibility. Of the spectral indices considered, the relativized burn ratio (RBR) was the best predictor of cumulative infiltration and mean weight diameter of soil aggregates. The differenced mid-infrared bispectral index (dMIRBI) was most closely correlated with soil organic carbon content.

Conclusions: The findings demonstrate the potential applicability of remote sensing to determining changes in soil properties after fire.

Keywords: soil burn severity, soil organic carbon, soil physical properties, spectral indices

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Resumen

Antecedentes: Los incendios forestales han incrementado en intensidad y extensión en la zona del Mediterráneo en años recientes, amenazando ecosistemas forestales a través de pérdidas de vegetación, y cambios en las propiedades e incrementos en la tasa de erosión de los suelos, particularmente en áreas severamente quemadas. Sin embargo, el poder establecer relaciones entre la severidad del fuego y las propiedades de los suelos que determinan la infiltración, es todavía un desafío. Determinar dónde debe de ser llevada a cabo la evaluación de la severidad del fuego resulta crítico para planificar medidas urgentes para mitigar la erosión del suelo en el post fuego. Aunque investigaciones previas han indicado que los índices espectrales son adecuados para determinar la severidad del fuego, la mayoría de las clasificaciones usadas consideran los efectos combinados en el suelo y la vegetación. Además, la relación entre los índices espectrales y la severidad del fuego en el suelo ha sido escasamente explorada hasta el presente.

Resultados: Seleccionamos tres rodales de pinos en España para ser estudiados inmediatamente después de haber sido afectados por incendios forestales. Analizamos varias propiedades de los suelos (conductividad hidráulica saturada, diámetro medio ponderado de agregados del suelo, y carbono orgánico del suelo), en relación a seis niveles de severidad del fuego sobre el suelo en los tres rodales. Adicionalmente, establecimos 25 parcelas en las áreas quemadas. Computamos diez índices espectrales para cada parcela usando datos del satélite Sentinel-2. Las categorías de severidad del fuego en el suelo indicaron el grado de degradación de propiedades importantes del suelo relacionadas con la susceptibilidad de erosión del suelo. De los índices espectrales considerados, la relación de índice de quemado (RBR) fue el mejor predictor de la infiltración acumulada y del diámetro medio de los agregados del suelo. El índice diferencial de infrarrojo-medio bi-espectral (dMIRBI) fue cercanamente correlacionado con el contenido de carbono orgánico del suelo.

Conclusiones: Los resultados demuestran la aplicación potencial de los sensores remotos para determinar cambios en las propiedades del suelo luego de un incendio.

Background

Wildfire represents the main type of perturbation threatening forests in Europe (San-Miguel-Ayanz et al. 2018). Quantification of the effects of wildfire is important for clarifying ecological impacts and assessing the need to plan and implement measures to restore ecosystems and to reduce flooding and erosion risk (Moody et al. 2016). The main impacts of forest fires include increased runoff and soil erosion, both of which are highly dependent on the level of alteration caused by fire in soil or soil burn severity (Benavides-Solorio and MacDonald 2005; Vega et al. 2005; Cawson et al. 2013; Fernández and Vega 2016; Schmeer et al. 2018; Fernández et al. 2020). Given the potentially large increases in overland flow events after wildfire and the associated flooding and erosion risk, accurate prediction and a good understanding of the relationships between soil properties that control infiltration and burn severity are essential, but remain challenging (Moody et al. 2013).

The normalized burn ratio (NBR) is generally accepted as the standard spectral index for assessing fire severity (*e.g.,* van Wagtendonk et al. 2004; Key and Benson 2006; Lentile et al. 2006; Hudak et al. 2007; De Santis and Chuvieco 2009; Holden et al. 2009; Miller et al. 2009; Harris et al. 2011; Veraverbeke et al. 2011; Veraverbeke et al. 2012). However, there is no agreement about the preferred conditions for determining the spectral indices (Soverel et al. 2010; Cansler and McKenzie 2012). Moreover, most of the above-mentioned studies use the Composite Burned Index (CBI) as a field measure for validating fire severity. The CBI is visually estimated and computes the combined effects of fire on soil and vegetation strata (Key and Benson 2006). However, its use is controversial (*e.g.,* Lentile et al. 2009; Morgan et al. 2014; Smith et al. 2016), and some authors have highlighted the need for independent validation of the approach for specific regions and vegetation types (Picotte and Robertson 2011; McCarley et al. 2018; Tran et al. 2018). In addition, some authors suggest the need for separate vegetation and soil burn severity assessment because these ecosystem components can be affected differently by wildfires depending on stand structure and fuel and fire behavior (Jain et al. 2004; Jain and Graham 2007; Fernández et al. 2020). The risk of soil erosion is higher in forest stands affected by crown fire than in stands in which the tree crowns are only scorched because the presence of needle cast enables water infiltration and thus favors a reduction in post-fire erosion loads (Cerdà and Doerr 2008; Neris et al. 2017; Fernández et al. 2020). Therefore, areas where soil burn severity should be assessed with a view to implementing urgent measures to mitigate post-fire soil erosion are those in which the vegetation is almost completely consumed during fire. However, evaluation of post-fire soil burn severity still relies almost completely on field surveys because the relationships between spectral indices and soil burn severity have scarcely been explored until now (Marcos et al. 2018; Sobrino et al. 2019), and few attempts have been made to quantify alteration in soil properties using spectral indices (Moody et al. 2016).

Post-fire changes in physical and hydraulic properties of soil are important for controlling the magnitude of the hydrological response to rainfall (Wieting et al. 2017). Fire severity alters the strength and persistence of soil water repellency (*e.g.,* Doerr et al. 2000; Huffman et al. 2001; Lewis et al. 2006), and the soil infiltration capacity typically decreases in magnitude when fire severity increases (*e.g.,* Ebel et al. 2012; Moody and Ebel 2012; Ebel et al. 2016; Moody et al. 2016). Pronounced alteration of soil aggregate stability and soil organic carbon content has been associated with high levels of burn severity (Mataix-Solera et al. 2011; Vega et al. 2013). Decreased soil aggregate stability has been related to increased susceptibility to erosion in unburned (Cantón et al. 2009) and burned soils (Fernández et al. 2016).

Pinus pinaster Ait., *Pinus sylvestris* L., and *Pinus pinea* L. are the most important forest species in the Iberian Peninsula, growing preferentially on acidic and well-drained soils (Ruiz del Castillo 1979). These forests are frequently affected by forest fires; in fact, almost a third of the area burned between 2006 to 2015 in Spain was pine forest (López and López 2019).

This study explored the relationship between soil burn severity and spectral indices by considering three soil properties related to the susceptibility to soil erosion after fire: saturated hydraulic conductivity, as a surrogate for soil water repellency; soil organic carbon content; and the mean weight diameter of soil aggregates. Quantification of these variables enabled their conversion into continuous variables and exploration of a set of spectral indices for determining the degree of alteration of soil properties after fire in three pine stands in central and southern Spain.

Methods

Study sites

The study was carried out in three wooded areas representative of the pine forests of central and southern Spain (Fig. 1). In all cases, they were pine forests with a shrubby understory of *Erica* L. sp., *Cistus* L. sp., and *Cytisus* Desf. sp. These pine stands were affected by wildfire in the summers of 2018 and 2019. In all cases, time since last fire was more than 20 years.

1. The Nerva Fire (Nerva) burned 1750 ha of forest and agricultural land in southern Spain from 2 to 10 August 2018. The field survey was carried out in forest stands mainly dominated by *Pinus pinea* L., covering 563 ha of public land. The soils are Eutric Cambisols developed on slates with sandy loam texture. Rainfall in the previous three months prior to fire was 39 mm.
2. The Gavilanes Fire (Gavilanes) burned 1415 ha of forest land in central Spain from 28 June to 4 July 2019, some of which (348 ha) was covered by *Pinus pinaster* Ait. stands. The soils are Cambisols and Leptosols developed on granite with sandy loam texture. Rainfall in the previous three months prior to fire was 60 mm.
3. La Granja Fire (La Granja) affected 370 ha of *Pinus sylvestris* L. stands in central Spain from 4 to 7 August 2019. The soils are Cambisols and Leptosols developed on gneiss with sandy loam texture. Rainfall in the previous three months prior to fire was 57 mm.

Experimental design and field sampling

We established 25 sampling plots in areas where the vegetation was fully consumed by crown fire (minimum size 60 m × 60 m) and where stone cover (particle diameter >10 cm) was <50%: nine plots in Nerva, four plots in Gavilanes, and 12 in La Granja. Physiographic characteristics are compiled in Table 1.

We assessed soil burn severity in plots of radius 20 m, centered in the larger plots. The soil burn severity was assessed with the aid of a 20 cm × 20 cm quadrat, which was placed at 80 systematically selected points along two perpendicular transects. The soil in each quadrat was classified using a modified version (Fernández and Vega 2016) of the soil burn severity index proposed by Vega et al. (2013). That classification considers six soil burn severity levels: (Level 1) very low soil burn severity: burned litter (Oi) but limited duff (Oe + Oa) consumption; (Level 2) low burn severity: Oa layer totally charred and covering mineral soil, possibly some ash; (Level 3) moderate soil burn severity: forest floor (Oi + Oe + Oa layers) completely consumed (bare soil), but soil organic matter not consumed and surface soil intact; (Level 4) high soil burn severity: forest floor completely consumed, soil organic matter in Ah horizon consumed and soil structure altered within a depth of less than 1 cm; (Level 5) very high soil burn severity: same as high soil burn severity but within a soil depth equal to or greater than 1 cm; and (Level 6) as Levels 4 and 5 and color altered (reddish).

In each burned area, we collected five soil samples (0 to 2 cm) for each level of soil burn severity identified. In addition, we collected five samples in unburned patches with similar soil characteristics. The samples were transported to the laboratory in plastic collars (10 cm diameter) to keep them intact. In all cases, we carried out soil sampling within two weeks following fire. Precipitation before

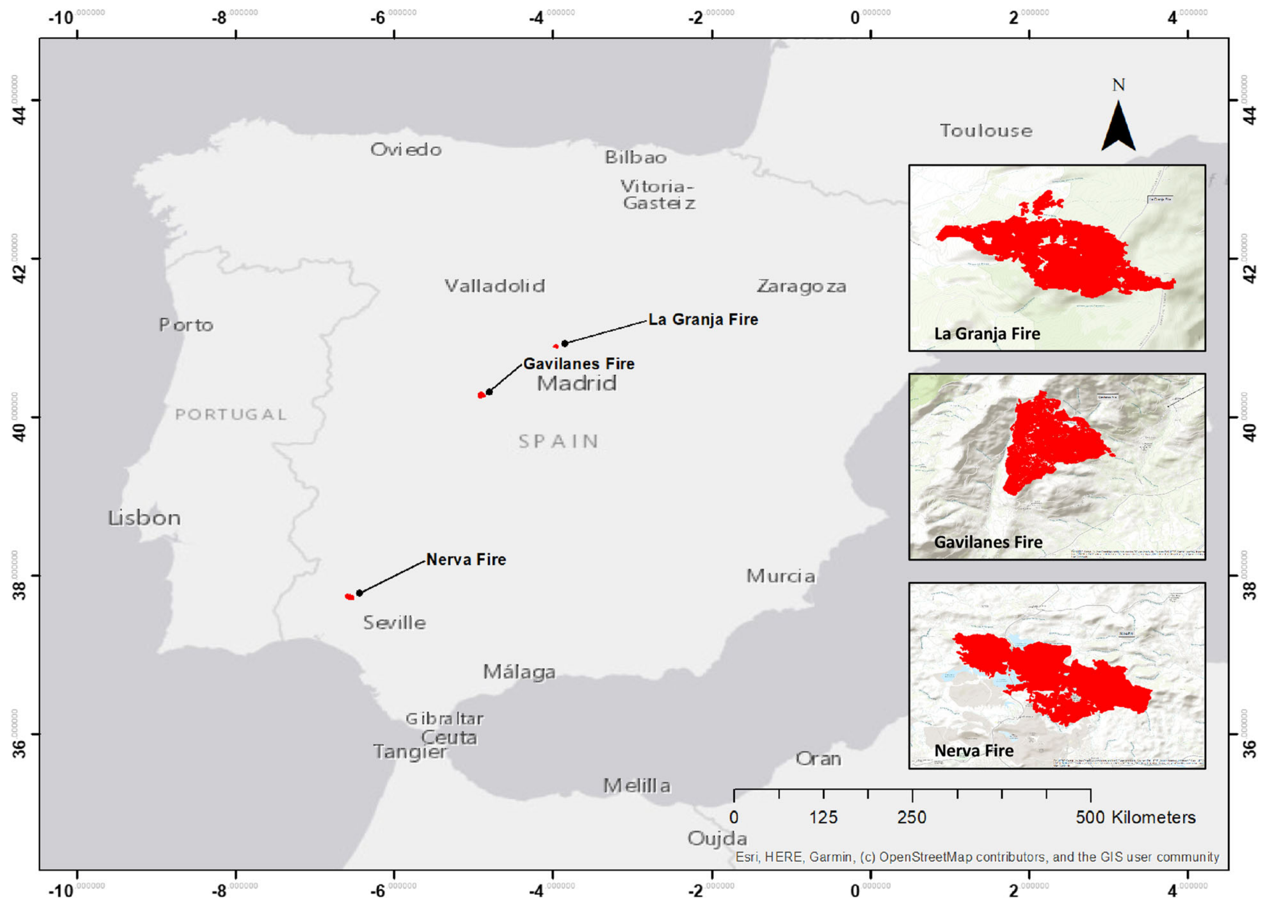

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Fig. 1 Location of wildfire-affected areas where study plots were located to assess alterations in soil properties using spectral indices in pine stands affected by crown fire in Spain, in 2018 and 2019

sampling varied from 6 mm in Nerva and Gavilanes fires to 10 mm in La Granja Fire.

Laboratory measurements

In each soil sample, saturated hydraulic conductivity (*K*) was estimated by means of the Decagon model S mini disc infiltrometer (Decagon Devices, Inc., Pullman, Washington, USA) according to the following formula:

$$K = \frac{C1}{A}, \tag{1}$$

where $C1$ is the coefficient of the second-order polynomial term fitting the curve of the cumulative infiltration versus the square root of time (Zhang 1997), and A is the value relating van Genuchten parameters based on the specific soil type to the suction rate and radius of the mini disc infiltrometer (unitless; here A = 3.9099 given an estimate of the soil as a sandy loam as well as a 2.25 cm infiltrometer radius and a suction rate of −2 cm). Duration of the infiltration experiments varied with soil burn severity level, but it was stopped after the maximum run time of 10 min when necessary. The soil samples were air dried and carefully crumbled by hand into small pieces after infiltration experiments. Soil aggregates were dry sieved (Kemper and Rosenau 1986) and separated into size fractions (10 to 5 mm, 5 to 2 mm, 2 to 1 mm, 1 to 0.25 mm, 0.25 to 0.05 mm, and <0.05 mm). Percentage by weight of aggregates in each fraction was determined to enable calculation of the mean weight diameter. Soil organic carbon content of soil samples after sieving (2 mm) was

Table 1 Mean physiographic characteristics of the study sites located in each burned area to assess alterations in soil properties using spectral indices in pine stands affected by crown fire in Spain, in 2018 and 2019. Range of variation is given in parentheses. N = north, S = south, E = east, W = west

Study site	Aspect	Slope (%)	Elevation (m)
Nerva	E, N, NW, S, SE, SW	34.8 (9.1 to 51.0)	521 (404 to 640)
Gavilanes	E, SE	29.7 (19.2 to 34.6)	1176 (943 to 1329)
La Granja	E, N, NW, S, SE, SW	26.4 (16.5 to 35.2)	1728 (1521 to 1877)

determined by dry combustion in a LECO Elemental Analyzer (LECO, St. Joseph, Michigan, USA).

We obtained mean values of soil parameters (saturated hydraulic conductivity, mean weight diameter of soil aggregates, and soil organic carbon content) for each plot by multiplying the corresponding value associated with each level of soil burn severity by the frequency of each level in each plot.

Spectral indices

We calculated the spectral indices using data from Sentinel-2 satellite (Table 2) provided by the European Space Agency (ESA). Sentinel-2 is a constellation of two satellites providing high-resolution multispectral optical imagery (Drusch et al. 2012; Brown et al. 2018). All study images used were downloaded from the ESA website (Copernicus Open Access Hub, https://scihub.copernicus.eu/dhus/#/home; accessed 10 January 2019) and were Level 2A (bottom of atmosphere) reflectance images, which are atmospherically corrected (Kaufman and Sendra 1988).

Different spectral indices have been specifically designed to discriminate between different levels of affectation in surfaces affected by fire (Table 3). From images available for each burned area, we selected those from dates as close as possible to the ignition and suppression of each wildfire. Although, *a priori,* the imagery was cloud free across the study area (both before and after fires), to avoid possible errors, we performed cloud correction using the Scene Classification Image, available in Sentinel-2 Level 2A, of 20 m spatial resolution. This cloud correction is based on a series of threshold tests using the Sentinel-2 bands and their ratios, providing a classification image that is applied as a mask to the original image (Muller-Wilm et al. 2013; Gascon et al. 2017).

Statistical analysis

We used a general linear mixed model to test the effect of soil burn severity on soil properties. The values were normalized by obtaining the relative difference between the value of each soil burn severity level and the corresponding mean value for the control plots in order to compare soil burn severity levels across fires. We considered site as a random factor in the models. When significant effects ($P <$ 0.05) were indicated, post hoc pairwise comparisons (with Bonferroni adjustment for multiple comparisons) were conducted to detect differences between the main effects of treatments and their interactions. Residuals were tested for autocorrelation, normality, and homogeneity of variance.

We used linear regression to detect any possible relationships between soil burn severity and spectral indices. We log transformed the data when necessary to achieve normality. We used the R statistical package (Core Team Development 2019) for all statistical analyses.

Results

Mean values of each soil property in each experimental site and for each soil burn severity level are listed in Table 4. No samples from soil burn severity Level 1 were identified in the burned areas. Soil burn severity Levels 2 and 3 were the most frequent in the field plots. Level 4 frequency ranged from 6% in Nerva and La Granja (soil perturbation depth = 0.5 cm) to 14% in Gavilanes (soil perturbation depth = 0.5 cm). In turn, soil burn severity Level 5 was identified in 6% of the quadrats in Nerva,

Table 2 Sentinel-2 bands characteristics. Bands shown in **boldface** were used to assess alterations in soil properties in three study areas in pine stands affected by crown fire in Spain, in 2018 and 2019: Study areas, with the pre- and post-fire image dates used for each in parentheses, were: Nerva (31 Jul 2018 and 4 Oct 2018), Gavilanes (1 Jun 2019 and 31 Jul 2019), and La Granja (2 Aug 2019 and 6 Sep 2019)

Sentinel-2 band name	Central wavelength (μm)	Resolution (m)
Band 1 - Coastal Aerosol	0.433	60
Band 2 - Blue	0.490	10
Band 3 - Green	0.560	10
Band 4 - Red	**0.665**	**10**
Band 5 - Vegetation Red Edge	0.705	20
Band 6 - Vegetation Red Edge	**0.740**	**20**
Band 7 - Vegetation Red Edge	**0.783**	**20**
Band 8 – Near Infrared	**0.842**	**10**
Band 8A - Vegetation Red Edge	**0.865**	**20**
Band 9 - Water Vapor	0.945	60
Band 10 - Short Wave Infrared - Cirrus	1.375	60
Band 11 - Short Wave Infrared 1	**1.610**	**20**
Band 12 - Short Wave Infrared 2	**2.190**	**20**

Table 3 Selected spectral indices, based on Sentinel-2 bands (Table 2), used to assess alterations in soil properties in three study areas in pine stands affected by crown fire in Spain, in 2018 and 2019: Study areas, with the pre- and post-fire image dates used for each in parentheses, were: Nerva (31 Jul 2018 and 4 Oct 2018), Gavilanes (1 Jun 2019 and 31 Jul 2019), and La Granja (2 Aug 2019 and 6 Sep 2019)

Spectral index	Formula[a]	Reference
NBR Normalized Burn Ratio	$NBR = \frac{(B8 - B12)}{(B8 + B12)}$	Key and Benson (2006)
dNBR differenced Normalized Burn Ratio	$dNBR = NBR_{\text{PRE-FIRE}} - NBR_{\text{POST-FIRE}}$	Key and Benson (2006)
RdNBR Relative difference Normalized Burn Ratio	$RdNBR = \frac{dNBR}{\sqrt{\frac{\lvert NBR_{\text{PRE-FIRE}}\rvert}{1000}}}$	Miller and Thode (2007)
RBR Relativized Burn Ratio	$RBR = \frac{dNBR}{(NBR_{\text{PRE-FIRE}} + 1.001)}$	Parks et al. (2014)
NDVI Normalized Difference Vegetation Index	$NDVI = \frac{(B8 - B4)}{(B8 + B4)}$	Rouse (1974)
dNDVI differenced Normalized Difference Vegetation Index	$dNDVI = NDVI_{\text{PRE-FIRE}} - NDVI_{\text{POST-FIRE}}$	Escuin et al. (2008)
BAIS2 Burned Area Index for Sentinel-2	$BAIS2 = (1 - \sqrt{\frac{B6 \times B7 \times B8A}{B4}}) \times (\frac{B12 - B8A}{\sqrt{B12 - B8A}} + 1)$	Filipponi (2018)
dBAIS2 difference Burned Area Index for Sentinel-2	$dBAIS2 = BAIS2_{\text{PRE-FIRE}} - BAIS2_{\text{POST-FIRE}}$	Filipponi (2018)
MIRBI Mid-Infrared Burn Index	$MIRBI = 10 \times B11 - 9.8 \times B12$	Trigg and Flasse (2001)
dMIRBI difference Mid-Infrared Burn Index	$dMIRBI = MIRBI_{\text{PRE-FIRE}} - MIRBI_{\text{POST-FIRE}}$	Tran et al. (2018)

[a] Central wavelength (µm) of Sentinel-2 bands used in the formulae: *B*4 = Red; *B*6 = Vegetation Red Edge, *B*7 = Vegetation Red Edge; *B*8 =Near Infrared, *B*8*A* = Vegetation Red Edge; *B*11 = Short Wave Infrared 1; *B*12 = Short Wave Infrared 2 (Table 2)

Table 4 Mean values of selected soil properties according to the level of soil burn severity in each burned area affected by crown fire in Spain, in 2018 and 2019. The values of adjacent unburned controls are also presented. The levels of fire severity varied from low (Level 2) to extreme (Level 6) following the classification by Fernández and Vega (2016). Standard error in parentheses

Wildfire	Soil burn severity level	Saturated hydraulic conductivity (mm h^{-1})	Weight diameter of soil aggregates (mm)	Soil organic carbon content (%)
Nerva	Unburned control	3.2 (1.6)	0.94 (0.01)	7.3 (0.1)
	Level 2	1.5 (0.4)	0.85 (0.04)	4.9 (0.2)
	Level 3	1.0 (0.3)	0.83 (0.10)	3.8 (0.1)
	Level 4	6.1 (3.1)	0.66 (0.03)	1.9 (0.3)
	Level 5	13.5 (2.2)	0.61 (0.02)	1.8 (0.1)
	Level 6	31.1 (0.9)	0.60 (0.01)	1.8 (0.1)
Gavilanes	Unburned control	3.5 (0.1)	1.04 (0.06)	7.6 (0.7)
	Level 2	3.2 (0.3)	1.10 (0.10)	5.7 (0.1)
	Level 3	2.7 (0.2)	0.76 (0.05)	4.0 (0.4)
	Level 4	10.4 (1.3)	0.64 (0.01)	2.8 (0.3)
	Level 5	14.0 (1.4)	0.61 (0.01)	1.3 (0.1)
	Level 6	27.1 (6.2)	0.57 (0.01)	1.1 (0.1)
La Granja	Unburned control	2.8 (1.2)	1.34 (0.07)	10.8 (0.9)
	Level 2	1.8 (0.9)	0.71 (0.09)	8.3 (0.1)
	Level 3	1.7 (0.8)	0.66 (0.01)	7.9 (0.1)
	Level 4	27.5 (5.4)	0.63 (0.01)	4.2 (0.1)
	Level 5	51.1 (25.2)	0.59 (0.01)	3.0 (0.4)
	Level 6	58.9 (12.6)	0.57 (0.03)	1.4 (0.2)

8% in Gavilanes, and 13% in La Granja. Only 1% of the quadrats were classified as Level 6 during sampling in the three study sites, with a mean soil perturbation depth of 1.5 cm.

The saturated hydraulic conductivity of unburned soils was around 3 mm h^{-1} in all cases (Table 4). In soils affected by moderate levels of soil burn severity (Levels 2 and 3), a similar and negative relative change was observed (Fig. 2).

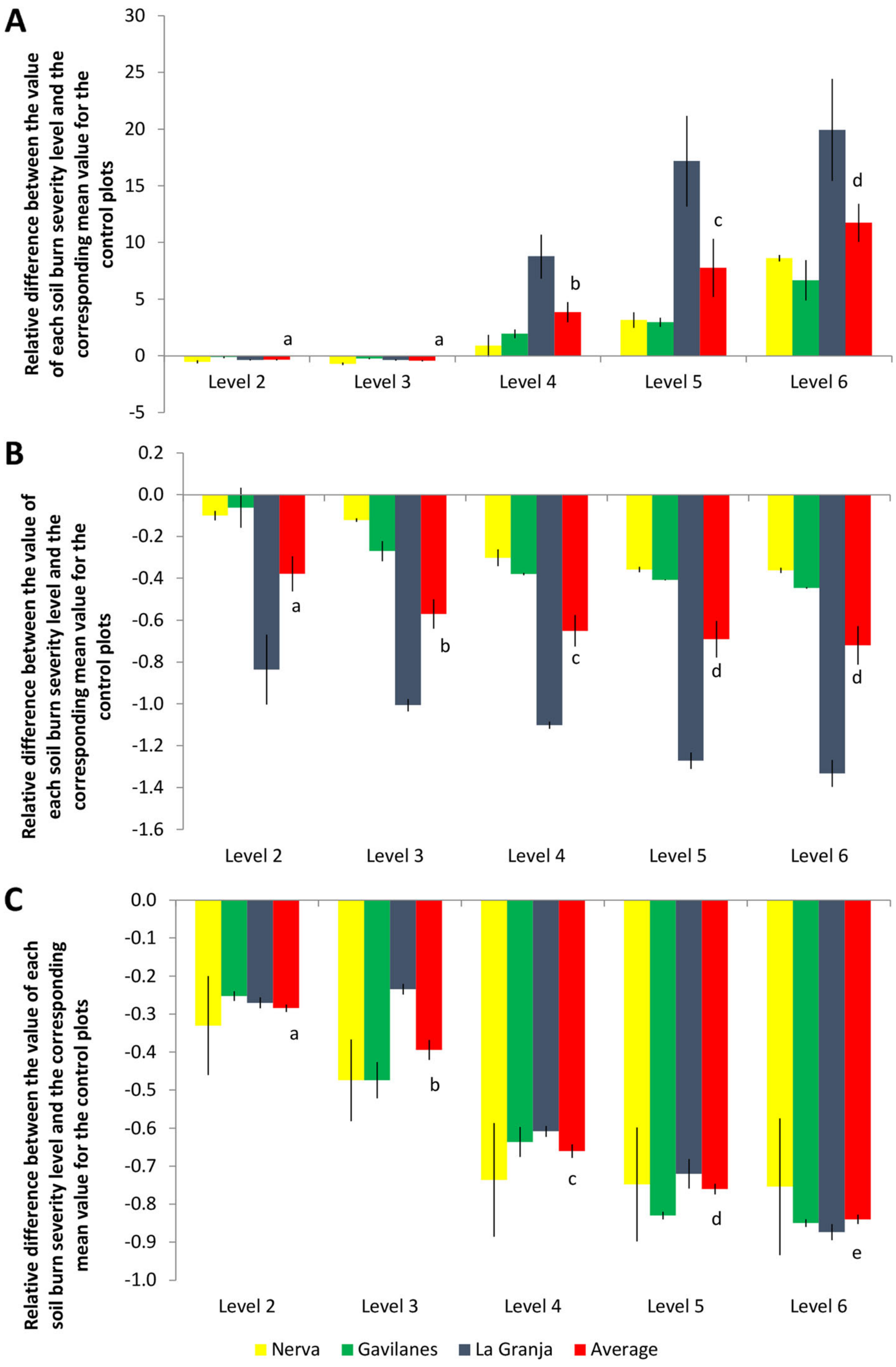

Fig. 2 Relative difference between the value of each soil burn severity level and the corresponding mean value for the control plots for (**A**) soil saturated conductivity, (**B**) mean weight diameter of soil aggregates, (**C**) and soil organic carbon measured in the set of field plots located in the burned areas affected by crown fire in Spain, in 2018 and 2019. Mean values are represented for each study site and for the average of the three study sites. Mean values followed by the same letter are not significantly different ($P < 0.05$). The levels of fire severity varied from low (Level 2) to extreme (Level 6) following the classification by Fernández and Vega (2016). Vertical bars indicate the standard error

In the most severely burned soils (Levels 4, 5, 6), the infiltration increased gradually and significantly with soil burn severity.

The mean weight diameter of soil aggregates decreased with fire severity (Fig. 2). There were no significant differences between the most severely burned soils (Levels 5 and 6). Soil organic carbon decreased gradually and significantly with soil burn severity (Fig. 2).

The significant correlations between the spectral indices and the mean soil parameters are listed in Table 5. The relativized burn ratio (RBR) was the best predictor of saturated hydraulic conductivity and mean weight diameter of soil aggregates. The relationships between the indices and soil organic carbon were weaker in most cases (Table 5), but the best predictor was the differenced mid-infrared bilateral index (dMIRBI), with R^2 and root mean square error equal to 0.548 and 0.087, respectively. The NBR spectral index performed similarly for the three variables analyzed (Table 5).

Discussion

Our study demonstrated that the proposed soil burn severity categories, based on visual signs, are useful for inferring the degree of alteration of three important soil physical properties. In terms of indicating a difference relative to the unburned soil, the best performance was observed for soil organic carbon content, as previously observed in northwest Spain by Vega et al. (2013). As soil organic matter is the principal binding agent in these coarse-textured granitic soils (Benito and Díaz-Fierros 1989; García-Corona et al. 2004), high soil burn severity levels are expected to be associated with decreased soil aggregate stability, as observed in our study. Regarding saturated hydraulic conductivity, our findings are similar to those of Wieting et al. (2017), who reported that this parameter was almost seven times higher in severely burned soils than in soils affected by a low level of burn severity. Soil saturated hydraulic conductivity mimicked the changes in soil water repellency, confirming that this parameter reaches maximum values at lower levels of burn severity (Benito et al. 2009; Fernández et al. 2019).

Information that would enable comparison of the correlations between spectral indices and soil parameters is scarce. Moody et al. (2016) observed significant and positive correlations between differenced Normalized Burn Ratio (dNBR) and some soil hydraulic properties for a burned area in Colorado, USA. In contrast to the observations made in our study, these authors found that soil infiltration decreased with increased fire severity. In our study, RBR performed better for the selected variables than dNBR, as observed by Parks et al. (2014) with CBI as an indicator of fire severity. The Mid-Infrared Burnt Index (MIRBI) and the Burned Area Index for Sentinel-2 (BAIS2) indices have been successfully used to determine differences in canopy cover as a consequence of fire (Filipponi 2018; McCarley et al. 2018). The findings of our study show that dMIRBI may also be a good index for quantifying changes in soil properties after fire, although further research is necessary to confirm this. The findings indicated that relativized metrics are better at detecting high severity effects in large geographic areas, as suggested by Parks et al. (2014).

Conclusions

Our study findings showed that the proposed categories of soil burn severity, based on visual signs, are useful for reflecting gradual changes in some soil variables that play a critical role in post-fire soil erosion susceptibility. The visual indicators were better for inferring the degree of degradation of the soil organic carbon content.

Table 5 Relationships between spectral indices and each soil property considered (transformed in logarithms) for the set of field plots located in the burned areas affected by crown fire in Spain, in 2018 and 2019. RMSE = root mean square error. See Table 3 for spectral index names

Spectral index	Soil saturated hydraulic conductivity (mm h^{-1})		Mean weight diameter of soil aggregates (mm)		Soil organic carbon content (%)	
	RMSE	R^2	RMSE	R^2	RMSE	R^2
BAIS2	0.263	0.548	0.030	0.531	0.100	0.406
dBAIS2	0.260	0.557	0.026	0.649	0.102	0.374
MIRBI	0.258	0.564	0.028	0.582	0.094	0.467
dMIRBI	0.280	0.486	0.029	0.563	0.087	0.548
NBR	0.264	0.544	0.028	0.588	0.090	0.511
dNBR	0.277	0.499	0.031	0.499	0.110	0.272
NDVI	0.286	0.464	0.034	0.404	0.114	0.224
dNDVI	0.379	0.058	0.043	0.039	0.129	0.005
RBR	0.251	0.588	0.028	0.595	0.098	0.422
RdNBR	0.373	0.062	0.044	0.112	0.155	0.328

The close relationship between the RBR and cumulative infiltration and mean weight diameter of soil aggregates, and between the dMIRBI and soil organic carbon content appears to be a consequence of the information provided by the Short-Wave Infrared (SWIR) spectral band.

Our study findings show the potential ability of spectral indices to reflect changes in some properties related to soil erosion susceptibility, although more data from different ecosystems is required to confirm the performance of each.

However, the variability found between sites in both soil properties and spectral index values seems to indicate the difficulty of establishing overall ranges of variation.

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Authors' contributions

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Availability of data and materials

The datasets used or analyzed during this study will be made available upon reasonable request.

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Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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References

Benavides-Solorio, J., and L.H. MacDonald. 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* 14: 457–474 https://doi.org/10.1071/WF05042.

Benito, E., and F. Díaz-Fierros. 1989. Estudio de los principales factores que intervienen en la estabilidad estructural de los suelos de Galicia. *Anales de Edafología y Agrobiología* 48: 229–253.

Benito E, Soto B, Varela ME, Rodríguez-Alleres M, Rodríguez-Suárez JA (2009) Modificaciones inducidas por los incendios forestales en las propiedades físicas de los suelos del noroeste de España: implicaciones en la respuesta hidrológica y en la erosión hídrica. In: Cerdá A, Mataix-Solera J (eds) Efectos de los incendios forestales sobre los suelos en España. El estado de la cuestión visto por los científicos españoles. Cátedra Divulgación de la Ciencia. Universitat de València, Valencia, pp 303-324

Brown, A.R., G.P. Petropoulos, and K.P. Ferentinos. 2018. Appraisal of the Sentinel-1 & 2 use in a large-scale wildfire assessment: A case study from Portugal's fires of 2017. *Applied Geography* 100: 78–89 https://doi.org/10.1016/j.apgeog.2018.10.004.

Cansler, C.A., and D. McKenzie. 2012. How Robust Are Burn Severity Indices When Applied in a New Region? Evaluation of Alternate Field-Based and Remote-Sensing Methods. *Remote Sensing* 4 (2): 456–483 https://doi.org/10.3390/rs4020456.

Cantón, Y., A. Solé-Benet, C. Asensio, S. Chamizo, and J. Puigdefábregas. 2009. Aggregate stability in range sandy loam soils Relationships with runoff and erosion. *Catena* 77 (3): 192–199. https://doi.org/10.1016/j.catena.2008.12.011.

Cawson JG, Sheridan GJ, Smith HG, Lane PNJ (2013) Effects of fire severity and burn patchiness on hillslope-scale surface runoff, erosion and hydrologic connectivity in a prescribed burn. Forest Ecology and Management 310 (0): 219-233. doi:https://doi.org/10.1016/j.foreco.2013.08.016.

Cerdà A, Doerr SH (2008) The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. Catena 74 (3): 256-263. doi: https://doi.org/10.1016/j.catena.2008.03.010.

Core Team Development (2019) R: A language and environment for statistical computing, in R Foundation for Statistical Computing, Vienna.

De Santis, A., and E. Chuvieco. 2009. GeoCBI: A modified version of the Composite Burn Index for the initial assessment of the short-term burn severity from remotely sensed data. *Remote Sensing of Environment* 113 (3): 554–562. https://doi.org/10.1016/j.rse.2008.10.011.

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews* 51 (1): 33–65. https://doi.org/10.1016/S0012-8252(00)00011-8.

Drusch, M., U. Del Bello, S. Carlier, O. Colin, V. Fernandez, F. Gascon, B. Hoersch, C. Isola, P. Laberinti, P. Martimort, A. Meygret, F. Spoto, O. Sy, F. Marchese, and P. Bargellini. 2012. Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sensing of Environment* 120: 25–36. https://doi.org/10.1016/j.rse.2011.11.026.

Ebel BA, Moody JA, Martin DA (2012) Hydrologic conditions controlling runoff generation immediately after wildfire. Water Resources Research 48 (3):n/a-n/a. doi:https://doi.org/10.1029/2011wr011470.

Ebel, B.A., F.K. Rengers, and G.E. Tucker. 2016. Observed and simulated hydrologic response for a first-order catchment during extreme rainfall 3 years after wildfire disturbance. *Water Resources Research* 52 (12): 9367–9389. https://doi.org/10.1002/2016wr019110.

Escuin, S., R. Navarro, and P. Fernández. 2008. Fire severity assessment by using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) derived from LANDSAT TM/ETM images. *International Journal of Remote Sensing* 29 (4): 1053–1073. https://doi.org/10.1080/01431160701281072.

Fernández, C., T. Fontúrbel, and J.A. Vega. 2019. Wildfire burned soil organic horizon contribution to runoff and infiltration in a Pinus pinaster forest soil. *Journal of Forest Research* 24 (2): 86–92. https://doi.org/10.1080/13416979.2019.1572091.

Fernández, C., and J.A. Vega. 2016. Modelling the effect of soil burn severity on soil erosion at hillslope scale in the first year following wildfire in NW Spain. *Earth Surface Processes and Landforms* 41 (7): 928–935. https://doi.org/10.1002/esp.3876.

Fernández, C., J.A. Vega, and T. Fontúrbel. 2016. Reducing post-fire soil erosion from the air: Performance of heli-mulching in a mountainous area on the coast of NW Spain. *Catena* 147: 489–495. https://doi.org/10.1016/j.catena.2016.08.005.

Fernández, C., J.A. Vega, and T. Fontúrbel. 2020. Comparison of the effectiveness of needle cast and straw helimulching for reducing soil erosion after wildfire in NW Spain. *J Soils Sediments* 20 (1): 535–541. https://doi.org/10.1007/s11368-019-02419-y.

Filipponi F. (2018) BAIS2: Burned Area Index for Sentinel-2. in Multidisciplinary Digital Publishing Institute Proceedings (Vol. 2, No. 7, p. 364). https://doi.org/10.3390/ecrs-2-05177

García-Corona, R., E. Benito, E. de Blas, and M.E. Varela. 2004. Effects of heating on some soil physical properties related to its hydrological behaviour in two north-western Spanish soils. *International Journal of Wildland Fire* 13: 195–199 https://doi.org/10.1071/WF03068.

Gascon, F., C. Bouzinac, O. Thépaut, M. Jung, B. Francesconi, J. Louis, V. Lonjou, B. Lafrance, S. Massera, A. Gaudel-Vacaresse, F. Languille, B. Alhammoud, F.

Viallefont, B. Pflug, J. Bieniarz, S. Clerc, L. Pessiot, T. Trémas, E. Cadau, R. De Bonis, C. Isola, P. Martimort, and V. Fernandez. 2017. Copernicus Sentinel-2A Calibration and Products Validation Status. *Remote Sensing* 9 (6): 584 https://doi.org/10.3390/rs9060584.

Harris, M.P.K., K.A. Allen, H.A. McAllister, G. Eyre, M.G. Le Duc, and R.H. Marrs. 2011. Factors affecting moorland plant communities and component species in relation to prescribed burning. *Journal of Applied Ecology* 48 (6): 1411–1421. https://doi.org/10.1111/j.1365-2664.2011.02052.x.

Holden, Z.A., P. Morgan, and J.S. Evans. 2009. A predictive model of burn severity based on 20-year satellite-inferred burn severity data in a large southwestern US wilderness area. *Forest Ecology and Management* 258 (11): 2399–2406. https://doi.org/10.1016/j.foreco.2009.08.017.

Hudak, A.T., P. Morgan, M.J. Bobbitt, A.M.S. Smith, S.A. Lewis, L.B. Lentile, P.R. Robichaud, J.T. Clark, and R.A. McKinley. 2007. The Relationship of Multispectral Satellite Imagery to Immediate Fire Effects. *Fire Ecology* 3 (1): 64–90. https://doi.org/10.4996/fireecology.0301064.

Huffman, E.L., L.H. MacDonald, and J.D. Stednick. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes* 15: 2877–2892 https://doi.org/10.1002/hyp.379.

Jain TB, Graham RT (2007) The Relation Between Tree Burn Severity and Forest Structure in the Rocky Mountains. Paper presented at the 2005 National Selviculture Workshop

Jain TB, Graham RT, Pilliod DS (2004) Tongue-tied: Confused meanings for common fire terminology can lead to fuels mismanagement. Wildfire July/August: 22-26

Kaufman, Y., and C. Sendra. 1988. Algorithm for automatic atmospheric corrections to visible and near-IR satellite imagery. *International Journal of Remote Sensing* 9: 1357–1381 https://doi.org/10.1080/01431168808954942.

Kemper WD, Rosenau RC (1986) Aggregate stability and size distribution. In: Klute A (ed) Methods of soil analysis. Part 1. Physical and Mineralogical Methods. American Society of Agronomy, Inc. Soil Science Society of America, Inc., Madison, Wisconsin USA, pp 425-442. https://doi.org/10.2136/sssabookser5.1.2ed.c17

Key CH, Benson NC (2006) Landscape Assessment: Ground measure of severity, the Composite Burn Index; and Remote sensing of severity, the Normalized Burn Ratio. FIREMON: Fire Effects Monitoring and Inventory System. Odgen, UT

Lentile, L.B., Z.A. Holden, A.M.S. Smith, M.J. Falkowski, A.T. Hudak, P. Morgan, S.A. Lewis, P.E. Gessler, and N.C. Benson. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire* 15 (3): 319–345. https://doi.org/10.1071/WF05097.

Lentile, L.B., A.M.S. Smith, A.T. Hudak, P. Morgan, M.J. Bobbitt, S.A. Lewis, and P.R. Robichaud. 2009. Remote sensing for prediction of 1-year post-fire ecosystem condition. *International Journal of Wildland Fire* 18 (5): 594–608. https://doi.org/10.1071/WF07091.

Lewis, S.A., J.Q. Wu, and P.R. Robichaud. 2006. Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. *Hydrological Processes* 20 (1): 1–16. https://doi.org/10.1002/hyp.5880.

López A, López M, cords (2019) Los incendios forestales en España. Decenio 2006-2015. Ministerio de Agricultura, Pesca y Alimentación, Madrid, 160 pp.

Marcos, E., V. Fernández-García, A. Fernández-Manso, C. Quintano, L. Valbuena, R. Tárrega, E. Luis-Calabuig, and L. Calvo. 2018. Evaluation of Composite Burn Index and Land Surface Temperature for Assessing Soil Burn Severity in Mediterranean Fire-Prone Pine Ecosystems. *Forests* 9 (8): 494 https://doi.org/10.3390/f9080494.

Mataix-Solera, J., A. Cerdà, V. Arcenegui, A. Jordán, and L.M. Zavala. 2011. Fire effects on soil aggregation: A review. *Earth-Science Reviews* 109 (1-2): 44–60. https://doi.org/10.1016/j.earscirev.2011.08.002.

McCarley, T.R., A.M.S. Smith, C.A. Kolden, and J. Kreitler. 2018. Evaluating the Mid-Infrared Bi-spectral Index for improved assessment of low-severity fire effects in a conifer forest. *International Journal of Wildland Fire* 27 (6): 407–412. https://doi.org/10.1071/WF17137.

Miller, J.D., E.E. Knapp, C.H. Key, C.N. Skinner, C.J. Isbell, R.M. Creasy, and J.W. Sherlock. 2009. Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. *Remote Sensing of Environment* 113 (3): 645–656. https://doi.org/10.1016/j.rse.2008.11.009.

Miller, J.D., and A.E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment* 109 (1): 66–80 https://doi.org/10.1016/j.rse.2006.12.006.

Moody, J.A., and B.A. Ebel. 2012. Hyper-dry conditions provide new insights into the cause of extreme floods after wildfire. *Catena* 93: 58–63. https://doi.org/10.1016/j.catena.2012.01.006.

Moody, J.A., B.A. Ebel, P. Nyman, D.A. Martin, C. Stoof, and R. McKinley. 2016. Relations between soil hydraulic properties and burn severity. *International Journal of Wildland Fire* 25 (3): 279–293. https://doi.org/10.1071/WF14062.

Moody, J.A., R.A. Shakesby, P.R. Robichaud, S.H. Cannon, and D.A. Martin. 2013. Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews* 122: 10–37. https://doi.org/10.1016/j.earscirev.2013.03.004.

Morgan, P., R.E. Keane, G.K. Dillon, T.B. Jain, A.T. Hudak, E.C. Karau, P.G. Sikkink, Z.A. Holden, and E.K. Strand. 2014. Challenges of assessing fire and burn severity using field measures, remote sensing and modelling. *International Journal of Wildland Fire* 23 (8): 1045–1060. https://doi.org/10.1071/WF13058.

Muller-Wilm U, Louis J, Richter R, Gascon F, Niezette M (2013) Sentinel-2 level 2A prototype processor: Architecture, algorithms and first results. Proceedings of the ESA Living Planet Symposium, Edinburgh, UK (pp. 9-13).

Neris, J., S. Doerr, J. Notario del Pino, C. Arbelo, and A. Rodríguez-Rodríguez. 2017. Effectiveness of Polyacrylamide, Wood Shred Mulch, and Pine Needle Mulch as Post-Fire Hillslope Stabilization Treatments in Two Contrasting Volcanic Soils. *Forests* 8 (7): 247 https://doi.org/10.3390/f8070247.

Parks, S., G. Dillon, and C. Miller. 2014. A new metric for quantifying burn severity: the relativized burn ratio. *Remote Sensing* 6 (3): 1827–1844 https://doi.org/10.3390/rs6031827.

Picotte, J.J., and K.M. Robertson. 2011. Validation of remote sensing of burn severity in south-eastern US ecosystems. *International Journal of Wildland Fire* 20 (3): 453–464. https://doi.org/10.1071/WF10013.

Rouse, J.W. 1974. *Monitoring the vernal advancement of retrogradation of natural vegetation*. Type III. Final Report: NASA/GSFG.

Ruiz del Castillo, J. 1979. *Arboles y arbustos de la España peninsular*, 512. Madrid: Servicio publicaciones ETS Ingenieros de Montes.

San-Miguel-Ayanz, J., D. Tracy, R. Boca, G. Libertà, A. Branco, D. de Rigo, D. Ferrari, P. Maianti, T. Artés Vivancos, H. Costa, F. Lana, P. Löffler, D. Nuijten, A.C. Ahlgren, and T. Leray. 2018. *Forest Fires in Europe, Middle East and North Africa 2017*. Ispra: UE JRC.

Schmeer, S.R., S.K. Kampf, L.H. MacDonald, J. Hewitt, and C. Wilson. 2018. Empirical models of annual post-fire erosion on mulched and unmulched hillslopes. *Catena* 163: 276–287. https://doi.org/10.1016/j.catena.2017.12.029.

Smith, A.M.S., A.M. Sparks, C.A. Kolden, J.T. Abatzoglou, A.F. Talhelm, D.M. Johnson, L. Boschetti, J.A. Lutz, K.G. Apostol, K.M. Yedinak, W.T. Tinkham, and R.J. Kremens. 2016. Towards a new paradigm in fire severity research using dose-response experiments. *International Journal of Wildland Fire* 25 (2): 158–166. https://doi.org/10.1071/WF15130.

Sobrino, J.A., R. Llorens, C. Fernández, J.M. Fernández-Alonso, and J.A. Vega. 2019. Relationship between Forest Fires Severity Measured in Situ and through Remotely Sensed Spectral Indices. *Forests* 10 (5): 457 https://doi.org/10.3390/f10050457.

Soverel, N.O., D.D.B. Perrakis, and N.C. Coops. 2010. Estimating burn severity from Landsat dNBR and RdNBR indices across western Canada. *Remote Sensing of Environment* 114 (9): 1896–1909. https://doi.org/10.1016/j.rse.2010.03.013.

Tran, B.N., M.A. Tanase, L.T. Bennett, and C. Aponte. 2018. Evaluation of Spectral Indices for Assessing Fire Severity in Australian Temperate Forests. *Remote Sensing* 10 (11): 1680 https://doi.org/10.3390/rs10111680.

Trigg, S., and S. Flasse. 2001. An evaluation of different bi-spectral spaces for discriminating burned shrub-savannah. *International Journal of Remote Sensing*. 22 (13): 2641–2647 https://doi.org/10.1080/01431160110053185.

van Wagtendonk, J.W., R.R. Root, and C.H. Key. 2004. Comparison of AVIRIS and Landsat ETM+ detection capabilities for burn severity. *Remote Sensing of Environment* 92 (3): 397–408. https://doi.org/10.1016/j.rse.2003.12.015.

Vega, J.A., C. Fernández, and T. Fonturbel. 2005. Throughfall, runoff and soil erosion after prescribed burning in gorse shrubland in Galicia (NW Spain). *Land Degradation and Development* 15: 1–15 https://doi.org/10.1002/ldr.643.

Vega, J.A., M.T. Fontúrbel, A. Merino, C. Fernández, A. Ferreiro, and E. Jiménez. 2013. Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical and microbial properties in pine forests and shrubland. *Plant and Soil* 369: 73–91. https://doi.org/10.1007/s11104-012-1532-9.

Veraverbeke, S., S. Harris, and S. Hook. 2011. Evaluating spectral indices for burned area discrimination using MODIS/ASTER (MASTER) airborne simulator data. *Remote Sensing of Environment* 115 (10): 2702–2709. https://doi.org/10.1016/j.rse.2011.06.010.

Veraverbeke, S., S. Hook, and G. Hulley. 2012. An alternative spectral index for rapid fire severity assessments. *Remote Sensing of Environment* 123: 72–80. https://doi.org/10.1016/j.rse.2012.02.025.

Wieting, C., B.A. Ebel, and K. Singha. 2017. Quantifying the effects of wildfire on changes in soil properties by surface burning of soils from the Boulder Creek Critical Zone Observatory. *Journal of Hydrology: Regional Studies* 13: 43–57. https://doi.org/10.1016/j.ejrh.2017.07.006.

Zhang, R. 1997. Determination of Soil Sorptivity and Hydraulic Conductivity from the Disk Infiltrometer. *Soil Science Society of America Journal* 61 (4): 1024–1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x.

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