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Using remote sensing to determine the effects of soil burn severity on soil properties. A case study of the 2021 Sierra Bermeja fire (S. Spain)

Cambios en las propiedades del suelo en función de la severidad del fuego en el suelo utilizando teledetección. Un caso de estudio en el incendio de Sierra Bermeja (S. España) de 2021

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Abstract

Assessment of the magnitude of change in soil erodibility, which varies depending on soil burn severity, is a critical step in post-fire restoration planning. Evaluation of post fire soil burn severity currently relies on field surveys, because the relationships between spectral indices and alterations in soil properties have scarcely been explored until now. A fire severity assessment was carried out after by a forest fire in October 2021 in Sierra Bermeja (S Spain). Several soil properties (mean weight diameter of soil aggregates, soil organic carbon and soil water repellency) were analyzed in relation to different levels of soil burn severity, at two soil depths (0-1 cm and 1-2 cm). In addition, for each sample plot, different spectral indices were computed using Sentinel-2 satellite data.

The mean weight diameter of soil aggregates and soil organic carbon decreased with soil burn severity in the surface layer (0-1 cm), but not at 1-2 cm depth. Soil water repellency was not observed in the soil surface at the higher levels of soil burn severity.

Burned Area Index for Sentinel-2 (BAIS2) was the best predictor of the mean weight diameter of soil aggregates and soil organic carbon. No correlations were obtained for soil water repellency.

The study findings confirm the importance of evaluating soil burn severity for planning post-fire restoration activities and show that the most significant changes in soil properties take place in the upper soil layer (0-1 cm). Although remote sensing techniques can help in the evaluation of soil burn severity, field evaluation are still required.

Key words: *soil organic carbon; soil water repellency; soil aggregate stability; spectral indices*

Resumen

La evaluación de los cambios en el suelo en función de la severidad es un paso crítico en la planificación de las acciones de restauración pero depende de muestreos de campo, ya que su posible relación con índices espectrales apenas se han explorado hasta ahora. En este trabajo se ha realizado una evaluación de la severidad del fuego tras un incendio forestal en Sierra Bermeja (S de España). Se analizaron varias propiedades del suelo indicadoras de su erodibilidad en relación con diferentes niveles de severidad del fuego en el suelo, a dos profundidades (0-1 cm y 1-2 cm). Además, para cada parcela de muestreo, se calcularon diferentes índices espectrales.

El diámetro medio de los agregados y el carbono orgánico del suelo disminuyeron con la severidad del fuego en el suelo solo en el estrato más superficial. No se detectó repelencia al agua del suelo en la superficie del suelo en los niveles más altos de severidad.

El Burned Area Index para Sentinel-2 (BAIS2) fue el mejor predictor del diámetro medio del peso de los agregados del suelo y del carbono orgánico del suelo.

Los resultados del estudio confirman la importancia de evaluar la severidad del fuego en el suelo y muestran que los cambios más significativos en las propiedades del suelo tienen lugar en el suelo más superficial. Aunque las técnicas de teledetección pueden ayudar a evaluar la severidad del fuego en el suelo, sigue siendo necesaria su evaluación sobre el terreno.

Palabras clave: *carbono orgánico del suelo, estabilidad de los agregados del suelo, índices espectrales, repelencia al agua del suelo.*

1. Introduction

Quantification of the effects of wildfire is important for clarifying the 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). Soil burn severity strongly affects erosion risk by altering key soil properties such as soil organic carbon, soil aggregation and soil water repellency (Doerr *et al.*, 2000; Vega *et al.*, 2013; Moody *et al.*, 2016; Fernández *et al.*, 2021). Fire severity is often assessed using an index that combines fire severity in vegetation and soil as a field measure for validating fire severity (Key and Benson, 2006) although vegetation and soil strata are usually affected differently by wildfire (Fernández *et al.*, 2020). However, evaluation of post fire soil burn severity relies almost completely on field surveys because, until recently, the relationships between spectral indices and soil burn severity (Sobrino *et al.*, 2019; Llorens *et al.*, 2022) and those between soil properties and spectral indices (Moody *et al.*, 2016; Fernández *et al.*, 2021) have scarcely been explored.

Previous research has demonstrated significant correlations between some soil properties (soil organic carbon, mean weight diameter of soil aggregates and soil saturated hydraulic conductivity) and different spectral indices calculated using Sentinel-2 data in burned soils developed on granite and slate substrates (Fernández *et al.*, 2021). The present study explored the relationship between the level of soil burn severity by considering three soil properties related to the susceptibility of soil to erosion following fire: soil water repellency; soil organic carbon content; and the mean weight diameter of soil aggregates. The performance of a set of spectral indexes in determining changes in these soil properties in areas where the level of fire severity on the vegetation strata was high was also tested.

2. Material and methods

2.1 Study area

The study was carried out in an area affected by the Jubrique Fire (Sierra Bermeja, Malaga, S. Spain), which burned about 8,000 ha of forest land in September 2021 *(Fig. 1)*. Climate is Mediterranean. Mean annual precipitation is 1200 and mean annual temperature is 15’6 º C. Parent material is peridotite. Soils are eutric cambisols (WSRR, 2015), moderately deep and sandy-clay textured. *Pinus pinaster* Ait. is dominant from 350 m to 1,100 m above sea level in very irregular stands. Dominant understory species are *Cistus populifolius* L., *Ulex baeticus* Boiss, *Daphne gnidium* L., *Arbutus unedo* L., *Erica scoparia* L., and *Brachypodium retusum* (Pers.) P.Beauv.

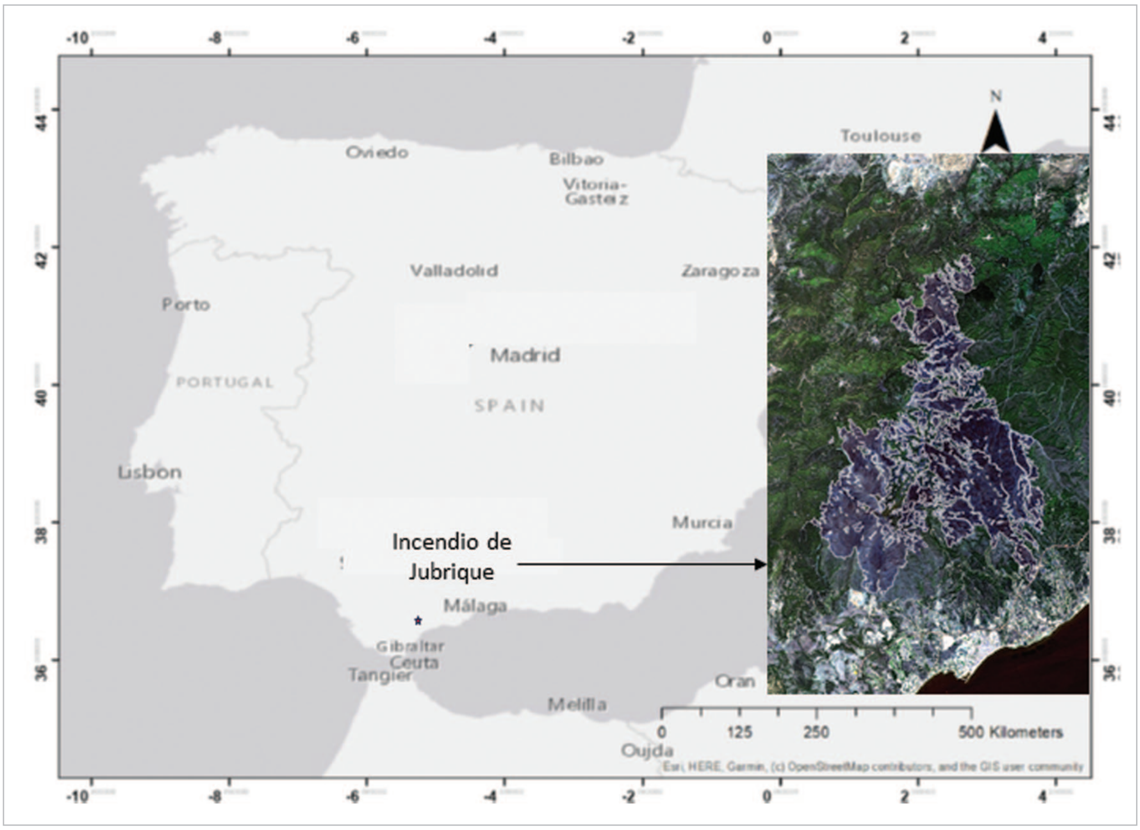

Figura 1. Location of the experimental site.

2.2 Experimental design and field sampling

Sampling sites (minimum size 60 m x 60 m) were established in *P. pinaster* stands affected by crown fire. Sites where stone cover was > 50% were avoided. In six sampling sites, the central coordinates of a plot of radius 20 m were recorded for posterior location. In each plot, the soil burn severity was assessed with the aid of a 20 cm x 20 cm quadrat, which was placed at 40 systematically selected points along two perpendicular transects. The soil in each quadrat was classified using the soil burn severity index developed by Fernández and Vega (2016), which considers six soil burn severity levels *(Tab. 1)*.

Table 1. Soil burn severity levels description.

Soil burn severity level	Description
1. Very low soil burn severity	Burnt litter (Oi) but limited duff (Oe + Oa) consumption
2. Low burn severity.	Oa layer totally charred and covering mineral soil, possibly some ash
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
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
5. Very high soil burn severity	As 4 but within a soil depth equal to or greater than 1 cm
6. Extreme soil burn severity	as 4 /5 and colour altered (reddish)

The mean depth of altered soil was 0.5 cm for level 4, 1 cm for level 5 and 1 cm for level 6. No samples of level 1 were identified during the field survey. The proportion of the transects affected by each level of soil burn severity was used to calculate a weighted mean value for each plot.

Five soil samples were collected for each level of soil burn severity identified in the six plots. The soil was sampled at two depths (0-1 cm, with the exception of soil burn severity level 4, for which samples were obtained at 0-0.5 cm and 1-2 cm). Soil sampling was carried out in October 2021, and no significant precipitation was recorded before sampling in any case. Before collecting each sample, the Water Drop Penetration Test (WDPT) was used to determine the level of soil water repellency. Briefly, eight drops of water were applied to the mineral surface of the samples from each depth. If any of the drops infiltrated the soil within 5 seconds the soil was considered hydrophilic. Soil water repellency was classified as severe when drops remained on the soil for more than 180 s (Robichaud *et al.*, 2016). The mean values of soil parameters (surface soil) for each plot were obtained by multiplying the corresponding value associated with each level of soil burn severity by the frequency of each level in each plot.

2.3 Laboratory measurements

The soil samples were air dried and carefully crumbled by hand into small pieces. Soil aggregates were dry sieved (Kemper and Rosenau, 1986) and separated into size fractions of 10-5 mm, 5-2 mm, 2-1 mm, 1-0.25 mm, 0.25-0.05 mm and <0.05 mm. The percentage by weight of aggregates in each fraction was determined to enable calculation of the mean weight diameter. The soil organic content of previously sieved (2 mm), ground samples was determined by dry combustion, in a LECO Elemental Analyzer.

2.4 Spectral Indices

The spectral indices were calculated using data from the Sentinel-2 satellite provided by the European Space Agency (ESA). All of the study images used were downloaded from the ESA website (Copernicus Open Access Hub, 2021) and are Level 2A (bottom of atmosphere [BOA]) reflectance images derived from the associated Level-1C products (Kaufman and Sendra, 1988). The spectral indices used in the present study are listed in Tab. 2. The closest (possible) images available around the ignition and suppression dates were used. Cloud correction was performed using the Scene Classification Image (Gascon *et al.*, 2017).

Table 2. Selected spectral indices.

Spectral Index	Reference
NBR = (B8 – B12)/(B8 + B12)	Key and Benson (2006)
dNBR = NBRPRE-FIRE - NBRPOST-FIRE	Key and Benson (2006)
RdNBR= dNBR/(| NBRPRE-FIRE |/1000)0.5	Miller and Thode (2007)
RBR= dNBR/(NBRPRE-FIRE + 1.001)	Parks *et al.* (2014)
BAIS2 = (1- ((B6 * B7 *B8A)/B4))0.5 * ((B12-B8A)/(B12 + B8A) 0.5) +1	Filipponi (2018)
dBAIS2 = BAIS2PRE-FIRE–BAIS2POST-FIRE	Filipponi (2018)
MIRBI=10 B11-9.8 B12	Trigg and Flasse (2001)
dMIRBI = MIRBIPRE-FIRE –MIRBIPOST-FIRE	Tran *et al.* (2018).

2.5 Statistical analysis

The effects of soil burn severity on soil properties at each depth were tested using a general linear model. 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 fire severity and their interactions. The same analysis was used to test the effect of soil depth for each soil burn severity level. Simple linear regression was used to explore the relationships between soil properties and spectral indices. Residuals were tested for autocorrelation, normality and homogeneity of variance. All of the statistical analyses were conducted using the R statistical package (Core Team Development, 2022).

3. Results

3.1 Soil burn severity and soil properties

There were no significant differences between the dry mean weight diameter of soil aggregates in the soil surface layer for soil burn severity (SBS) levels 2 and 3

(Fig. 2). The values were significantly higher than for SBS levels 5 to 6, for which there were no significant differences. For the 1-2 cm soil depth, there were no differences in this parameter at the different soil burn severity levels. The dry mean weight diameter of soil aggregates in the soil surface layer was significantly lower than at 1-2 cm depth for SBS levels 4 to 6.

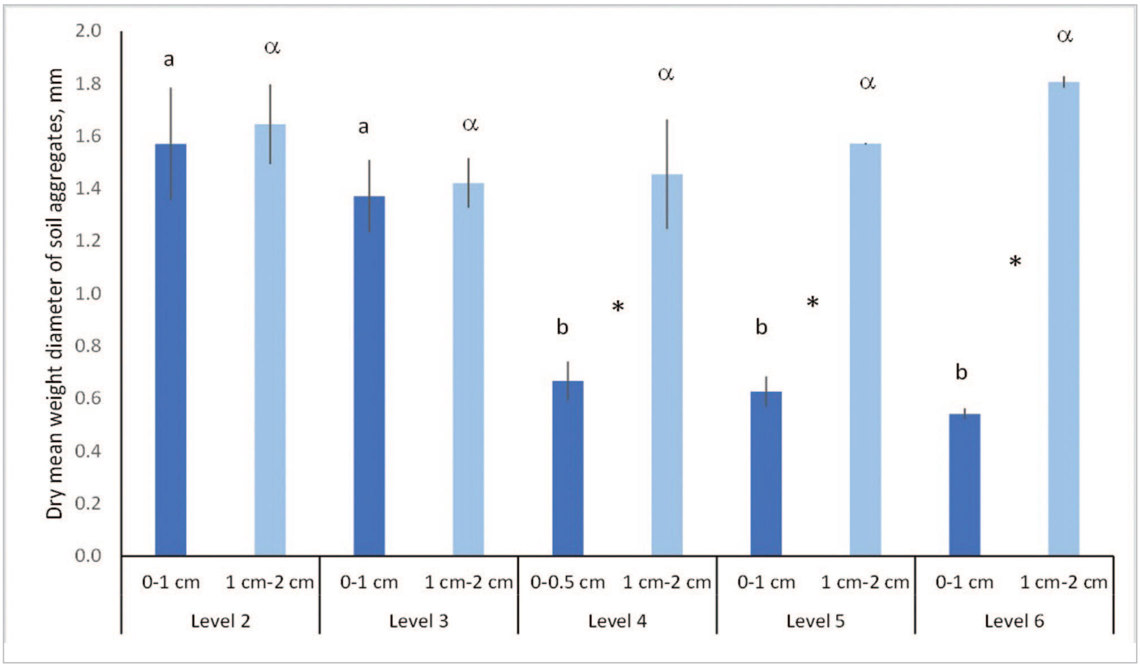

Figure 2. Mean weight diameter of soil aggregates for each soil burn severity level at two soil depths. Mean values followed by the same letter are not significantly different ($p < 0.05$). Asterisks indicate significant differences between soil depths for each soil burn severity level. Vertical bars, standard error.

Soil organic carbon content in the mineral soil surface layer was similar for SBS levels 2 and 3 but significantly higher than for SBS levels 4 to 6 *(Fig. 3)*. In this case, the soil organic content was significantly lower for SBS level 6 than SBS levels 4 and 5, between which there were no significant differences in this parameter. Again, there were no differences in soil organic content between SBS levels at 1-2 cm soil depth. The soil organic content in the soil surface layer was significantly lower than at 1-2 cm depth for SBS levels 4 to 6.

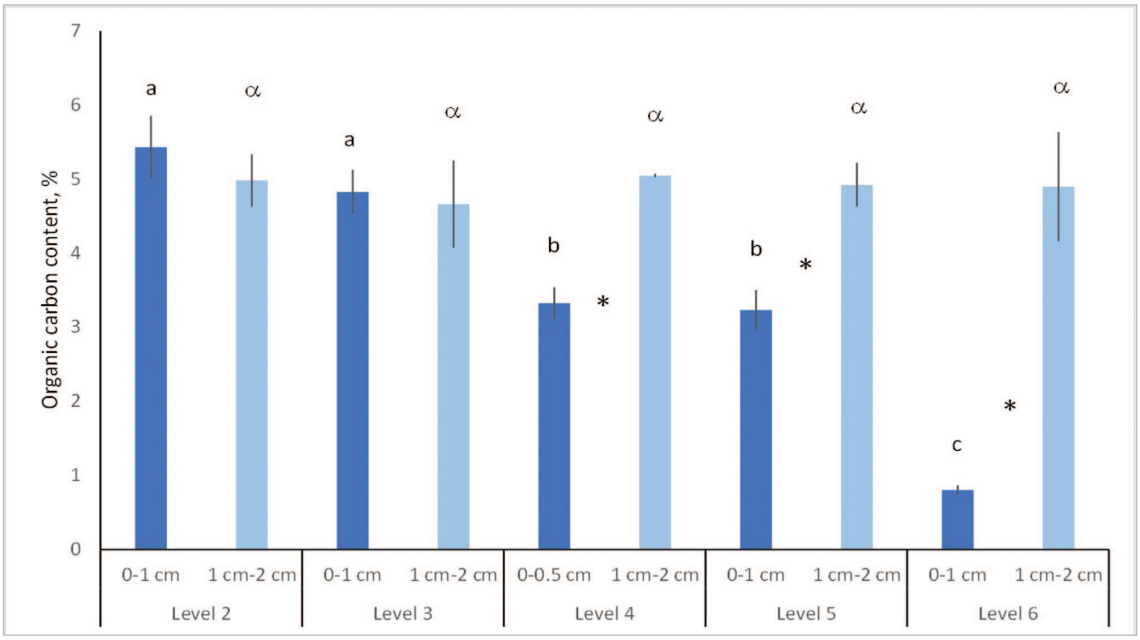

Figure 3. Mean soil organic carbon content for each soil burn severity level at two soil depths. Mean values followed by the same letter are not significantly different ($p < 0.05$). Asterisks indicate significant differences between soil depths for each soil burn severity level. Vertical bars, standard error.

In the soil surface layer, soil water repellency varied from severe for SBS levels 2 and 3 to absent (hydrophilic soil) at SBS levels 4 to 6 *(Fig. 4)*. The level of soil water repellency was severe for all SBS levels at 1-2 cm depth.

3.2 Spectral indices and soil properties

Mean soil burn severity in the field plots was moderate (3.0), ranging from low to high (2.2-4.5). The significant correlations between the spectral indices and the mean soil parameters are listed in *Tab. 2*. BAIS2 was the best predictor of the mean weight diameter of soil aggregates and soil organic carbon. Similar, although weaker, correlations with the MIRBI index were observed. Soil water repellency was not significantly correlated with any of the indexes considered.

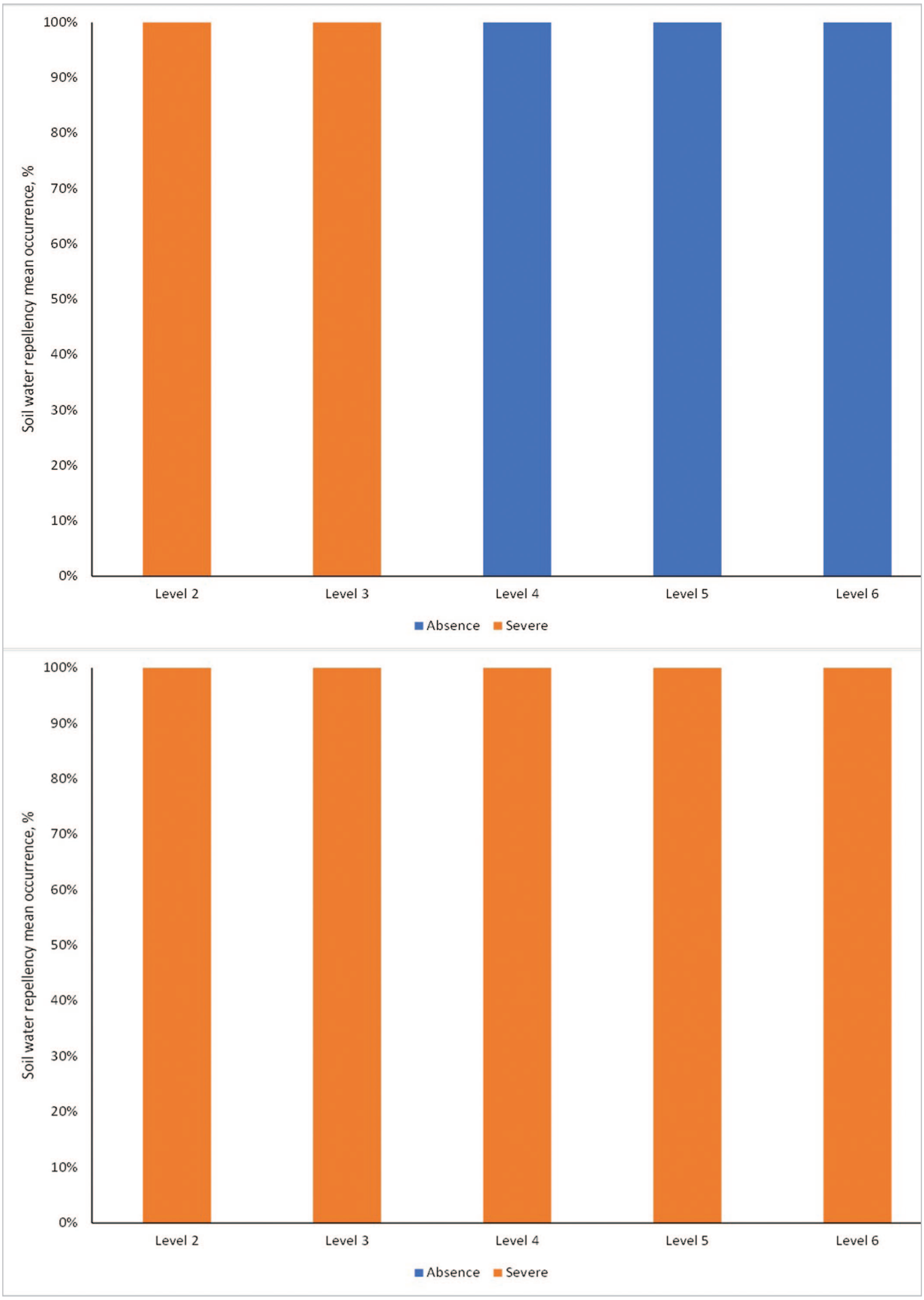

Figure 4. Mean occurrence and level of soil water repellency in the surface mineral soil (upper bar chart) and below 1 cm depth (lower bar chart).

Table 3. Significant relationships between spectral indices and soil properties measured in field plots.

	Mean weight diameter of soil aggregates (mm)		**Soil organic carbon content (%)**		**Soil water repellency**	
Spectral Index	RMSE	R^2	RMSE	R^2	RMSE	R^2
BAIS2	0.182	0.647	0.455	0.719	---	---
dBAIS2	---	---	---	---	---	---
MIRBI	0.196	0.591	0.512	0.644	---	---
dMIRBI	---	---	---	---	---	---
NBR	---	---	0.505	0.654	---	---
dNBR	---	---	---	---	---	---
RBR	---	---	---	---	---	---
RdNBR	---	---	---	---	---	---

4. Discussion

4.1 Soil burn severity and soil properties

The proposed soil burn severity index seems suitable for reflecting soil organic carbon contents in the conditions under study, as previously observed in other burned areas (Vega *et al.*, 2013; Fernández *et al.*, 2021). Although the soil aggregate stability decreased as soil burn severity increased, no differences were observed at the higher levels of soil burn severity. This result contrasts with previous findings (Fernández *et al.*, 2016; Fernández *et al.*, 2021) and may be related to differences in the depth of soil sampling. The different soil burn severity levels did not have different effects at 1cm-2cm depth. The lack of differences in the effects of SBS levels 4 and 5 is probably also associated with the depth at the altered soil surface was sampled (0.5 cm vs 1 cm).

Regarding soil water repellency, the study findings confirm that this parameter reaches maximum values at lower levels of burn severity (Benito *et al.*, 2009 Fernández *et al.*, 2019).

4.2 Spectral indices and soil properties

Information that enables comparison of the correlations between spectral indices and soil parameters is scarce. Moody *et al.* (2016) observed significant and positive correlations between dNBR and some soil hydraulic properties for a burned area in Colorado. Fernández *et al.* (2021) found that dMIRBI and dBAIS2 were useful for quantifying changes in soil properties after fire. However, in the present study the post-fire values were intermediate, and the relativized metrics did not yield any significant findings.

5. Conclusions

The study findings showed that the proposed categories of soil burn severity, based on visual signs, are useful for reflecting gradual changes in soil organic carbon. The changes in weight mean diameter of soil aggregates and soil water repellency could only be grouped in two levels.

All of the observed changes in soil properties were detected in the surface layer, demonstrating that fire did not affect the soil below 1 cm depth.

For BAIS2 and MIRBI, the relationships with soil organic carbon content and weight diameter of soil aggregates seem to depend on the information provided by the SWIR spectral band.

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