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Prediction of soil properties immediately after fire using SAR backscatter data

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Keywords

ALOS-2; nutrients; organic carbon; radar; wildfire

Abstract

The physical sense of synthetic aperture radar (SAR) backscatter data is of particular interest for characterizing soil spatial variability in burned areas. The objective of this study was to evaluate the potential of SAR backscatter data in L-band (Advanced Land Observing Satellite-2; ALOS-2) for assessing fire effects on soil organic carbon, total nitrogen and available phosphorous immediately after wildfire in a burned landscape of the western Mediterranean Basin. ALOS-2 backscatter coefficients were used to estimate soil properties measured in the field in immediate post-fire situation through generalized linear models. The retrieval of soil properties from ALOS-2 L-band SAR backscatter data featured a high overall fit (R2 = 0.37-0.59) and low error (nRMSE = 12.7%-22.5%). ALOS-2 co-polarized channel showed the highest sensitivity to spatial variation in soil properties, and there were no noticeable under and overestimation effects. These results support the applicability of SAR sensors operating at long wavelengths for monitoring fire effects on soil properties, reducing data gathering costs within large burned landscapes.

1. Introduction

Wildfires are a frequent disturbance in the Mediterranean Basin, entailing shifts in the multifunctionality of terrestrial ecosystems as a consequence of fire impacts on the (i) composition and structure of vegetation communities (Fernández-Guisuraga et al., 2019) and (ii) soil properties, among others processes. Fire effects on physical and biochemical soil properties have been widely documented from in-situ field research (e.g. Fernández-García et al., 2019; Huerta et al., 2020). However, the identification of fire effects on soil properties through conventional methods based on field trials is not functional for assessing large burned landscapes due to the fine scale of variation of soil effects, even more when dealing with high environmental variability in plant communities.

Remote sensing techniques (RST) based on multispectral and hyperspectral passive optical data, acquired from space-borne and aerial platforms, have been extensively used for retrieving soil properties in agroforestry systems (e.g. Mirzaee et al., 2016; Gholizadeh et al., 2018). However, the remote estimation of soil properties using multispectral and hyperspectral passive optical sensors might be limited to secondary correlations in vegetated areas, since the reflectance signal is mostly determined by top-of-canopy traits (Healey et al., 2020), and this behaviour may lead to soil properties overestimation (Angelopoulou et al., 2019). To deal with this constraint, active remote sensing data acquired by synthetic aperture radar (SAR) sensors are among the most reliable RST for digital mapping of soil properties because SAR signal can penetrate the soil through vegetation canopy, especially with increasing wavelength (Jagdhuber, 2012).

In the field of fire disturbance, SAR backscatter data have been used to map burnt area (Belenguer-Plomer et al., 2019) and fire severity (Tanase et al., 2014) with high confidence. Nonetheless, the characterization of soil spatial variability in burned landscapes leveraging SAR strengths for this purpose, remains completely unexplored. For that reason, we aimed to evaluate the potential of L-band SAR backscatter data acquired from Advanced Land Observing Satellite-2 (ALOS-2) satellite for assessing fire effects on soil properties in a burned landscape of the western Mediterranean Basin.

2. Material and methods

The study site is located within the perimeter of a wildfire that burned 9,940ha of shrubland and forest communities in the Sierra de Cabrera mountain range (N-NW Iberian Peninsula; Figure 1) between 21th and 27th August 2017. The following plant communities were affected by the wildfire: (i) gorse shrublands dominated by *Genista hystrix* Lange; (ii) heathlands dominated by *Erica australis* L.; (iii) broom shrublands dominated by *Genista florida* L.; (iv) Pyrenean oak forests dominated by *Quercus pyrenaica* Willd.; and (v) Scots pine forests dominated by *Pinus sylvestris* L.

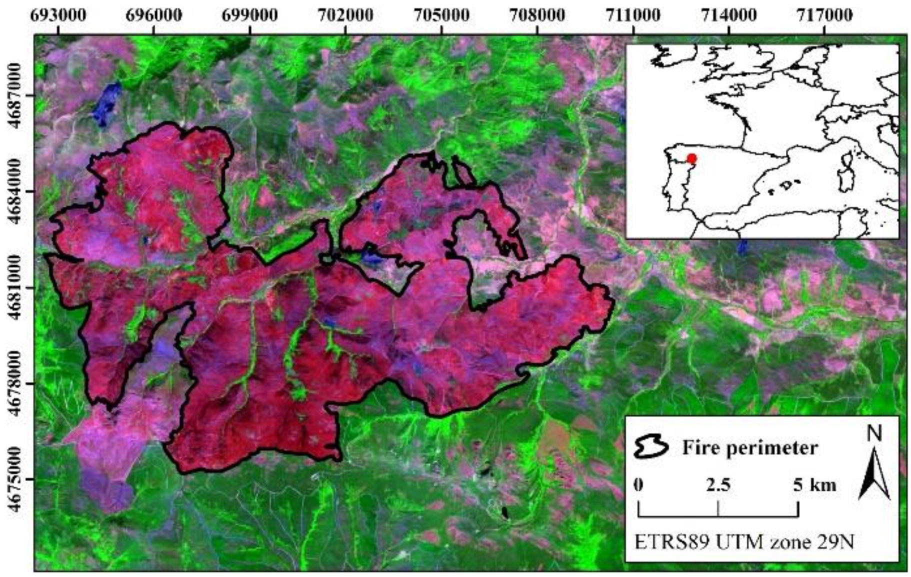

Figure 1- Sierra de Cabrera wildfire (NW Spain). Background image corresponds to a Sentinel-2 false-colour composite (SWIR-NIR-red) in immediate post-fire situation.

In September 2017, the month following the wildfire, a set of 35 plots of 30m x 30m were established in the field following a stratified random design using the dominant plant communities as strata. The area occupied by each plot was homogeneous regarding vegetation legacies and soil characteristics. Two composite soil samples were systematically collected at a depth of 3cm within the plots for obtaining a representative sample. Soil samples were homogenized, air dried and sieved in the laboratory (2mm mesh). Soil organic carbon (SOC; %) was determined following the combustion method (Dumas, 1831). We analysed soil total nitrogen (STN; %) by the Kjeldahl procedure (Bremner and Mulvaney, 1982) and available P (mg/kg) was determined through Olsen et al. (1954) method.

Remote sensing data used to predict soil properties in immediate post-fire situation consisted on ALOS-2 L-band SAR backscatter at dual polarization. ALOS-2 mission carries the Phased Array L-band SAR-2 (PALSAR-2) instrument, with a long operating wavelength of 23.6cm. Starting from 2015, the Japan Aerospace Exploration Agency (JAXA) has delivered 25m ALOS-2 global mosaics of Fine Beam Dual-polarization (FBD) SAR data strips (stripmap mode) acquired in ascending orbits with HH and HV polarizations. Mosaic data for the study site were acquired on 3rd October 2017 from JAXA Earth Observation Research Centre (https://www.eorc.jaxa.jp/). The product was pre-processed by JAXA using the mosaicking algorithm developed by Shimada and Ohtaki (2010), which includes (i) radiometric calibration, (ii) slope correction and

(iii) orthorectification. Product data stored in digital numbers were converted to γ^0 backscatter intensity in dB units. The values of ALOS-2 predictors (HH and HV γ^0 backscatter coefficients, as well as and HV/HH ratio) were extracted for each 30m x 30m field plot.

Soil properties in immediate post-fire situation were modelled by means of ALOS-2 predictors using generalized linear models (GLMs). The response variables were: (i) soil organic carbon, (ii) total nitrogen and (iii) available phosphorous, which were modelled following a Gamma error distribution with a log link function. Prediction performance of soil properties in immediate post-fire situation was evaluated through the coefficient of determination (R^2), the root-mean-squared error (RMSE) and the normalized RMSE (nRMSE). All statistical analyses were implemented in R (R Core Team, 2021).

3. Results and Discussion

ALOS-2 L-band SAR backscatter data featured a high overall fit (R^2 = 0.37-0.59) and predictive capacity (nRMSE = 12.7%-22.5%) for predicting each of the soil properties in immediate post-fire condition (Table 1). This could be attributed to the increased interaction of L-band SAR backscatter signal with soil surface properties because of the long operating wavelength of the instrument (Tanase et al., 2014), namely with soil moisture and surface roughness (Zribi and Dechambre, 2003), these properties being highly correlated with soil carbon and nutrients content (Moser et al., 2009). The soil property best predicted by ALOS-2 data was organic carbon (nRMSE = 12.7%), followed by total nitrogen (nRMSE = 14.1%) and available phosphorous (nRMSE = 22.5%). The slightly better predictive capacity of soil organic carbon content may be related to the lower carbon spatial variability in the plant communities of the study site immediately after fire relative to total nitrogen and available phosphorous content (Huerta et al., 2020).

Table 1- Soil organic carbon, total nitrogen and available phosphorous model performance evaluated through the coefficient of determination (R^2), root-mean-squared error (RMSE) and normalized RMSE (nRMSE).

	Organic C	**Total N**	**Available P**
R^2	0.59	0.48	0.37
RMSE	4.107	0.213	26.772
nRMSE	12.7%	14.1%	22.5%

All ALOS-2 predictors (HH and HV γ^0 backscatter coefficients and HV/HH ratio) featured a high signification in the models (*p-values* ≤ 0.01), being noticeable the strength of the correlation of the ALOS-2 HH polarization with all soil properties ($R^2 > 0.3$) (Table 2). This behaviour could be explained by the higher sensitivity of co-polarized SAR backscatter to soil dielectric properties as compared to cross-polarized data (Burgin et al., 2011).

Table 2- Relationship between ALOS-2 backscatter predictors and soil organic carbon, total nitrogen and available phosphorous evaluated through the coefficient of determination (R^2).

	Organic C	**Total N**	**Available P**
HH γ^0	0.30	0.33	0.31
HV γ^0	0.22	0.26	0.30
HV/HH	0.32	0.24	0.11

Soil organic carbon, total nitrogen and available phosphorous model predictions in immediate post-fire situation based on ALOS-2 fitted data were closely tailored to the 1:1 line, with the absence of under or overestimation effects for the entire range of field values of soil properties (Figure 2), which could be attributable to the lower attenuation of SAR backscatter signal in the L-band by vegetation canopies than in shorter wavelengths (Tanase et al., 2014).

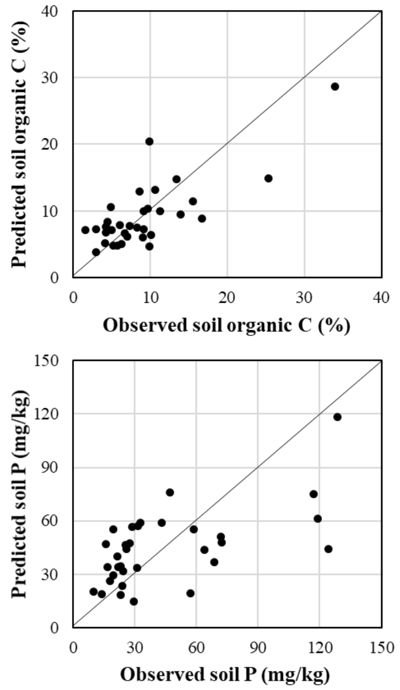

Figure 2- . Relationship between observed and predicted soil organic carbon, total nitrogen and available phosphorous in immediate post-fire situation from ALOS-2 backscatter data. The dotted black line represents the 1:1 line. Overall fit and predictive statistics are displayed in the Table 1.

The mean soil organic carbon, total nitrogen and available phosphorous content within the burned scar immediately after fire, extracted from spatially explicit prediction maps of GLM objects (Figure 3), were 4.78%, 0.65% and 34.13 mg/kg, respectively.

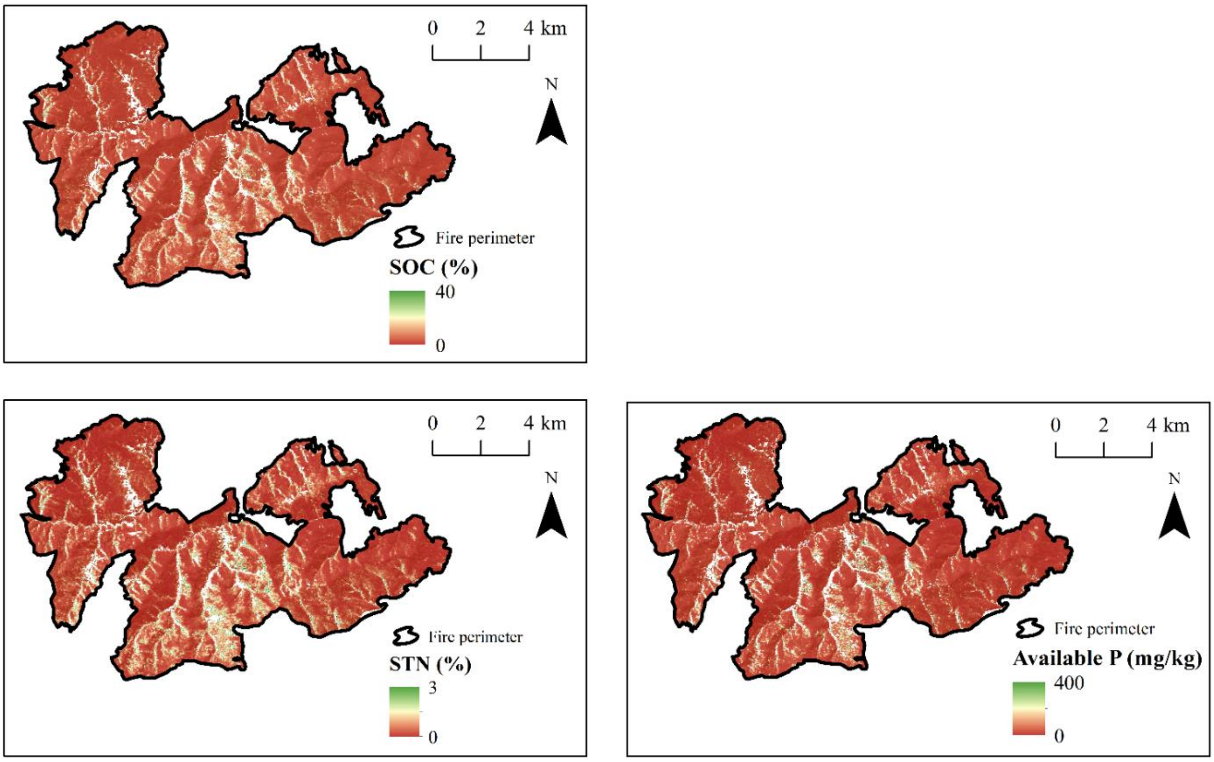

Figure 3- . Spatially explicit maps of predicted soil organic carbon, total nitrogen and available phosphorous. Blank regions within the fire perimeter correspond to unburned valley-bottom areas.

4. Conclusions

The use of remote sensing techniques for monitoring fire impact on soils is essential to determine the implementation of post-fire emergency actions aimed at mitigating soil degradation in extensive burned landscapes. This is a pioneer study evaluating the potential of L-band SAR data for this purpose. The estimation of soil organic carbon and nutrients content immediately after fire from L-band SAR backscatter featured a high performance because of the low attenuation of backscatter signal in the L-band by vegetation canopies and increased interaction with soil surface properties. The results of this study support the applicability of SAR sensors operating at long wavelength for monitoring fire effects on soil properties, reducing field data gathering costs.

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