The use of near infrared spectroscopy to estimate fire residence time

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Introduction

Forest fires are one of the main disturbances in Mediterranean ecosystems and their number, size and intensity have increased over the last few decades [1, 2]. Although fire effects on soil depend on many factors, one of the main factors that control these effects is fire intensity, which depends on two components: temperatures reached and time of residence of the heat [3, 4].

Different temperatures cause different effects on soil properties. Giovannini [5] summarized the effects of heating on the soil quality in these distinct sections: heating up to 220ºC: complete dehydration of the soil, including the gel forms; heating from 220º to 460ºC: combustion of the soil organic matter, most of the nutritional elements are mineralized; heating from 460º to 700ºC: produces the loss of the OH groups from the clays; heating beyond 700ºC: produces the disruption of the carbonates.

However, the rate at which energy can be transmitted through the soil is also limited by the thermal properties of the soil. Consequently, the duration of burning (fire residence time) is a key factor controlling the effects on soils properties [6, 7]. Thus, the time the heating remains can be considered the most damaging component of fire intensity to soil [8].

Despite the general agreement about the importance of determining fire residence time, this parameter is not available in studies of fire affected soils; therefore, obtaining this data can be very useful to assess fire effects on soil.

Near infrared reflectance (NIR) spectroscopy has been used to develop predictive models of the Maximum Temperature Reached (MTR) in burned soils [9, 10]. NIR spectroscopy obtains the reflectance spectra of a sample in the range of the NIR region (780-2500 nm). In this region, different chemical bonds of organic molecules absorb the radiation. The radiation is absorbed in accordance with the concentration of these compounds. Therefore, NIR spectra contain information about the organic composition of the soil, which is modified by the effect of fire [9].

Objectives

The main objective is to study the use of NIR to developed models that will be able to estimate how long a burned soil remained over a temperature (Time Over Temperature - TOT).

Methodology

a) Sample analyses:

Four different soils were used for this study (the main characteristics of soils are given in Table 1). Soil samples were air-dried and sieved through a 2-mm mesh. Samples of approximately 40 g were placed in ceramic cups and heated in a muffle-furnace at different temperatures and times. The temperature was recorded every 30 seconds with a thermocouple. Based on the results of Giovannini [5], and effects on soils, we established four temperatures (150ºC, 300ºC, 500ºC and 700ºC).

With the aim of covering a great variability, 24 heating times were selected, between 5 and 120 minutes with a five minutes interval.

Once the samples were burned, five different temperatures were selected to calculate the time over them (100ºC, 200ºC, 300ºC, 400ºC and 500ºC).

Table 1. Main characteristics of soils (0-5 cm).

Site[a]	Tm[b] (ºC)	Pm[b] (mm)	Soil type [11]	Texture[c] (% sand, silt, clay)	OM[d] (%)	pH	$CaCO_3$ (%)
PI	15.8	277.5	Xerorthent Rhodoxeralf Xerorthent Haploxeroll	31, 56, 13 SL	7.7	8.0	7.0
G	21.0	724.3		21, 28, 51 C	8.5	7.8	Bdl*
M	18.2	302		57, 22, 21 CSL	6.2	7.9	57.6
A	13.8	706		33, 32, 35 CL	12.6	7.5	46.9

[a] PI: Sierra de Pinoso in Alicante; G: Sierra de la Granadella in Alicante; M: Sierra del Maigmó in Alicante; A: Sierra de Aitana in Alicante.
[b] Tm: Mean annual temperature; Pm: Mean annual precipitation.
[c] Sand: 2-0.05 mm; silt: 0.05-0.002 mm; clay: <0.002 mm.; SL: silty loam; C: clay; CSL: clay sandy loam; CL: clay loam.
[d] OM: organic matter.
*Bdl: below detectable limits.

As a result of the combinations of heating temperatures and selected temperatures to estimate TOT, 19 models for each soil were constructed (Table 2). Five of them (one per temperature to estimate TOT) were constructed with all the data of the burned samples pooled (samples heated at 150ºC+300ºC+500ºC+700ºC). The other 14 models were constructed only with samples heated at the same temperature (i.e.: the model to estimate time over 100ºC, constructed only with samples heated at 150ºC).
For example, to estimate time over 100ºC 5 models were constructed: 1. Using only heated samples at 150ºC, 2. Using only heated samples at 300ºC: 3. Using only heated samples at 500ºC, 4. Using only heated samples at 700ºC, and 5. Using all pooled sample data.

Table 2. Scheme of the models constructed for each soil.

	Heating temperatures				
	150ºC	300ºC	500ºC	700ºC	All temperatures (150º+300º+500º+700º)
Time over 100ºC	X	X	X	X	X
Time over 200ºC	-	X	X	X	X
Time over 300ºC	-	X	X	X	X
Time over 400ºC	-	-	X	X	X
Time over 500ºC	-	-	X	X	X

* X: models constructed using samples heated at that temperature.

b) Development of NIR models:
Samples were scanned on reflectance mode with a NIR spectrophotometer. Samples were measured in duplicate to increase the surface of soil sample scanned.
Each spectrum was composed of more than 2000 values of absorbance at the different wavenumbers between 12,000 and 3,800 cm^{-1}.
For model construction, the spectral data was related to the TOT for each sample, using partial least squares regressions (PLS). This statistical method reduces the NIR data to a few components, taking into account the data of the target parameter. The number of PLS components used, is the rank of the model. In general, models with low ranks are preferred because the higher PLS components included, the higher the noise included in the model.
The method of model construction was "leave one out", which excludes one sample during the calibration of the model. Then, the excluded sample is estimated (and validated) with the model constructed with the other samples. This step is repeated until all samples have been

validated with calibrations performed by the others. All of these analyses were performed with the software OPUS 5.5 (Bruker Optik GmbH, 2004).

Finally, the selected models were those that had higher values of the regression coefficient (r^2), and lower values of estimation error (root mean square error cross validated: RMESCV) and rank.

Results and conclusions

All soils analyzed followed the same pattern; for this reason, we show here only the results of a selected soil (Maigmó).

The models constructed with samples burned at the same temperature showed lower values of RMSECV and higher values of r^2 than those constructed mixing data of all temperatures (Figure 2).

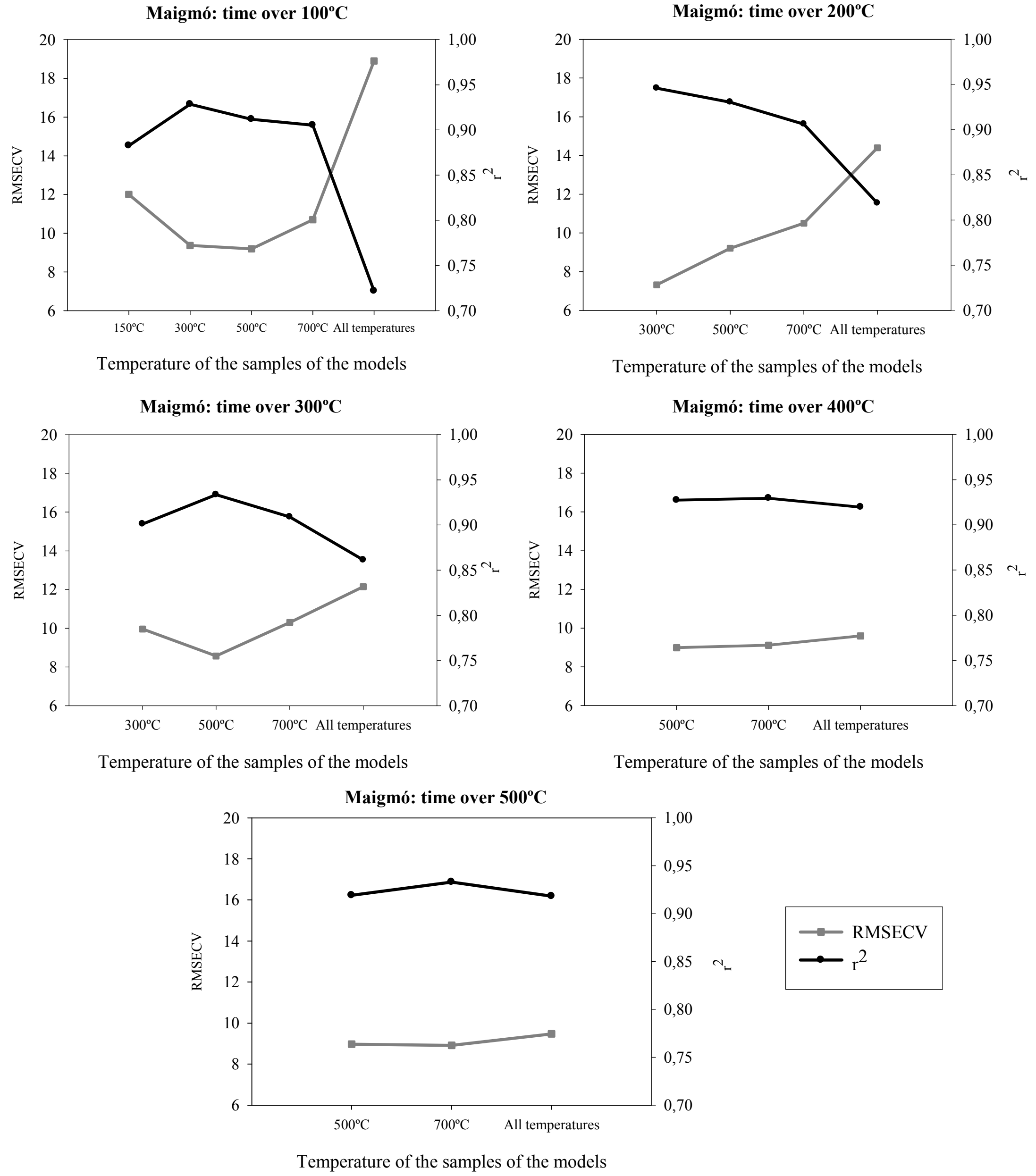

Figure 2. Changes in the RMSECV and the r^2 for each of the temperatures selected to estimate TOT for soils of Maigmó.

Generally, as can be observed, the higher the heating temperatures, the lower the RMSECV and the higher the r^2. Although changes in soil properties (mostly organic compounds) are reflected in NIR spectra, low temperatures may not produce appreciable changes in the soil organic matter [12]. So, it made difficult to relate the changes in NIR spectra with MTR or TOT at low temperatures.

In conclusion, these results show that it is possible to estimate the fire residence time in burned soils using NIR. To obtain good results, it is recommended to construct models with samples heated at the same temperature. Therefore, it is previously necessary to estimate the maximum temperature reached of a soil sample with the aim of selecting the corresponding TOT model.

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