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# Burn effects on soil properties associated to heat transfer under contrasting moisture content

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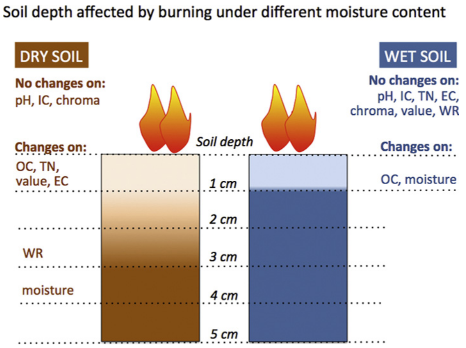
## HIGHLIGHTS

- High soil moisture content attenuates the heat transmission within burned topsoil.
- Soil thickness affected by burning is mainly limited to the first cm, either wet or dry.
- Fire leads to a C loss of 50% in dry soil and 25% in wet soil for up to the 1st cm.
- SWR is tightly linked with fire, soil moisture content and soil depth.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The aim of this work is to investigate the topsoil thickness affected by burning under contrasting soil moisture content (field capacity versus air-dried conditions). A mollic horizon of an Aleppo pine forest was sampled and burned in the laboratory, recording the temperature continuously at the topsoil surface and at soil depths of 1, 2, and 3 cm. Changes in soil properties were measured at 0–1, 1–2, 2–3, and 3–4 cm.

Both the maximum temperature and the charring intensities were significantly lower in wet soils than in air-dried soils up to 3 cm in depth. Moreover, soil heating was slower and cooling faster in wet soils as compared to dry soils. Therefore, the heat capacity increase of the soil moistened at field capacity plays a more important role than the thermal conductivity increase on heat transfer on burned soils. Burning did not significantly modify the pH, the carbonate content and the chroma, for either wet or dry soil. Fire caused an immediate and significant decrease in water repellency in the air-dried soil, even at 3 cm depth, whereas the wet soil remained hydrophilic throughout its thickness, without being affected by burning. Burning depleted 50% of the soil organic C (OC) content in the air-dried soil and 25% in the wet soil at the upper centimeter, which was blackened. Burning significantly decreased the total N (TN) content only in the dry soil (to one-third of the original value) through the first centimeter of soil depth. Soluble ions, measured by electrical conductivity (EC), increased after burning, although only significantly in the first centimeter of air-dried soils. Below 2 cm, burning had no significant effects on the brightness, OC, TN, or EC, for either wet or dry soil.

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## 1. Introduction

Wildfires may induce changes in many soil properties and components, such as soil organic matter (DeBano et al., 1998; Certini et al., 2011), nutrient availability (Giovannini, 2012; Badía et al., 2014a), or soil water repellency (Badía et al., 2013a; Bodí et al., 2013; Keesstra et al., 2017). These changes, combined with the removal of plant cover after burning, may lead to direct or indirect soil loss (Badía and Martí, 2008; Shakesby, 2011; Vega et al., 2014; García-Orenes et al., 2017). The maximum temperature reached at the mineral soil surface during a fire has been positively related to the accumulated soil loss during the first year after the fire (Fernández et al., 2008; Vega et al., 2014). The impact of fire reported in the literature varies from negligible to very severe depending on several thresholds and factors (Santín and Doerr, 2016), e.g., the natural variability between the study sites in terms of soil moisture content (Campbell et al., 1995; Vadilonga et al., 2008; Santín et al., 2016), soil type (Badía and Martí, 2003a), and vegetation type (Bento-Gonçalves et al., 2012; Cawson et al., 2012). Additionally, some discrepancies in the effects of a fire on soil properties can result from the sampling time (Pereira et al., 2012) and even the scale of the measurement (Cawson et al., 2016). Another relevant source of variability is related to fire characteristics or thermal signature (maximum temperature, heat duration, and oxygen availability) and heterogeneous spatial heating, even in experimental burns (Santín et al., 2016; Vega et al., 2014).

Other discrepancies described in the literature about the effects of fire on soil have been related to the soil depth sampled and the mixture of ashes and charred organic material together with the mineral topsoil (Certini et al., 2011). Because soil is a poor conductor of heat (DeBano, 2000), there is a strong gradient of temperatures with soil depth during wildfires and prescribed fires (Úbeda and Outeiro, 2009; Cawson et al., 2012). For these reasons, direct fire-induced changes in soils are mainly noticeable in the organic layer or in the most superficial centimeters of the mineral topsoil (Fernández et al., 2013; Vega et al., 2014). Nevertheless, high-intensity burns, e.g., with a large fuel load, affect mineral topsoil at the decimetric (up to 15 cm) level (Ulery et al., 2017). An accurate sampling, centimeter by centimeter, is required to acknowledge the affected soil thickness and to avoid dilution effects (Badía et al., 2014a,b; San Emeterio et al., 2016). However, this detailed soil sampling is subjected to several problems in the field, such a high spatial variability (Cawson et al., 2016), thus generating wide variations between replicates and making the interpretation of results difficult.

In addition, heat transmission into soil can be modified under high moisture and low temperature conditions. For instance, Dimitrakopoulos and Martin (1994) considered than the increase of thermal conductivity associate to moist soils can render a fire burning more detrimental for seed banks and underground plant organs. Instead, Santín et al. (2016) indicated that the experimental burn of boreal forest has negligible direct effects on the moist mineral soil. Also Vadilonga et al. (2008), after prescribed burning of the understory in Catalonia (NE Spain) forests, observed that the presence of moist organic litter prevented the underlying soil from excessive heating. The use of prescribed fire to control shrub encroachment in grasslands in European mountains is recommended in wet seasons (De Partearroyo et al., 2012). However, recent studies on this subject have had contrasted results (Armas-Herrera et al., 2016; San Emeterio et al., 2016; Girona-García et al., 2017). As DeBano et al. (1998) warned, heat transfer in wet soils is complex because water increases both the heat capacity and the heat conductivity of the soil, properties with opposite effects.

Predicting changes in soil properties induced by fires in the field often yields inconsistent results due to the soil thickness sampled, the mixture of ashes and charred material with the mineral soil, the sampling time, the soil moisture content, and the soil type. Moreover, heat transfer behavior is not always well known, and, therefore, burning soils under controlled conditions could be a useful method to check specific changes, centimeter by centimeter, on soil properties (Badía et al., 2013a, 2014b; Prat-Guitart et al., 2016).

The objective of this research was to examine the burn effect, under contrasting soil moisture content conditions (air-dried versus field conditions), on the heat transfer and several key physical and chemical soil properties of a mollic horizon at the centimeter scale (Ah horizon at depths of 1, 2, 3, and 4 cm).

## 2. Material and methods

### 2.1. Soil description and soil sampling

Topsoil was sampled from a long-unburned, wooded, mountainous environment in the northern foothills of Montes de Zuera (NE Spain), 630 m above sea level. This topsoil is a mollic horizon from a Rendzic Phaeozem, under a dense Aleppo pine forest (*Pinus halepensis*) with kermes evergreen oak (*Quercus coccifera*) and Mediterranean false-brome (*Brachypodium retusum*). Dry topsoil is strongly water repellent, with a clay loamy texture (Table 1). Additional details of the soils and the study area have been previously published (Badía et al., 2013b).

To keep the original soil structure, nine unaltered topsoil monoliths were carefully removed with a steel cylinder (15 cm diameter × 6.5 cm deep) and transported to the laboratory. Although it is common to find an O-Ah sequence, the O horizon was removed before burning since the role of this layer was previously addressed in a similar study (Badía et al., 2014b). Six monoliths were air-dried to constant weight in the laboratory. Then, three of them were selected as controls (unburned) and the other three were burned (burned dry); additionally, three more monoliths were moistened to field capacity and then burned (burned wet).

### 2.2. Burning treatment and characterization of the fire's thermal signature

Each soil monolith was burned separately in a combustion tunnel by applying a flame with a blowtorch placed 0.4 m above. The heating time was 15 min and the temperature was continuously recorded with four type-K thermocouples (1 mm in diameter) placed at the soil surface and at depths of 1, 2, and 3 cm. The thermocouples were connected to a datalogger (Picotech TC-08), and data were recorded every 8 s until cooling (~210 min), using the PicoLog R5.21.9 program. The heating duration for a range of temperatures, the maximum temperature (Tmax), and the charred intensity (CI) were calculated as the fire's thermal signature characterization. CI is a metric that integrates the temperature and the duration of the burn (Pyle et al., 2015), which may characterize the heat effects on the soil better than these parameters individually. For instance, $CI_{100}$ integrates the area of the curve generated over time in which the temperature exceeds 100 °C during the heating phase and drops to 100 °C during the cool-down phase. We calculated the CI

**Table 1**
Main physical and chemical properties of the experimental mollic Ah horizon (0–30 cm).

| Soil properties | Mollic horizon |
|---|---|
| Color (dry) | 10YR 5/1 |
| Color (moist) | 10YR 3/1 |
| Soil aggregate stability (%, w/w) | 95 |
| Bulk density/($kg/m^3$) | 790 |
| Field capacity (%, w/w) | 36.2 |
| Textural classes (USDA) | Clay loam (22, 44, 34)[a] |
| Gravels (% w/w) | 18.7 |
| pH ($H_2O$) 1:2.5 | 8.0 |
| $CaCO_3$ equivalent (%, w/w) | 49 |
| ECe (dS/m) | 1.8 |
| Soil organic matter (%, w/w) | 9.8 |
| C/N ratio | 15.9 |
| Cation exchange capacity ($cmol_c/kg$) | 27.7 |

Abbreviations: ECe, Electrical conductivity of saturated paste extract.

[a] The percentage of each main fraction is in parentheses: sand, 2–0.05 mm; silt, 0.05–0.002 mm; clay, <0.0002 mm.

by summing all the temperatures between these two limits and multiplying the sum by the measurement time interval, as in Eq. (1):

$$\mathrm{CI} = \left(\sum_{i=N}^{M} T_i\right) \cdot \Delta t \tag{1}$$

Similarly, we calculated $\mathrm{CI}_{200}$ and $\mathrm{CI}_{300}$ according to the threshold temperatures of the soil sample reaching 200 °C and 300 °C, respectively.

### 2.3. Laboratory methods

Air-dried monoliths were divided into four layers: 0–1 cm, 1–2 cm, 2–3 cm, and 3–4 cm in depth. Each layer was weighed to calculate the bulk density. After hand sieving, the fractions >2 mm and <2 mm were weighed separately to calculate the percentage of coarse elements, so as to transform % (w/w) to t/ha.

Soil water repellency (WR) persistence and intensity were measured in the 2 mm hand-sieved samples. Soil WR persistence was determined by the water drop penetration time (WDPT) method (Doerr, 1998). This test consists of placing drops of distilled water on the soil surface and recording the time it takes for the water to penetrate completely into the soil. The WR intensity was measured using the ethanol percentage (EP) test (Doerr et al., 2002; Badía et al., 2013a). Six drops of standardized solutions of ethanol in water (0.0, 5.0, 8.5, 13.0, 18.0, 24.0, and 36% v/v) were applied to the soil samples using a hypodermic syringe, and their instant or short-term infiltration behavior was observed.

Soil pH was determined potentiometrically in a 1:2.5 ratio in $H_2O$ (McLean, 1982). The total carbon and total soil nitrogen contents were determined using an elemental autoanalyzer (Vario Max CN Macro Elemental Analyser). Organic C (OC) was determined by the wet oxidation method (Nelson and Sommers, 1982). The inorganic Carbon (IC) was measured volumetrically (with a calcimeter) after being treated with 6 M hydrochloric acid and expressed as equivalent $CaCO_3$ (Nelson, 1982). The electrical conductivity (EC) in a 1:5 ratio (soil:water) at 25 °C was obtained as a measure of the total dissolved solutes (Rhoades, 1982).

### 2.4. Statistical analysis

To identify the differences in the soil parameters due to the different treatments (unburned, dry burned, and wet burned monoliths) and the sampling soil depth, a two-way factorial ANOVA (treatment × depth) was used. Assumptions of normality and homoscedasticity were tested. Data that did not meet the prerequisites of the analysis were transformed. In cases where, even after transformation, the prerequisites of normality were not met, a Kruskal-Wallis test was used. In normally distributed data, the separation of means was tested by Fisher's partial least-squares difference (PLSD) test with a significance level of $p < 0.01$ or $p < 0.05$. Differences between treatments at the same sampled depth were evaluated by means of the *t*-test or Mann-Whitney *U* test. All these statistical analyses were conducted with StatView (SAS Institute Inc.). We also used a principal component analysis (PCA) of the obtained data using XLSTAT software to investigate the relationships between the soil properties over soil depth of the three treatments (unburned, dry burned, and wet burned). After standardization of the data, PCA was performed using the Pearson correlation matrix, and a Varimax rotation was applied to the first two main components.

## 3. Results

### 3.1. Fire's thermal signature with soil depth

The highest temperatures (Tmax) were found at the soil surface and declined gradually with soil depth (Table 2). It can be observed a strong thermal gradient across a short thickness (from the surface to a soil depth of 3 cm): from 590 °C to 131 °C in dry topsoil and from 324 °C to 47 °C in wet topsoil. The Tmax measured in dry soils was three to four times higher than that in wet soils at each depth (Table 2). The effect of moisture content was also verified in the duration of the heat at the different soil depths (Table 3). The maximum temperature (Tmax) reached in the soil monoliths clearly depended on the initial soil water content (F = 124.3; $p < 0.0001$) and soil depth (F = 51.3; $p < 0.0001$). The interaction of soil humidity × depth was also significant (F = 15.6; $p < 0.0001$).

**Table 2**
Maximum temperatures (°C) reached in a mollic horizon burned in wet and dry conditions (mean of three replicates by each moisture content and soil depth).

| | Soil depth | | | | |
|---|---|---|---|---|---|
| Burning in | Surface | 1 cm | 2 cm | 3 cm | *p* |
| Dry | 589.0a | 426.8b | 234.7c | 130.9c | *<0.001* |
| Wet | 324.4a | 123.3b | 60.3c | 47.3c | *<0.044* |
| *p* = | *0.082* | *0.006* | *0.023* | *0.057* | |

Lowercase letters compare between soil depths (within each line); *p* in the last row compares between dry and wet soil, within each soil depth (column).

At the beginning of the heating process (minute 5), the temperature curves over time have a lower slope in the burned wet soil than in the burned dry soil (Fig. 1); the water contained within the soil tends to hold back the soil heating until it is vaporized (Campbell et al., 1995). The energy applied as heat is invested at the phase change of the water, which is 2257 kJ/kg (539.4 cal/g) at 100 °C (latent heat of vaporization of water), and it does not provide a thermal increase of the soil. In our experiment, the water content was not exhausted in the wet soil after 15 min of burning, retaining approximately 300–400 g water/soil kg. However, the moisture content of air-dried soil (115–130 g water/soil kg) decreased to 30–42 g/kg after burning even at 3–4 cm soil depth (Appendix).

At the end of heating, cooling is much faster in the wet-burned soil because the thermal conductivity is higher for moist soils than for dry soils (Dimitrakopoulos and Martin (1994). The heat in depth tended to last longer than on soil surface. For that reason, the surface temperature curve overlaps the curves at depth (the first, second, and even third centimeter) after removing the heat source (Fig. 1).

The charred intensities ($\mathrm{CI}_{100}$, $\mathrm{CI}_{200,}$ and $\mathrm{CI}_{300}$) were clearly dependent on the soil water content and soil depth (Table 4). The interaction of soil humidity × soil depth was also always significant, suggesting again the influence of soil water amount on heat transfer. The $\mathrm{CI}_{100}$ values were positively and highly correlated ($p < 0.01$) with the $\mathrm{CI}_{200}$ and $\mathrm{CI}_{300}$ values, as well as with Tmax. Therefore, all CIs were negatively and significantly correlated with the soil moisture content (Table 5). The strong decrease of these indexes with depth, which characterizes

**Table 3**
Heating duration (min) of range temperatures, maximum temperatures (Tmax in °C), and time (minute) when Tmax has been reached at four measurement points (surface, and 1, 2 and 3 cm Ah soil depth) of burned monoliths of a mollic horizon (mean of three replicates by each moisture content and soil depth).

| | Dry burned | | | | Wet burned | | | |
|---|---|---|---|---|---|---|---|---|
| Soil depth (cm) | Surface | 1 | 2 | 3 | Surface | 1 | 2 | 3 |
| Tmax (°C) | 589.0 | 426.8 | 234.7 | 130.9 | 324.4 | 123.3 | 60.3 | 47.3 |
| Time (min) | 9.7 | 15.3 | 19.9 | 20.6 | 17.8 | 20.2 | 20.8 | 24.5 |
| Duration (min) | | | | | | | | |
| 0–100 °C | 179.8 | 180.3 | 181.0 | 189.1 | 192.8 | 202.2 | 208.4 | 208.4 |
| 100–200 | 10.2 | 9.5 | 19.2 | 19.3 | 2.6 | 6.2 | | |
| 200–300 | 3.5 | 6.5 | 8.2 | | 12.3 | | | |
| 300–400 | 1.5 | 7.3 | | | 0.7 | | | |
| 400–500 | 3.2 | 4.8 | | | | | | |
| 500–600 | 10.2 | | | | | | | |

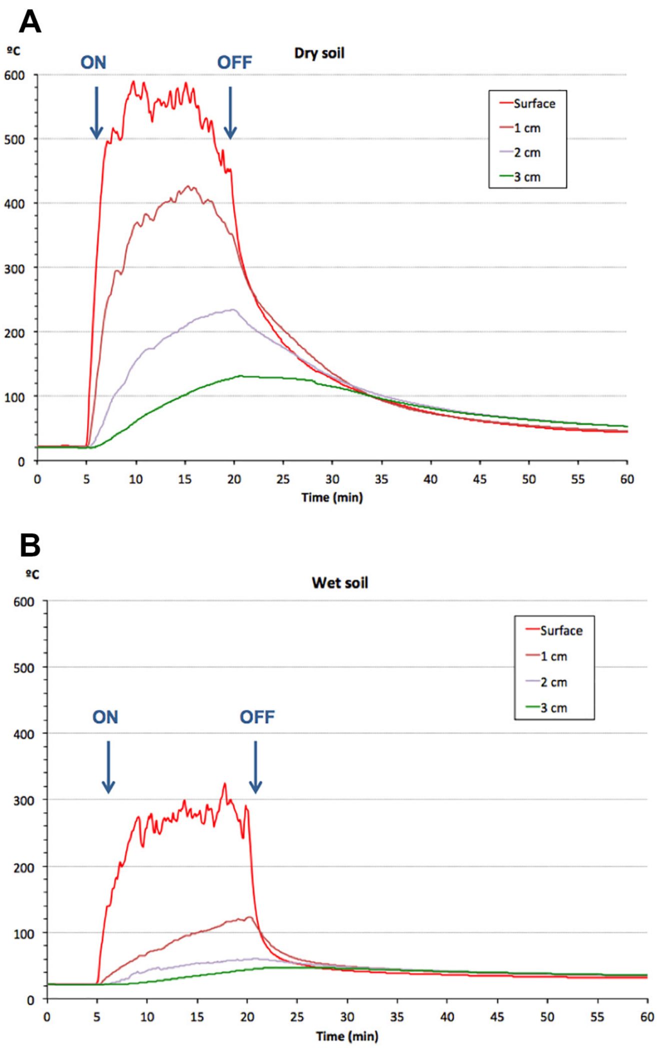

**Fig. 1.** a, b. Temperature behavior on the surface and at the first centimeters of depth of a burned mollic topsoil under contrasted soil moisture content: a) air-dried versus b) field capacity. The flame was switched on at minute 5 and switched off at minute 20 (blue arrows). Although the temperature measurements were recorded for 210 min, in this figure, only the first 60 min are shown to remark on the main variations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 4**
Charred intensities at different temperatures (CI 100, CI 200 and CI 300), in °C min, obtained in a mollic horizon burned in wet and dry conditions.

| | | | Soil depth | | | |
|---|---|---|---|---|---|---|
| CI 100 (°C min) | Burning in | | Surface | 1 cm | 2 cm | 3 cm |
| | Dry | | 9992 ab | 7599 b | 4618 bc | 2130 c |
| | Wet | | 3593 a | 722 b | 0 | 0 |
| | | $p =$ | *0.1552* | *0.0013* | – | – |
| CI 200 (°C min) | Burning in | | Surface | 1 cm | 2 cm | 3 cm |
| | Dry | | 8676 a | 6316 a | 2101 b | 0 |
| | Wet | | 3177 a | 228 b | 0 | 0 |
| | | $p =$ | *0.0396* | *<0.0001* | – | – |
| CI 300 (°C min) | Burning in | | Surface | 1 cm | 2 cm | 3 cm |
| | Dry | | 7691 a | 4740 b | 563 c | 0 |
| | Wet | | 2388 | 0 | 0 | 0 |
| | | $p =$ | *0.1648* | – | – | – |

Lowercase letters compare between soil depths (within each line); $p$ in the last row compares between dry and wet soil, within each soil depth (column).

**Table 5**
Correlation matrix (Pearson) between the maximum temperature (Tmax) and charred intensities (CI) for mollic horizon burned in dry and wet conditions (n = 24). Values in bold are significantly different at $p < 0.05$.

| Properties | Tmax | Charred intensity (CI) | | |
|---|---|---|---|---|
| | | CI-100 | CI-200 | CI-300 |
| Tmax (°C) | **1** | | | |
| CI-100 (°C min) | **0.955** | **1** | | |
| CI-200 (°C min) | **0.964** | **0.952** | **1** | |
| CI-300 (°C min) | **0.942** | **0.899** | **0.968** | **1** |
| Soil moisture (%) | **−0.611** | **−0.734** | **−0.579** | **−0.519** |
| Organic C (%) | 0.213 | 0.063 | 0.163 | 0.156 |
| Total N (%) | 0.266 | 0.124 | 0.204 | 0.185 |
| Total C (%) | 0.341 | 0.195 | 0.280 | 0.261 |
| C/N ratio | −0.189 | −0.238 | −0.148 | −0.111 |
| Inorganic C (%) | -0.336 | −0.254 | −0.291 | −0.243 |
| pH (1:2.5) | **−0.413** | **−0.426** | −0.371 | -0.242 |
| EC 1:5 (μS/cm) | **0.812** | **0.808** | **0.849** | **0.866** |
| WDPT (class) | 0.085 | 0.249 | 0.063 | −0.046 |
| Ethanol (class) | −0.011 | 0.118 | −0.049 | −0.118 |
| Value (dry) | **−0.767** | **−0.722** | **−0.754** | **−0.802** |
| Chroma (dry) | −0.383 | **−0.437** | −0.352 | −0.330 |

$p < 0.05$ when $R > 0.404$; $p < 0.01$ when $R > 0.515$.

the amount of heat input to the topsoil during burning, provides additional evidence about the thermal inertia of the soil.

The maximum values of $CI_{100}$ were found in the first centimeter of the dry soil (9992 ± 1286 °C min), whereas only 3593 ± 3054 °C min was reached in the same soil in wet conditions. The CI values obtained by Pyle et al. (2015) in the pyrolysis of plant biomass for charcoal production are, logically, many orders of magnitude ($10^4$) higher than the ones obtained in this controlled burn, due to the differences in the durations of the process. Variations in soil properties with heat can be linear from relatively low temperatures, e.g., mass yield, or show drastic decreases from a certain thermal threshold, e.g., C and N contents (Pyle et al., 2015). In our work, the correlation of the three CIs with soil properties are similar to the relation of the Tmax with these properties (Table 5), which indicates that this heat duration don't give us additional information on soil effects by burning.

### *3.2. Soil physical properties: soil moisture, water repellency (WR), and color*

The soil moisture content decreased significantly up to 4 cm depth after burning the air-dried soil. Air-dried topsoil had 130 g of water/kg of soil, which decreased to 30 g of water/kg of soil after burning through the first centimeter, and there was up to 40 g of water/kg of soil below the first centimeter. Wet topsoil at field capacity contained approximately 510 g of water/kg of soil in the first centimeter,decreasing to 302 g of water/kg of soil after burning. However the moisture content did not undergo major changes below. This is related to the temperatures above 100 °C reached in dry soils, even at 3 cm depth. In the wet soils, there were only temperatures higher than 100 °C in the first centimeter of depth.

No significant differences in the soil moisture content were found in any sample depth after burning wet soils; although the moisture content in the first centimeter of wet-burned soil (302 g/kg) was slightly lower than the content in the second centimeter (408 g/kg). We assume some loss of water by vaporization in this first centimeter, because the Tmax reached for this centimeter ranged from 334 °C to 124 °C. However, apparently little soil water vaporized below the first centimeter since the Tmax registered at a soil depth of 2 cm was 61 °C. We have not detected any transport of evaporated soil moisture to cooler regions deeper in the soil, referred to as “evaporative front” by Massman (2012).

Burning significantly decreased the WR persistence (WDPT test) at the first, second, and third centimeter of the Ah horizon. The main changes were found in the first centimeter, where the high WDPT in air-dried unburned soil (923 s) disappeared after burning, thus turning the severely repellent topsoil into a hydrophilic topsoil; the severe repellency of the second and third centimeter decreased to strong repellency. Although dry soils maintain some WR level after burning in depth, WR is practically absent in the wet soils (after and before the fire).

Burning also significantly decreased the WR intensity (EP test) in the first, second and third centimeter of the air-dried Ah horizon, converting the strong or very strong intensity of the repellence into a very hydrophilic layer (first centimeter) or a strong intensity layer (second and third centimeter). Only in the fourth centimeter did the EP remain unchanged, as occurred with the WDPT. In fact, EP and WDPT data are positively and significantly correlated ($R = 0.903$; $p < 0.01$) in this work.

The color (Munsell code) was significantly darker in the first centimeter, but only after burning in dry conditions, from 10YR 5/2 to 10YR 3/1. No significant changes were detected at greater soil depths. The value or brightness decreased significantly from 4.7 ± 0.8 (unburned) to 2.7 ± 0.6 (dry burned); the chroma decreased not significantly from 2.0 ± 0.0 (unburned) to 1.3 ± 0.6 (dry burned). We obtained (Table 5) a highly significant and negative correlation ($p < 0.01$) between the value (or brightness) and heating (both Tmax and CIs).

### 3.3. Chemical properties: organic C, total N, EC, pH, and carbonates

As expected, the OC content in the unburned topsoil samples progressively and significantly ($p = 0.027$) decreased with depth, from the first to the fourth centimeter. But burning dry soil drastically reduced the highest OC content at the surface and eliminated the usual OC decrease with soil depth. Specifically, the initial OC content in the first centimeter of the Ah horizon (143.55 g/kg) decreased significantly by approximately half (to 77.07 g/kg). In the burned wet soil, this decrease was also significant in the first centimeter of the mollic horizon, although it was less intense (to 104.57 g/kg). Burning lead to losses of 2.53 and 3.86 Mg TOC $ha^{-1}$ at 1-cm depth in the previously wet and dry soil monoliths, respectively. This means that burning resulted in the loss of one-quarter of the pre-fire OC of the wet monolith and one-half of the OC under the dry conditions of the upper centimeter of the Ah horizon. Instead, soil burning only caused a (not significant) loss of one-seventh of the pre-fire total N (TN) in the upper centimeter of the Ah horizon under wet conditions, but it causes a significant loss of one-third of the total N under dry conditions. The original C/N ratio (15.3 ± 2.5) decreased to 13.5 ± 1.0 for burning wet soils and 12.5 ± 0.9 for burning dry soils in the first centimeter. Neither OC nor TN were significantly reduced at depths below 2 cm. The OC and TN contents are positively and significantly correlated ($R = 0.962$; $p < 0.01$); thus, much of the discussion regarding OC can be applied to TN.

The EC in the unburned mollic horizon had similar values across the upper 4 cm (approximately 200 µS/cm). Burning resulted in an increase in EC, which was significant for the uppermost centimeter when the soil was dry, but not when the soil was wet. Specifically, EC in the first centimeter of unburned topsoil (220 µS/cm) was doubled for wet soil (433 µS/cm) and increased by a factor of five for dry soil (1060 µS/cm). Thus, the homogeneous EC distribution in the first 4 cm of topsoil ($p = 0.627$) was replaced by a strong heterogeneity due to the significant increase ($p = 0.004$) in the concentration of soluble ions in the top of the soil after burning in both situations, wet and dry soil conditions (Fig. 2).

The inorganic C, expressed as carbonate content, was very high (ranging from 35% to 47% from the first to the fourth centimeter of depth), which determines the basic reaction (pH ranging from 7.9 to 8.1) of the soil. Neither carbonates nor the pH were significantly affected by burning, unlike other properties (Table 6).

### 3.4. Overall analysis

To investigate the relationships between the effects of controlled burning on wet and dry conditions and the soil properties affected at different soil depths (1, 2, 3, and 4 cm), we used a PCA of the entire set of data and the replicates. The factor scores of the soil samples and the scores of the individual soil properties on the two first axes (which accounted for 62.6% of the variance) are displayed (Fig. 3). Based on the PCA results, the following can be seen:

- The soil samples (three replicates) are distributed according to the burning treatment (unburned or burned), original moisture content (dry or wet), and soil depth (Fig. 3, above). Axis I had large positive loadings (right half) for the unburned soil samples. The distribution of the soil samples along this axis was conspicuously related to depth. Thus, most samples at the top (first and second centimeter) had large positive scores (on the right side of the graph) corresponding to high total C, OC, TN, and WR, whereas the deeper soil samples had the lowest scores (on the left of the graph), corresponding to higher inorganic C and less OC. Axis II had positive loadings (Fig. 3 above) for dry-burned soils, which are again distributed along this axis in relation to their sampled depth: at the top, the most superficial soil samples and, at the bottom, the deepest soil samples.

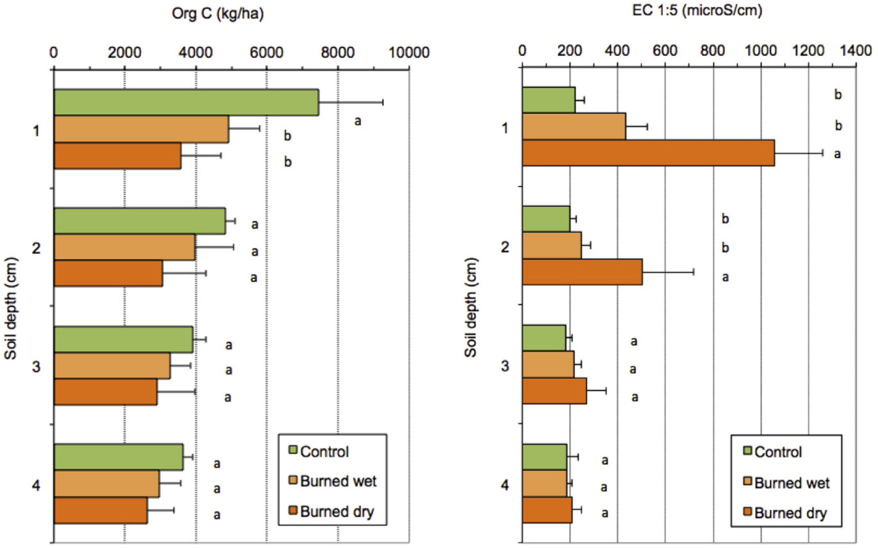

**Fig. 2.** Effect of soil moisture on the OC content (in Mg/ha) and EC (µS/cm) of burned soils. Significant differences ($p < 0.05$) between the treatments for each soil depth are represented by different letters by Mann-Whitney U test (for OC content) and *t*-test (for EC).

**Table 6**
Significant effects of experimental burning of a mollic horizon beneath contrasted moisture content: the decrease, in red, and the increase, in green. Properties without significant changes are not indicated (pH, inorganic C, chroma).

| Soil depth (cm) | Soil moisture content | | Water repellency | | Color: value | | Organic C | | Total N | | Total dissolved solutes | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet |
| 0–1 | 🟥 | 🟥 | 🟥 | Zero | 🟥 | | 🟥 | 🟥 | 🟥 | | 🟩 | |
| 1–2 | 🟥 | | 🟥 | Zero | | | | | | | | |
| 2–3 | 🟥 | | 🟥 | Zero | | | | | | | | |
| 3–4 | 🟥 | | | Zero | | | | | | | | |

— The soil properties and heat signature (Tmax and CI) are shown in the lower part of Fig. 3. The parameters related to heat, as well as the dissolved solutes (or EC), all of them close, have very positive loadings (at the top of the graph). This finding mirrors the effect of the controlled fire on air-dried soils, especially at the surface. Soil samples with negative loadings (down and left) are not affected by fire, and analogously, the soil parameters are scarcely affected by fire.

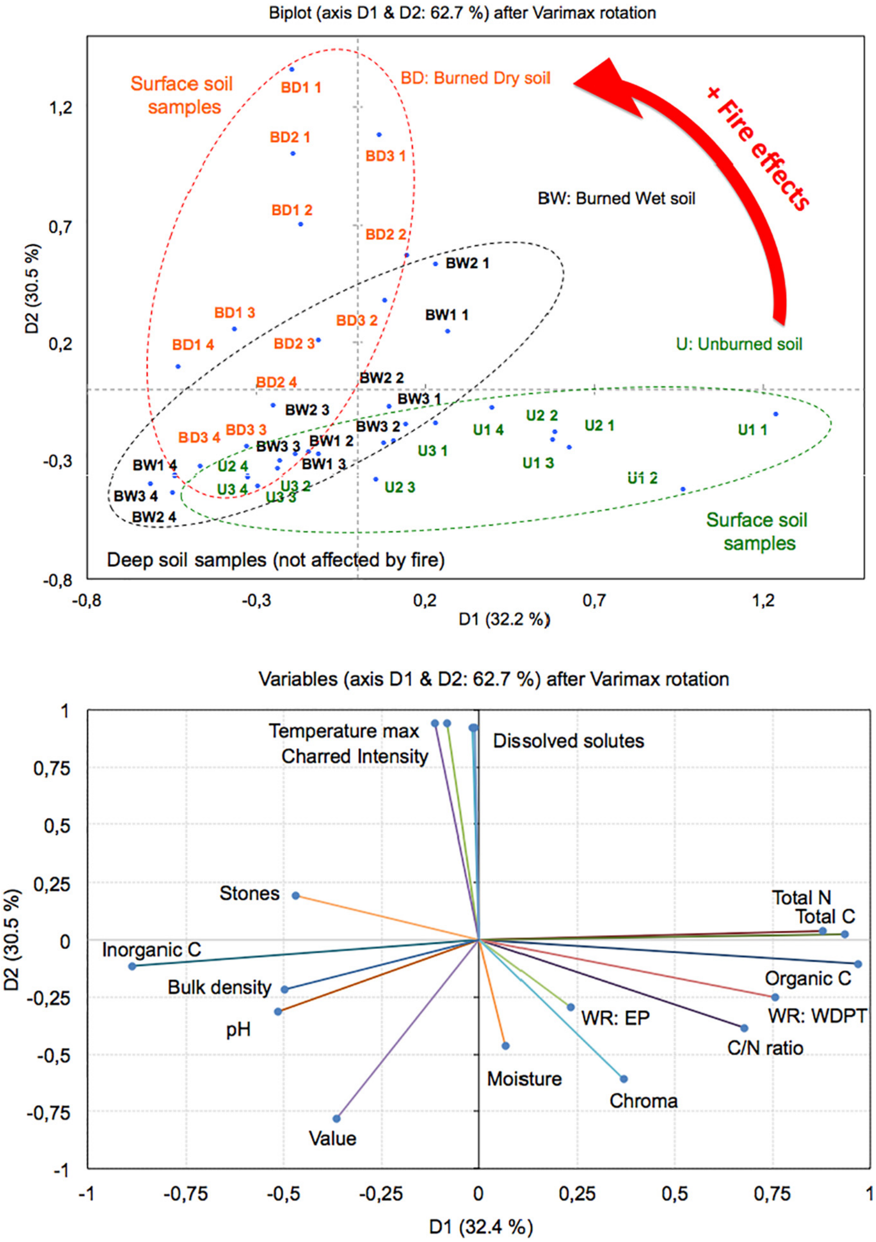

**Fig. 3.** a, b. Biplot diagram of the first and second axes obtained from principal component analysis (PCA) of the soil sample (a) and soil property (b) data. The first number indicates the replicate and the second number is the soil depth sampled (cm).

## 4. Discussion

### *4.1. Fire's thermal signature with soil depth*

The temperatures obtained in the experimental burn were within the range offered in a recent review on prescribed burns (Cawson et al., 2012), with Tmax from 300 °C to 900 °C at the litter layer, 100 °C to 625 °C at the litter-duff interface, 80 °C to 210 °C at the mineral soil surface, and 25 °C to 200 °C at 2.5 cm soil mineral depth. However, in a previous review, Úbeda and Outeiro (2009) reported temperatures higher than 1000 °C on the ground surface affected by wildfires; the temperatures seldom exceeded 100 °C (e.g., under dense pine forest) below a soil depth of 5 cm. DeBano et al. (1979) reported heating surface temperatures in North American forests over 300 °C and lasted for 5–10 min. In the shrublands and woodlands of SE Australia, Bradstock and Auld (1995) found temperatures of 60 °C–120 °C in subsurface soil (3 cm), with heating durations up to 20 min.

Fernández et al. (2013) investigated burned scrublands (mixed heathlands of *Erica australis* L., ssp. *aragonensis* (Willk.) and *Pterospartum tridentatum* (L.) Willk.) in experimental plots in NW Spain. They found extraordinarily low temperatures, with a mean Tmax of 152 °C (ranging from 70.0 °C to 402.6 °C) at the soil organic layer surface and a mean Tmax at the mineral soil surface of 58.1 °C (ranging from 11.5 °C to 293.8 °C); the soil was not heated at 2 cm below the mineral surface. Similarly, Vega et al. (2014), in an experimental prescribed burning of shrublands dominated by gorse (*Ulex europaeus* L.) in NW Spain, found a mean Tmax of 162 °C on the soil surface and a Tmax range of 22 °C to 43 °C at 2 cm below the mineral soil surface. In these experimental burns, the heat did not noticeably penetrate the soil because the fires only lasted for a short period and the soil moisture was high, approximately 60% w/w in the organic layers and 30%–40% w/w in a 0–5 cm mineral horizon (Fernández et al., 2013; Vega et al., 2014). In addition, in a prescribed burn of the understory of dry eucalyptus forests in the uplands of Victoria (Australia), Cawson et al. (2016) found that the heating duration was very short, i.e., surface temperatures that were >400 °C lasted for 2 s, and temperatures >200 °C lasted for 6 s. But in prescribed burns of thorny cushion dwarf *Echinospartum horridum* at the Buisán location in the Pyrenees range (Girona-García et al., 2017), the residence time of heat was higher than in understory burns; so, the temperature at the mineral soil surface reached 438 °C and remained above 200 °C for 6.5 min; however, there were negligible increases at a soil depth of 1 cm. In contrast, at the neighboring Tella location (Armas-Herrera et al., 2016), and with a similar prescribed burn, the temperature at 1 cm soil depth reached nearly 400 °C and remained above 200 °C for 25 min. This resulted in a heat signature with a strong impact, especially on the soil biological properties. Cawson et al. (2016) carried out prescribed burns of the shrubby or grassy understory of dry *Eucalyptus* forests at different locations in the uplands of Victoria; these had low moisture values, both in the surface litter (10%–15%) and for 0–5 cm of mineral topsoil (7%–9%). They found a Tmax of 969 °C at the surface and peak temperatures of 728 °C at shallow soil depths (0.5 cm), but they seldom detected changes in temperature at a depth of 4 cm. Below the surface, the peak temperatures were lower but the heating durations were longer, with temperatures over 100 °C lasting 23 min on average. The same authors remarked on the spatial heterogeneity of temperatures in prescribed burned landscapes. Also, Santín et al. (2016), in a high-intensity experimental fire of a Canadian boreal forest of jack pine (*Pinus banksiana*), found that sensors placed only 2 m apart registered Tmax values ranging from 550 °C to 976 °C at the forest floor surface. Even in experimental plots using the backfire burning technique (against the wind to favor slow fire propagation and fuel combustion), litter and duff consumption was irregular (Vega et al., 2014).

Dry soil acts as a thermal insulator, resulting in slow rates of heat transfer within the soil. In wet conditions, the water content increases both the heat capacity and the heat conductivity of the soil (Massman, 2012), being the effect of the former much more important than the latter on fire's thermal signature. If the soil is saturated, the opposite may occur (Dimitrakopoulos and Martin, 1994).

### *4.2. Soil physical properties: soil moisture, water repellency (WR) and color*

WR (both WDPT and EP) naturally occurs in unburned air-dried soils. This naturally very high “background” level of repellency was previously reported for mollic horizons (Badía et al., 2014b) and, to a lesser extent, for ochric horizons (Aznar et al., 2016) under an Aleppo pine forest (*Pinus halepensis* L.), as well as for other soil types under different vegetation (Doerr et al., 2006; Jordán et al., 2010; Keesstra et al., 2017). WR decreased progressively with soil depth (as reported by Badía et al., 2013a; Bodí et al., 2013; Benito et al., 2016; Keizer et al., 2008; among others).

Although the mollic horizon is extremely water repellent when dry, it is wettable at field capacity, at practically any measured thickness (0 to 4 cm of soil depth). The burning of the wet soil cannot dry the soil, which stays wettable (Appendix). Soils exceeding a certain threshold of moisture content may shift from water-repellent to wettable (DeBano, 2000). Bodí et al. (2013) found a critical soil moisture threshold above which the soil becomes wettable, ranging from 5% (sandy soils) to 30% (clay soils). Benito et al. (2016) found that the moisture range defining the presence or absence of repellency under field conditions was 22%–57% in pine plantations in NW Spain. It is common that the soil surface will be largely wettable in wet seasons and extremely water repellent during dry seasons (Benito et al., 2016; Bodí et al., 2013; Keizer et al., 2008; Keesstra et al., 2017).

A fire-induced decrease in WR has been found in depth, up to 2–3 cm, where a Tmax range of 241 °C–132 °C (and a $CI_{100}$ range of 4618–2130 °C min) was measured. According to DeBano et al. (1998) this temperature range should have formed a water-repellent layer either in place or in underlying soil layers. The conspicuous elimination of WR without a significant decrease in total organic C content could be related to the fragmentation by heat of the long-chain molecules of the alkylic series: n-alkanes, alkenes, fatty acids and methylated fatty acids (Badía et al., 2014b). Fire-induced reduction in WR is usually related with high temperatures (Jordán et al., 2010; Giovannini, 2012; Keesstra et al., 2017). For instance, Giovannini (2012) found that temperatures above 550 °C completely destroyed soil hydrophobicity. Jordán et al. (2010) showed that soil water repellency decreased after intense burning of a Mediterranean heathland (SW Spain); these decreases were strong at the soil surface but diminished progressively with soil depth, as was observed in our mollic horizon. Keesstra et al. (2017) found a high WR on the surface of long-unburned soils (>50 years unburned) in a *Pinus halepensis* forest from Mount Carmel range; in contrast, burned and twice-burned areas have low and negligible soil WR, respectively, demonstrating that recurrent fires reduce topsoil WR.

However, fire-induced reduction in WR is not always observed and, conversely, many other studies have reported increases in WR after heating. For example, heating soil samples at 205 °C for 10 min or at 305 °C for 5 min increased water repellency (DeBano et al., 1998); the same authors indicates that the exposure to 480 °C completely eliminated hydrophobicity. Robichaud and Hungerford (2000) described millimetric displacements of the WR layer and reported a WR increase at a soil depth of 2–5 cm, although the temperatures remained below 260 °C. Vadilonga et al. (2008) found that WDPT increased moderately at the soil surface in the plots exposed to high burn severity, and decreased slightly when the burn severity was low. Atanassova and Doerr (2011) observed an increase in soil WR after heating (at 300 °C for 10 min) eucalyptus forest topsoils (0–5 cm depth) with a sandy texture. Cawson et al. (2016) found that slight soil heating (temperatures about 200 °C at the surface, lasting an average of 6 s), during prescribed burns of shrubby or grassy understories of dry *Eucalyptus* forests, was related to the strength of soil water repellency at the soil surface. The effect of heating on soil WR definitely depends on the fire signature and soil moisture content, among other soil properties and components (Cawson et al., 2012; Bodí et al., 2013; Jordán et al., 2010; Benito et al., 2016; Prat-Guitart et al., 2016).

The darkening of the first centimeter by burning in dry conditions is related to the charring of soil organic matter (Ulery and Graham, 1993). Heating soils for 30 min in a muffle furnace at 25 °C, 150 °C, 250 °C, and 500 °C linearly decreased significantly ($p < 0.01$) the luminosity or brightness ($R = -0.58$) and even the chroma ($R = -0.75$) in an ochric calcareous horizon (Badía and Martí, 2003a). Instead, Cancelo et al. (2014), heating sieved samples of umbric horizons, found an increase in the luminosity and chroma of burned soils, which is related to a decrease in the amount of organic matter. This relation between organic matter and color in burned soils could be a useful tool to evaluate the evolution of burned landscapes by VIS-NIR-SWIR spectroscopy (Rosero-Vlasova et al., 2016). In other cases, reddening and yellowing of soils after burning have been related to the transformation of iron oxides at high temperatures as well as OC losses. For instance Ulery et al. (2017) found strong changes in soil color (hue, value, and chroma) at soil depths up to 15 cm, after severe fires under burned slash piles or fallen logs.

### 4.3. Chemical properties: organic C, total N, EC, pH, and carbonates

In our previous studies, in which a mollic horizon was burned in a similar way but with preservation of the upper O horizon (2.5 cm thick), the decrease in OC was not significant in the Ah horizon, although the O horizon was partially transformed by combustion into ashes and charred litter (Badía et al., 2014b). Its burning resulted in the loss of two-thirds of the pre-fire OC of the O horizon and one-third of the OC of the upper centimeter of the Ah horizon (Badía et al., 2014b). In absolute terms, O burning implies much higher C losses, with a total loss of 13.1 Mg of TOC $ha^{-1}$ (Badía et al., 2014b). Our results, obtained in controlled laboratory experiments, were quite similar to reported losses by Certini et al. (2011) in the field in sandy soils from pine forests affected by severe wildfires (14.3–17.8 Mg TOC $ha^{-1}$). The C losses were attributed to the complete removal of the O horizon, whereas the underlying Ah horizon soil did not show any significant change in its carbon content.

With similar experimental burning in an ochric horizon with a thinner O horizon (1 cm thick), the decrease in OC in the first centimeter of the Ah was significant (Aznar et al., 2016). In this case, burning resulted in the loss of three-quarters of the pre-fire OC of the O horizon and one-half of the OC of the upper centimeter of the Ah horizon, which amounted to 3.6 Mg TOC $ha^{-1}$ (Aznar et al., 2016). We have not found significant soil OC losses in the second burned centimeter of the Ah horizon, neither in the mollic horizon nor in the ochric, with or without an overlaying O horizon.

The OC losses depend mostly on the duration of heating and the temperatures reached during burning (DeBano et al., 1979). As summarized by Certini (2005), there is partial consumption of organic matter at 200 °C–250 °C and complete consumption at 460 °C. In laboratory experiments, we found C losses of approximately 90% in different Ah horizons heated 30 min to 500 °C, while heating to 250 °C caused a reduction of approximately 15%–20% (Badía and Martí, 2003a, 2003b); the progressive increase in temperatures caused a decrease in the OC content and many other related properties, such as cation exchange capacity (CEC), soil aggregation stability, microbial biomass, and soil respiration (Badía and Martí, 2003a, 2003b). In this sense, Ulery et al. (2017), studying the effect of severe, high-intensity burning under heavy fuel loads in five wooded sites of California, found an extreme loss of OC and therefore a large decrease of CEC, even at a soil depth of 15 cm. Hinojosa et al. (2016), in an experimental burning of *Cistus-Erica* shrubland in central Spain, found that soil organic matter content was significantly lower in the burned soils (7.43 ± 0.61%) than in the unburned ones (9.75 ± 0.55%), collecting the top 5 cm of the soil. In this case, the average Tmax was 710 °C at the soil surface, and the mean residence time was 13.5 min above 100 °C.

Armas-Herrera et al. (2016), in a prescribed burning of thorny shrubs (Tella, NE Spain), found a decrease in total soil OC content up to 3 cm (and total N up to 1 cm). This was due to an exceptional thermal signature because, as we mentioned above, the temperature at a soil depth of 1 cm reached nearly 400 °C and remained above 200 °C for 25 min. San Emeterio et al. (2016) studied soil N changes in a prescribed burning of *Ulex gallii* shrubland in the western Pyrenees (NE Spain), sampling 10 cm of soil thickness. They found that the total N content decreased significantly just after burning and it stayed lower in burned soils than unburned soils two years later. This TN decrease was followed by an increase in mineral N content. In this experimental burning, the highest temperature recorded was 71 °C at a soil depth of 2 cm. Instead, the organic matter and total N usually increase in burned soils if external black ashes and vegetation inputs are sampled with the mineral topsoil (Jiménez-González et al., 2016; Yusiharni and Gilkes, 2012). These ashes and charcoal, with mineral topsoil, can be quickly lost after erosive rainstorms following the fire due to transport with the runoff (Badía and Martí, 2008; Hosseini et al., 2016).

A sharp increase in the pH of soil samples heated to 500 °C or higher has been commonly observed in various mineral soils (Badía and Martí, 2003a; Giovannini, 2012) probably related to thermal decomposition of calcite to CaO (Rodríguez-Navarro et al., 2009). But in this study, neither carbonates nor pH were significantly affected by burning because, temperatures lower than 500 °C were recorded at a soil depth of 1 cm: 439 °C in dry monoliths and 124 °C in wet monoliths. Only dry monoliths, in their most superficial millimeters, can exceed 500 °C for some seconds, which is not enough to modify the pH or the carbonates content.

Some prior works have reported an increase in topsoil pH (as well as EC) in high-intensity fires, because the combustion of the plant biomass and/or organic layer released ash and charcoal that were rich in base cations (Certini, 2005; Pereira et al., 2012; Ulery et al., 2017, among others). However, Marcos et al. (2009), in a low-intensity prescribed fire of heathlands in three acid soils (pH < 4.3) in the Cantabrian mountains (NW Spain), observed no significant differences between the pH in burned and control soils (0–5 cm soil thickness), in spite of the extreme basicity (pH 8.5–9.5) of the ashes covering the mineral soil.

The increase in EC or total dissolved solutes, in burned dry soil is not related to release of ash from burned plant biomass, so it should be related to the mineralization of the soil organic matter by heating. In our previous studies, the EC increased significantly heating ochric calcareous samples for 30 min at temperatures above 250 °C (Badía and Martí, 2003a). The original EC of the saturated extract paste (ECe) of this ochric horizon (0.9 dS/m) increased slightly to 1.2 dS/m at 150 °C and significantly to 3.4 dS/m at 250 °C, decreasing to 2.4 dS/m by heating at 500 °C when calcium precipitates are formed (Badía and Martí, 2003a).

Definitely, we provide evidence of changes just for the most superficial centimeter of soil depth in some soil physical and chemical properties, either wet or dry. The increase in the heat capacity of the soil, due to its high water content, "protect" some of these properties because significant amount of heat are lost in order to evaporate water in moist soils. However, a high water content can increase the heat conductivity of the soil and transfer soil-sterilizing temperatures by the porous phase to a greater soil depth (Dimitrakopoulos and Martin, 1994). This would affect some biological soil properties, which are more sensitive than the physical and chemical properties (Santín and Doerr, 2016; Hinojosa et al., 2016; García-Orenes et al., 2017), which require further studies.

## 5. Conclusions

Tmax and the heating duration are significantly lower in the wet soil than in air-dried soil in the first and second centimeters of depth. At field capacity, water fills a significant volume fraction of the soil medium, which increases the heat capacity of the soil. This increase allows the soil to absorb certain amount of heat without a subsequent temperature increase, which slows the heat transmission to deeper soil layers. Once the fire is extinguished, the cooling is faster in the still wet soil than in dry soil due to the higher heat conductivity of the former.

The original high WR in unburned air-dried soil, both persistence and intensity, decreased significantly to the third centimeter of soil depth by burning. OC and total N losses were higher by burning soil in air-dried conditions than in wet conditions, but only in the upper topsoil centimeter. Neither OC nor TN were significantly reduced by burning at soil depths below 1 cm. The remaining organic matter was intensely charred, which blackens the first centimeter of air-dried soils, reducing its brightness or luminosity. As a result of OC oxidation, the soluble ions (EC) significantly increased due to burning in the first centimeter of air-dried soils. Both the pH and carbonates do not vary significantly, even in the first centimeter. The effects of burning soil at field capacity were shallower and less intense than in the air-dried conditions, proving that soil moisture provides a certain degree of protection against fire; this should be taken into account when performing a prescribed burn.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.05.254.

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