SJSS
SPANISH JOURNAL OF SOIL SCIENCE

Impact of thermal shock on forest soils affected by fires of different severity and recurrence

Impacto de choques térmicos sobre suelos forestales afectados por incendios de diferente severidad y recurrencia
Impacto de tratamentos térmicos en solos florestais afetados por incêndios de diferente severidade e recorrência

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Received: 12.06.2015 | **Revised:** 22.06.2015 | **Accepted:** 23.06.2015

ABSTRACT

Thermal treatments in the laboratory were conducted using unburned and burned samples of two soils affected by low- or high severity fires in order to study their impact on forests ecosystems with different fire regimes (severity, recurrence). Soils samples were heated in a furnace for 15 minutes at 50 °C, 75 °C, 100 °C, 125 °C, 150 °C, 175 °C, 200 °C and 300 °C to simulate different fire intensities; the process was repeated after a 1 month incubation of the burned, rewetted samples in order to simulate fire recurrence. The soil temperature was measured with thermocouples at the surface and 1 cm depth. The maximum temperature reached (Tmax) and the amount of heat supplied to the samples (degree-hour, DH) were calculated from the temperature-time curves. A total of 128 temperature-time curves (4 soil field samples x 8 heating temperatures x 2 depths x 2 successive heat treatments) were analyzed and the estimation of several soil physical and chemical properties (color, moisture content, pH, total C, total N, soluble C) was carried out in the different soil treatments. High-severity burning provoked significant changes on these physical and chemical properties, whereas slight modifications or even no changes were due to low-severity burning or soil heating under laboratory conditions. The thermal properties exhibited a higher sensitivity for the detection of the fire regime impact than the physical and chemical properties. The results showed that the temperature-time curves and derived parameters (slope, Tmax, DH) can be successfully used to quantify the impact of thermal shocks at low and high temperatures and to evaluate the effect of fire/heating recurrence on forests ecosystems.

RESUMEN

Se realizaron, en condiciones de laboratorio, diversos tratamientos térmicos con muestras no quemadas y quemadas de dos suelos afectados por incendios de alta y baja severidad con el fin de determinar su impacto sobre ecosistemas forestales con diferente régimen del fuego (severidad y recurrencia). Las muestras se quemaron en una mufla durante 15 minutos a 50 °C, 75 °C, 100 °C, 125 °C, 150 °C, 175 °C, 200 °C y 300 °C para simular diferentes intensidades del fuego; tras un mes de incubación de las muestras quemadas rehumectadas, se procedió a una segunda quema para simular la recurrencia del fuego. Se midió la temperatura del suelo con termopares en la superficie y a 1 cm de profundidad y, a partir de las curvas de temperatura-tiempo, se calcularon la temperatura máxima alcanzada (Tmax) y la cantidad de calor suministrada a la muestra (grados-hora, GH). Se analizaron un total de 128 curvas de temperatura-tiempo (4 muestras de suelo x 8 temperaturas de calentamiento x 2 profundidades x 2 tratamientos térmicos consecutivos) y se realizó la caracterización física y química (color, humedad, pH, C total, N total, C soluble en agua) de las muestras de suelo sometidas a los diferentes tratamientos térmicos. Las propiedades físicas y químicas experimentaron cambios significativos como consecuencia del incendio de alta intensidad y no se detectaron variaciones tras el impacto del incendio de baja severidad y del quemado del suelo en condiciones de laboratorio. Las propiedades térmicas mostraron una mayor sensibilidad que las propiedades físicas y químicas para detectar el impacto del régimen del fuego. Los resultados obtenidos demostraron que las curvas de temperatura-tiempo y

DOI: 10.3232/SJSS.2015.V5.N2.06

los parámetros derivados (pendiente, Tmax, GH) pueden usarse satisfactoriamente para cuantificar el impacto del tratamiento térmico a bajas y altas temperaturas y para evaluar el efecto de la recurrencia del fuego/calentamiento en los ecosistemas forestales.

RESUMO

Realizaram-se ensaios de laboratório com diferentes tratamentos térmicos em amostras queimadas e não queimadas de dois solos afetados por incêndios de alta e baixa severidade, para determinar o seu impacto em ecossitemas florestais sob diferente regime de fogo (severidade e recorrência). As amostras queimaram-se na mufla durante 15 minutos a 50 °C, 75 °C, 100 °C, 125 °C, 150 °C, 175 °C, 200 °C e 300 °C com o objectivo de simular diferentes intensidades de queima; após de um mês de incubação das amostras queimadas e umedecidas, foi feita uma segunda queima para simular a recorrência do fogo. A temperatura do solo foi medida com termopares na camada superior e a 1 cm de profundidade. A partir das curvas de temperatura-tempo, foi calculada a temperatura máxima alcançada (Tmax) e a quantidade de calor fornecida (graus-hora, DH). Analisaram-se um total de 128 curvas de temperatura-tempo (4 amostras de solo x 8 temperaturas de aquecimento x 2 profundidades x 2 tratamentos térmicos subsecutivos) e caracterizaram-se as propriedades físicas e químicas (color, umidade, pH, C total, N total, C solúvel em agua) das amostras de solo submetidas aos diferentes tratamentos térmicos. As propriedades físicas e químicas apresentaram alterações significativas com respeito à queima de alta intensidade e não foram detectadas variações após o impacto da queima de baixa severidade e também não no que diz respeito ao aquecimento do solo em condições de laboratório. As propriedades térmicas mostraram uma maior sensibilidade que as propriedades físicas e químicas para a detecção do impacto do regime do fogo. Os resultados obtidos mostram que as curvas de temperatura-tempo e os parâmetros derivados (pendente, Tmax, DH) podem ser utilizados satisfatoriamente para a quantifição do impacto do tratamento térmico a baixas e altas temperaturas, e para avaliar o efeito da recorrência do fogo/aquecimento nos ecossistemas florestais.

KEY WORDS
Low- and -high-severity burning, thermal shock, temperature-time curves, Tmax and degrees-hour, soil physical and chemical properties

PALABRAS CLAVE
Quemado de baja y alta severidad, tratamiento térmico, curvas temperatura-tiempo, Tmax y grados hora, propiedades físicas y químicas del suelo

PALAVRAS-CHAVE
Queima de baixa e alta intensidade, tratamento térmico, curvas de temperatura-tempo, Tmax e graus hora, propriedades físicas e químicas do solo

1. Introduction

Forest wildfires mainly contribute to the destruction of Mediterranean and Atlantic ecosystems and these events are predicted to increase, aided by a general warming and drying trend, but driven primarily by socioeconomic changes, including rural depopulation, land abandonment and afforestation with flammable species (Shakesby 2011). Wildfires, as well as prescribed fires, produce important effects on soil, whose physical, chemical and biological properties are more or less affected depending on the type of property, fire intensity or soil heating and post-fire climatic conditions (Certini 2005). In general, soil structure is destroyed, and pH and available nutrients increase, while microbial communities (density, biomass and activity) and organic C and N decrease; the remaining C and N forms becoming more recalcitrant to microbial attack (Neary et al. 1999; Carballas et al. 2009; Almendros and González-Vila 2012); in addition, color soil variations can also be detected after high severity burn (Ketterings and Bingham 2000; Cancelo-González et al. 2014).

Changes in soil properties associated with fire and soil heating in the first cm of the top layer can be extreme depending on fire temperature and duration. The impact of prescribed fires is relatively small compared to the substantial modifications of wildfires; the heat transfer to soil may explain the observed differences. Soil response can range from positive transitory slight changes in low intensity prescribed fires (nutrients availability increase)

(Barreiro et al. 2010; Bento-Gonçalvez et al. 2012; Fontúrbel et al. 2012; Gómez-Rey et al. 2013) to negative long lasting, even irreversible, soil quality modifications (physical, chemical and biological degradation), in medium- or high intensity wildfires affecting shrublands or forest ecosystems (Neary et al. 1999; Certini 2005; Díaz-Raviña et al. 2012; Lombao et al. 2014). Thus, the intensity and duration of burning determine the combustion of fuels and the input of heat to the soils and consequently the soil recovery after fire. Although fire effects depend on many factors such as soil characteristics, soil-water conditions, vegetation type, etc., the changes caused in the soil quality are directly related to fire intensity and fire residence time, as well as factors determining the transmission of heat through the soil (moisture, texture, organic matter content, etc.) (Martín et al. 2009, 2012; Keeley 2009; Vega et al. 2013a, 2013b). Surprisingly however, despite its interest, the fire severity is not considered in most investigations concerning burned forest soils.

In order to properly evaluate the damage caused by fires on forest ecosystems, the maximum temperature reached and the time that the heating remains should be measured, the latter being considered the most damaging factor of fire severity to soil (Neary et al. 1999; Keeley 2009). Under field conditions during the wildfire events the temperatures cannot be recorded, and it is very difficult to control fire intensity and fire residence time in prescribed fires due to irregular fuel distribution and climatic conditions. In contrast, soil heating under laboratory conditions allows us to evaluate the thermal severity by recording the maximum temperature reached in the soil and the residence time of this heating. Applying a representative temperature gradient (temperature and duration) during the soil heating, temperature-time curves (heating-curves), which can be determined experimentally or predicted theoretically, enable the effect of heat and heat duration on soil to be determined (Molina and Llinares 2001; Mendes-Lopes et al. 2003; Cancelo-González et al. 2012; Thomaz and Fachin 2014). In principle, the measurement of degree hours, giving information on the amount or degree of heat provided to soil, can be also used to determine the combined influence of a given temperature threshold and the duration of temperature above this threshold (Busse et al. 2005). However, studies using this methodology to evaluate the effect of the thermal shock are limited to the soil exchange complex using undisturbed soil samples heated at 200 ºC and 400 ºC during a long-time period (Cancelo-González et al. 2012, 2015). Therefore, results of these laboratory experiments cannot be extrapolated to field conditions where both soil heating temperature and exposure time are lower.

Galicia and the North of Portugal are the areas of Europe most affected by forest wildfires, and worldwide they are amongst the areas with the greatest number of fires per hectare and inhabitant. In the last 42 years 250,000 forest fires were registered in Galicia, which produced 1,711,000 ha of burnt surface from which 700,000 ha were wooded surface (Carballas 2014), causing huge economic and ecological damages that probably will be worse in the foreseeing scenario of climate change. Throughout the last few decades, this area has been affected by a change in fire regime -temporal and spatial- resulting in a dramatic annual increase in the surface burned by wildfires due to human actions, changes in land use, policies and climatic fire risk. Soil studies in this temperate humid zone have been focused on the effects of a single fire, dealing mainly with the short- or medium term-impact of prescribed fires or wildfires of different intensities on soil quality (physical, chemical, biochemical and microbiological properties); the natural recovery of a wide range of burned forest ecosystems under different post-fire climatic conditions (Carballas et al. 2009; Martín et al. 2012; Lombao et al. 2014); and, to a lesser extent, on the efficacy and effects of the implementation of post-fire stabilization and rehabilitation treatments to minimize wildfire risk and to mitigate post-fire soil erosion (Díaz-Raviña et al. 2010a, 2012; Fontúrbel et al. 2012; Vega et al. 2013b; Barreiro et al. 2014; Lombao et al. 2015). However, the evolution of burned soils with time and the cumulative effects of successive fires on soil properties have not been studied. We hypothesized that previous exposition to high temperatures during wildfires, prescribed fires or soil heating at laboratory conditions can alter the soil quality and hence the resistance to further fire events. The aim of the present work is to study the influence of thermal treatments under controlled conditions on soil thermal, physical and chemical properties of forest soils with different fire regimen (severity, recurrence). The topic is of great interest in this temperate humid zone (Galicia, NW Iberian Peninsula) where the most dense and high fuel load forests have been affected by fires and current fire occurrence risk is high.

2. Materials and Methods

2.1. Soil sampling and experimental design

Two Galician (NW Spain) soils over acid rocks, which are representative of the main shrubland ecosystems affected by fires in this temperate humid region, were selected for study. One soil, which was affected by a wildfire in September 2010 (1,700 ha of surface affected), was an Entisol developed over metamorphic rocks (phyllites) located in Laza (Ourense, L soil). The dominant vegetation was *Erica* spp., *Vaccinium myrtillus, Pterospartum tridentatum, Cistus* spp. with reforested *Pinus sylvestris* (mean height of 1-1.60 m). The prevalence of black and white ashes and the total consumption of the ground plant communities (vegetation and litter layers) suggested that fire severity has been moderate to high in the study area (Díaz-Raviña et al. 2012). The other soil, affected by an experimental fire, was a Humic Cambisol developed over granite located in A Estrada (Pontevedra, E soil) and had vegetation dominated by gorse: *Ulex europaeus L.* and some *Pteridium aquilinum* (L.) *Kuhn., Ulex gallii Planch., Daboecia cantabrica* (Huds.) *K. Koch* and *Pseudoarrenhaterum longifolium Rouy.* The shrub was cut six months before the burning and laid over the soil to facilitate its consumption and favor heat transfer to soil. The rate of fire spread was slow (0.30-0.33 m/min) and the soil temperature reached, monitored with chromel alumel thermocouples, was moderate at the mineral soil surface (mean 153 ºC, range 48-420 ºC) and low at 2 cm soil depth (mean 34 ºC, range 22-43 ºC) (Fontúrbel et al. 2012). A total of 50 soil subsamples, of about 100 g each, were collected immediately after the fire from the top layer (0-2 cm depth) of the A horizon of the burned soil and mixed to obtain a representative composite soil sample. Unburned samples from each zone located next to the burned samples but not affected by the fire were also collected at the same depth. The soil was sieved (< 2 mm), homogenized and stored at 4 ºC until the soil heating experiment.

Under laboratory conditions, the unburned and burned samples of both soils were subjected to two successive thermal shocks by applying a representative temperature gradient (temperature and duration) to the soil heating process in order to simulate field conditions, with an interval of one month incubation between the two heat treatments. The temperature-time curves were analyzed and the amount of heat supplied to the soils was calculated for each thermal shock (a total of 128 temperature-curves = 4 soil field samples x 8 temperatures x 2 depths x 2 successive heat treatments). In addition, measurements of different physical and chemical soil properties (color, moisture content, pH, total C, total N, soluble C) were carried out in the different soil treatments. A scheme of the experiment design is shown in **Figure 1**.

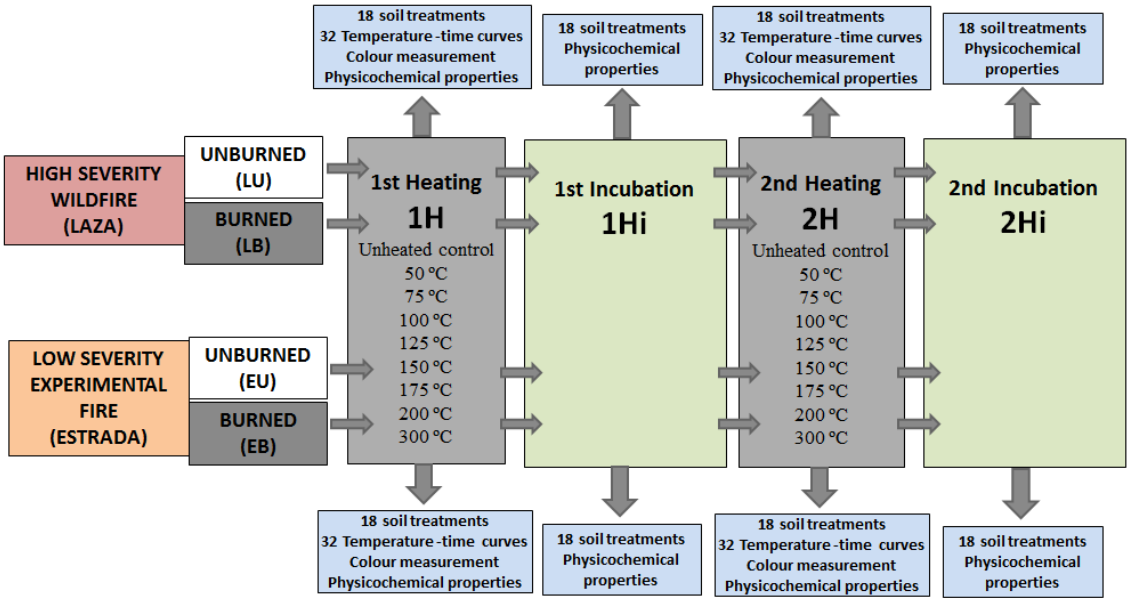

Figure 1. Scheme of the experimental design for the heating treatment. LU, Unburned L soil; LB, Burned L soil; EU, Unburned E soil; EB, Burned E soil.

2.2. Soil heating and incubation

The unburned and burned soil samples (4 samples) from both soils were subjected to 8 different heating treatments to simulate different fire intensities (50 ºC, 75 ºC, 100 ºC, 125 ºC, 150 ºC, 175 ºC, 200 ºC, 300 ºC) using a muffle furnace. The lower temperature of this interval has been chosen to ensure that the effects of low intensity fires were included in the experiment; and the ambient temperature (20 ºC) was also used as reference unheated control. Soil subsamples containing about 200 g of fresh soil were distributed in a layer of 2 cm and placed in a metallic tray. After reaching the selected heating temperature in the muffle furnace, the soil subsamples were placed in the oven and were removed after being kept at the specific temperature for 15 minutes (1H, first heating treatment). The real temperature reached by the soil was measured each minute with thermocouples in the sample at 1 cm depth and at the surface. Each heated soil subsample (a total of 36 = 4 soils x 8 treatments) was divided into two parts; one part was stored and used for analysis, and the other part was rewetted with distilled water to achieve 75-80% of field capacity, re-inoculated with original fresh soil at 1% and incubated in plastic pots at laboratory conditions (dark, 21 ºC) for 1 month (1Hi, incubation following 1H). After soil incubation, the samples were divided again into two parts and one of them was subjected to the same heating process to simulate fire recurrence (2H, second heating treatment; 2Hi, incubation following 2H treatment), thus obtaining a total of 144 different samples (4 soil field treatments x 9 heating temperatures x 2 heating cycles x 2 incubations).

2.3. Temperature-time curves and calculation of degrees-hour

The data obtained each minute from the thermocouples placed at different depths were used to build the temperature-time curves. The exponential equation $y = ae^{bx}$ was used to model the temperature-time curves, where “a” is the ascending slope and “b” is the temperature peak reached by the soil, two parameters used to define the curve and to analyze the susceptibility of the soil to heating. The data fitting was carried out with Origin Pro 8 software. The temperature data recorded during the soil heating were used to calculate the degree hours (DH) that affect each sample as an estimation of the amount of heat supplied to the samples or the fire severity with the following equation modified by Cancelo-González et al. (2012), DH= Σ (Tx-Ti)/60, where Tx is the temperature in ºC measured every minute and Ti is the initial temperature of the sample (room temperature).

2.4. Soil analysis

The physical and chemical characterization of the soil samples (moisture content, pH in water and KCl, total C content, soluble C) was performed following the procedures described in a previous article (Lombao et al. 2015). The water soluble C (WSC) was determined after extraction with distilled water (1:5 w/v) at 20 ºC for 2 h; and the hot water extractable C (HWC) after extraction with distilled water (1:5 w/v) at 80 ºC for 24 h. The total soluble C in the extracts was measured by oxidation with dichromate in an acidic medium. The color measurements were performed in quintuplicate with a portable spectrophotometer (Konica Minolta CM-700d) equipped with CM-S100w (SpectraMagicTM NX) software as previously described by Cancelo-González et al. (2014) considering the CIELAB color system. Then the mean values of the Cartesian (L*a*b*) and cylindrical (L* C^*_{ab} h_{ab}) coordinates were calculated. From them, only L* and h_{ab} showed significant changes following high temperature stress (field conditions, laboratory conditions) and were therefore considered in the present study.

3. Results and Discussion

3.1. Physical and chemical properties

The two selected soils were acid (pH in water around 4) with a high organic matter content (L soil, 35% moisture level, 23.4 g total C kg^{-1}, 1.1 g N kg^{-1}, 700 mg soluble C kg^{-1}; E soil, 40% moisture level, 17.4 g total C kg^{-1}, 1.1 g total N kg^{-1}, 589 mg soluble C kg^{-1}) (**Figure 2**). The fire under field conditions modified the soil properties; however, in line with previous studies performed in the same region (Fernández et al. 1997; Prieto-Fernández et al. 1998; Carballas et al. 2009; Martín et al. 2012), a different effect was observed depending on fire severity. The passage of a high severity wildfire caused a decrease in the soil organic matter content and the related moisture content (reductions of 17% in moisture level, 37% in total C content and 50% in soluble C) and an increase of soil pH (0.5 units); in contrast, the prescribed fire produced only significant changes in the labile fraction of the organic matter (50% reduction in soluble C). Changes in color parameters were also observed as consequence of the fire (**Figure 3**). In the L soil samples the wildfire led to a significant decrease in lightness (L*) of 2.4-2.8 CIELAB units; furthermore, the differences in the L* parameter between the burned and the unburned samples in the area affected by the wildfire were notably higher than those observed between the unburned and the burned samples in the area affected by the prescribed fire, which could be due to the fire severity. Likewise, a significant difference (higher than 3 CIELAB units) appears between the L soil burned and unburned samples in the color tone (h_{ab}, from 60.7 to 64.6) whereas only slight differences were observed in the E soil. Differences in burning temperature and duration can explain the results obtained in both experimental areas. In the E soil, the low soil temperatures (around 153 ºC and 34 ºC in the surface and at 2 cm depth, respectively) measured under field conditions did not provoke changes in most soil properties analyzed, while in the L soil, drastic changes in pH, organic matter pool and soil color clearly indicated that the burning temperatures had exceeded 400 ºC (Fernández et al. 1997; Certini 2005; Marcos et al. 2007).

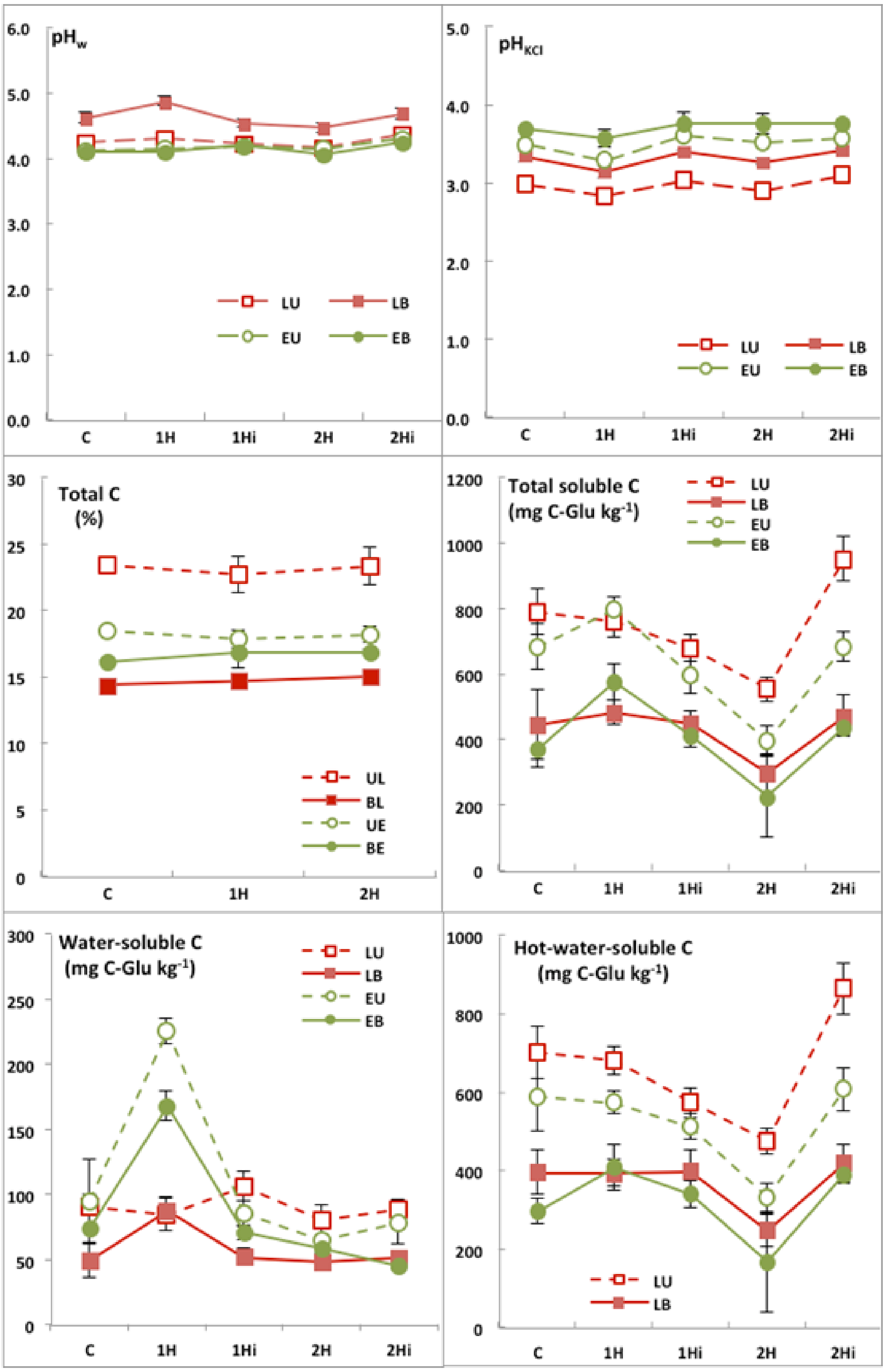

Figure 2. Soil physical and chemical properties (mean value of the 8 different heating treatments applied to each soil ± SE) in the unburned (U) and burned (B) samples of two studied soils (L, soil affected by a wildfire; E, soil affected by a prescribed fire). C, unheated control soil; 1H, first heating; 1Hi, incubation following 1H; 2H, second heating; 2Hi, incubation following 2H.

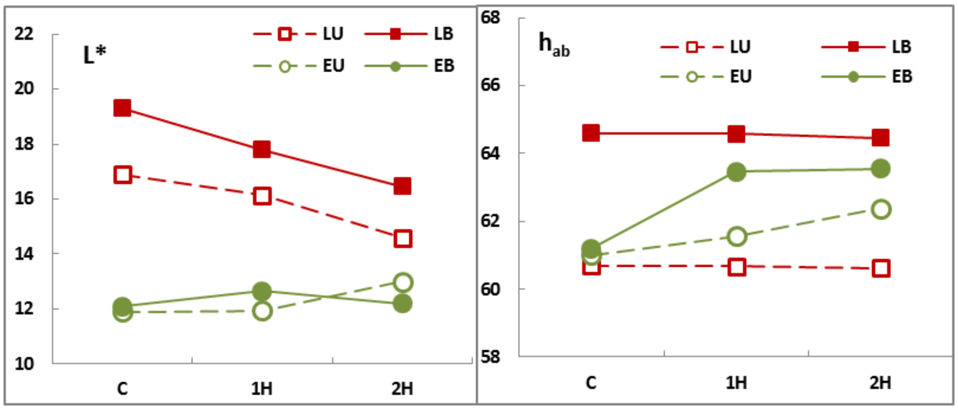

Figure 3. Color parameters (L, lightness; h_{ab}, tone of color; mean value of the 8 different heating treatments applied to each soil±SE) for the unburned (U) and burned (B) samples of the two studied soils (L, soil affected by a wildfire; E, soil affected by a prescribed fire). C, unheated control soil; 1H, first heating; 1Hi, incubation following first heating; 2H, second heating; 2Hi, incubation following second heating.

As expected, the soil moisture level was modified by the soil heating under laboratory conditions, a negative and significant relationship being observed between the degree-hour values and the loss of moisture content (R = 0.8795, $p < 0.005$, n = 96). In contrast, no variations in the physical and chemical properties (color parameters, pH, total C, total N, soluble C) were detected under laboratory conditions in the unburned and burned samples of both selected soils as consequence of the thermal shock in the temperatures range of 50-300 ºC (data not shown). Therefore, in order to facilitate the comparison of data, for each soil the mean value of the 8 different soil heating treatments (± SE) was calculated. The values clearly showed no changes or slight changes in soil pH and total C content due to the successive thermal shock treatments (C, unheated control; 1H, first heating treatment; 1Hi, incubation following 1H; 2H, second heating; 2Hi, incubation following 2H). This behavior can be explained by the fact that the combustion of the organic matter occurred at higher temperatures than those in our experiment (temperature measured with thermocouples 28-255 ºC) (Díaz-Raviña et al. 1992; Fernández et al. 1997; Almendros and González-Vila 2012). However, the soluble C showed variations with peaks after the thermal shock, the changes being more pronounced in the E soil following the first soil heating event (1H); and in the L soil following the second heating event (2H). These data are consistent with the findings of several authors showing increases in the labile C after soil heating below 200 ºC (attributed to nutrients produced by the death and lysis of microorganisms) and a further decrease after the incubation period caused by the use of this labile pool as source of energy during the recovery of the microbial population (Díaz-Raviña et al. 1992; Prokushkin and Tokareva 2007). The results seem to suggest that, despite of the low values for the Tmax reached by the soil samples, somehow the successive thermal shocks can provoke changes in the quality of the organic matter. This supports the fact that labile fractions of the soil organic matter (soluble C, microbial C, carbohydrates) rather than the total organic matter content should be used to detect the impact of fire (Prieto-Fernández at al. 1998; Villar et al. 2004; Díaz-Raviña et al. 2010b; Martín et al. 2012; Almendros and González-Vila 2012). As observed for most physical and chemical properties, no modifications in color parameters (L, lightness; h_{ab}, tone) were detected after consecutive thermal shocks (H1 and H2) under laboratory conditions.

3.2. Temperature-time curves (TTC) and degrees-hour

A total of 128 temperature-time curves (surface, 1 cm depth) were obtained for the different soil heating treatments (data not shown). The results showed that the soil response differed notably depending on the soil heating temperature; for the soil samples heated at 50-75 ºC the data fitted to the linear model R^2 = 0.821-0.984 ($p < 0.001$) whereas for the soil samples heated in the range of 100-300 ºC the data fitted to the exponential model R^2 = 0.741-0.987 ($p < 0.001$). An example of the time-temperature curves obtained for some heated samples of the L soil is illustrated in **Figure 4**. The Tmax values estimated from the exponential method (parameter "b") were almost identical to the maximum temperature measured by the thermocouples (real temperature) (values of 28-255 ºC in surface; 23-240 ºC at 1 cm depth). It should be noticed, however, that these values were lower (around 20-122 ºC) than the theoretical temperature applied to soil (muffle furnace temperature 50-300 ºC). The differences between the real (thermocouples) and the theoretical temperatures varied depending on both the temperatures applied and the soil characteristics (soil type, depth, fire history), higher differences being detected in the surface at higher temperatures (mean difference values of 20 ºC, 40 ºC and 80 ºC for the soil temperature ranges of 50-100 ºC, 100-200 ºC and 200-300 ºC, respectively). The data clearly point out to the importance of the measurement of the real temperature in laboratory heating experiments. It should be noticed, however, that most published studies concerning thermal shock impact on soil properties are related to the furnace temperature (Díaz-Raviña et al. 1992; Terefe et al. 2008; Marcos et al. 2007; Bárcenas-Moreno and Bååth 2009); therefore, this makes difficult the comparison between different studies.

For both L and E soil samples, the parameters obtained from the exponential model (a, ascending slope and Tmax, maximum temperature) varied depending on previous soil fire history. There are notable differences between the unburned and burned samples following the prescribed fire or the wildfire (field conditions) and between the unheated and heated samples following the thermal shocks (first and second heating under laboratory conditions, 1H and 2H) (**Figure 4**). For all soil heating treatments, the temperature reached by the soil was higher in the surface than at 1 cm depth (e.g. 1H LU300, Tmax 184 ºC and slope 0.204 at the surface; 1H LU300, Tmax 177 ºC and slope 0.167 at 1 cm depth), which can be attributed to the low thermal conductivity of the soil (Terefe et al. 2008; Badía-Villas et al. 2014). In most cases, the Tmax and slope values (a) were also higher in the burned samples after the wildfire or prescribed fire (field conditions) than in the corresponding unburned ones (i.g. LU300, 1H Tmax 184 ºC and slope 0.204; LB300, 1H, Tmax 199 ºC and slope 0.249) as well as in the samples subjected to the second thermal shock treatment (laboratory conditions, 2H treatment) compared with the corresponding first thermal shock (1H treatment) (i.g. LB300, 1H Tmax 199 ºC and slope 0.249; 2H, Tmax 268 ºC and slope 0.221). The samples previously heated under field or laboratory conditions also showed a lower amplitude in the difference of temperatures between the surface and 1cm depth compared with the corresponding unburned samples, indicating that previous heating had an effect on the vertical heat transmission. The data are in accordance with a previous study of Massman et al. (2008) indicating differences in the surface temperature following a prescribed fire; at a burn site the amplitude of the daily cycle of soil heating and cooling could be as much as 10 ºC greater within the burnt area than at a nearby no-burned area, whereas for the annual cycle, the amplitude difference was about 2 ºC greater.

The degree-hours (DH) applied to the whole data set samples (a total of 128) varied from 2.1 to 74.6 DH (data not showed). The DH values for the thermal treatments were different depending on the range of temperatures (values <10 DH for treatments lower than 100 ºC; 10-30 DH for treatments in the range of 100-200 ºC; and > 30 DH for soil heating at 300 ºC). These values were lower than those obtained in previous studies performed with soils of the same area (Cancelo-González et al. 2012, 2014), which can be explained by differences in both soil heating temperature and exposure time (28-255 ºC during 15 minutes in our experiment, 200-400 ºC for more than 100 minutes in the above mentioned studies).

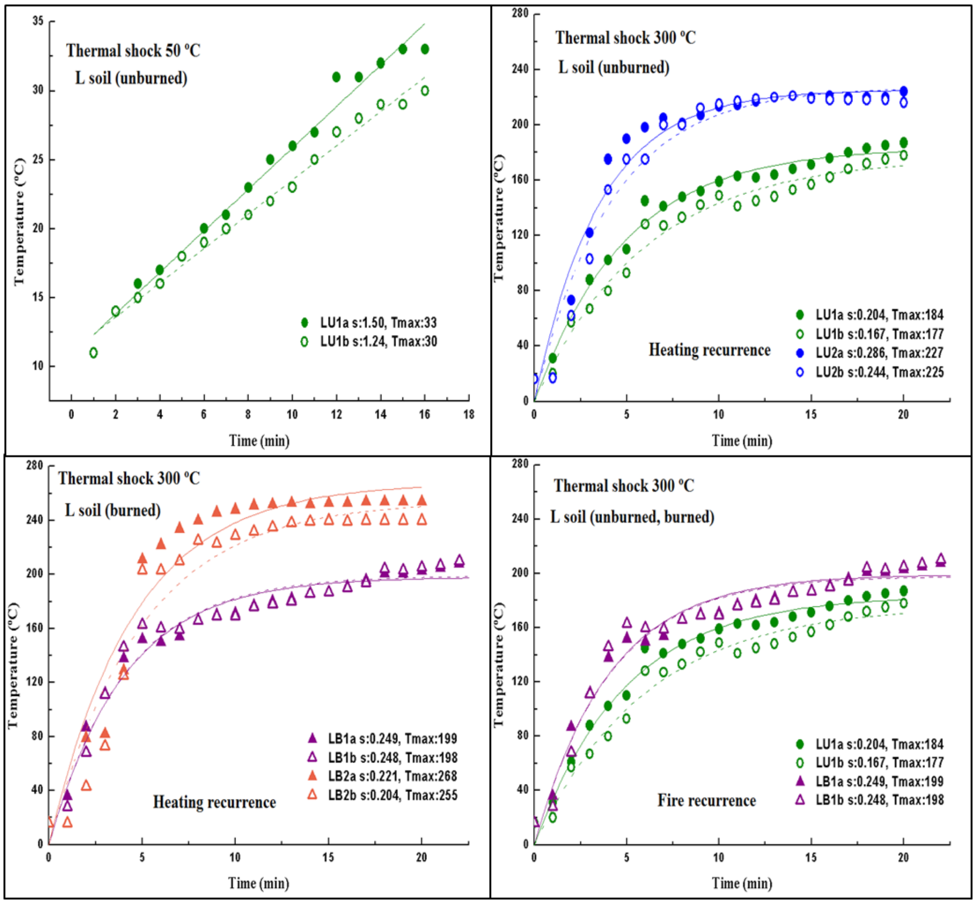

Figure 4. Temperature-time curves for the surface and 1 cm depth of samples from the L soil subjected to different thermal shock treatments (A, soil heating at 50 ºC; B, C and D, soil heating at 300 ºC). (LU, unburned L soil samples; LB, burned L soil samples).

For the same thermal treatment (specific furnace temperature during 15 minutes), differences in DH values, and therefore in the heat accumulated, were observed among the samples with successive soil heating treatments (1H and 2H treatments). The values of all the data obtained in the temperature-time curves were integrated into one figure representing the theoretical temperature applied to the soil (furnace temperature) against the degree-hours values (Figure 5). This was done to summarize the 64 heating treatments and make it easier to analyze and compare the soil response to the thermal shock of the different samples collected under field conditions from the two selected soils subjected to a prescribed fire or a wildfire. As expected, the degree-hours, and hence the heat accumulated in the soil, increased with the temperature and the data fitted well to the linear model (y = ax + b) with a high degree of confidence (R^2 = 0.996-0.923; $p < 0.001$). This is in accordance with other studies showing higher values of degree-hours at 400 ºC compared with those obtained at 200 ºC (Cancelo-González et al. 2012, 2015), although the relationship between soil temperature and heat accumulated has not been established. It should be noticed that a low range of soil heating temperatures for a short time (50-300 ºC, 15 minutes of exposure to the specific temperature) was considered in the present study; however, different relationships might be observed under field conditions when temperature and time exposure reach higher values (high severity wildfires). Likewise, reported DH values at the surface and at 1 cm depth also differed notably, higher DH values being exhibited by the soil samples at the surface of the burned/heated samples.

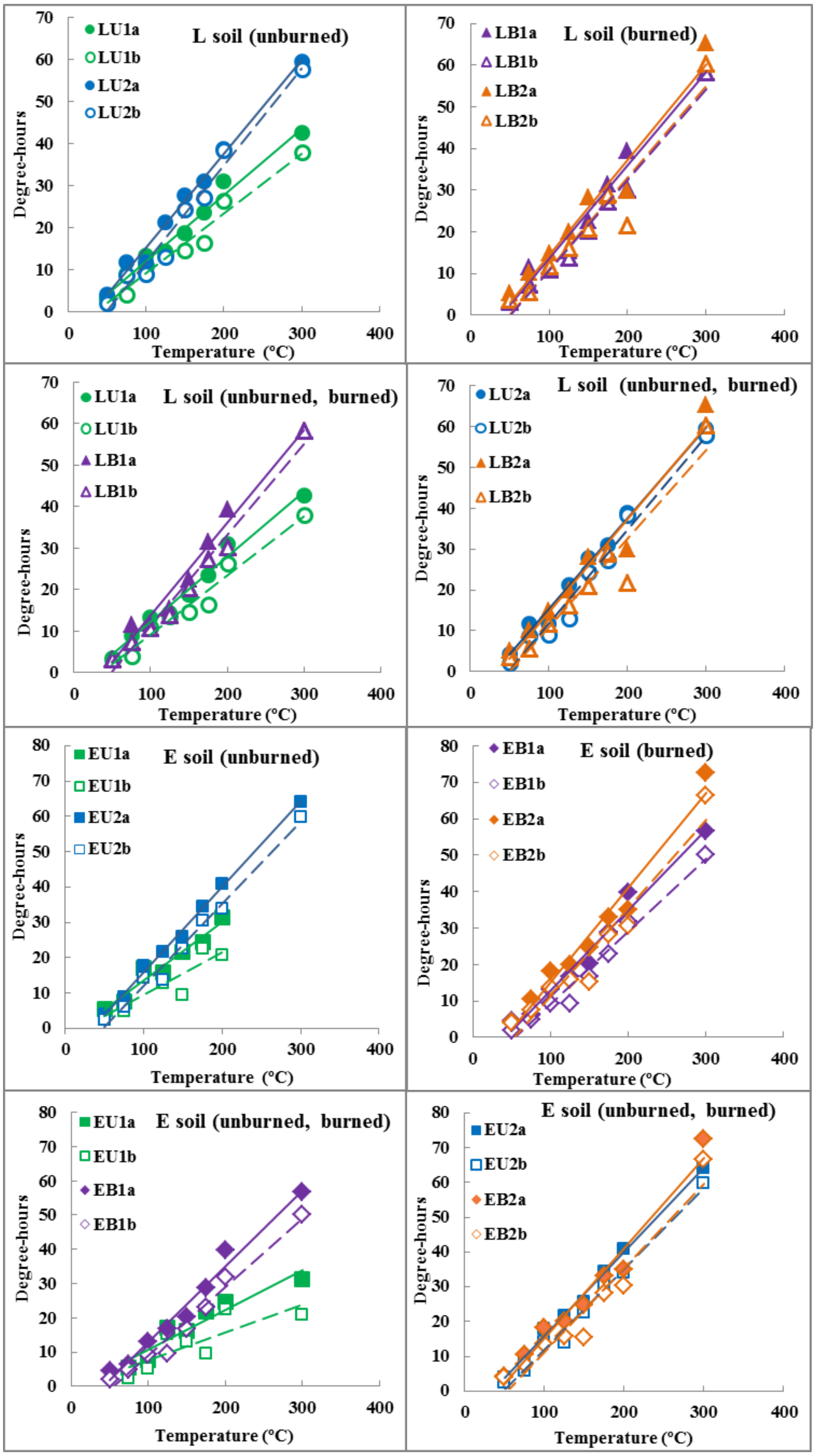

Figure 5. Relationships between the temperature applied to soil and the accumulated heat in the unburned (U) and burned (B) samples from the L and E soils subjected to thermal shock at different temperatures (50, 75, 100, 125, 150, 175, 200 and 300 °C) under laboratory conditions (1, first heating; 2, second heating; a, surface; b, 1 cm depth).

Figure 5 also allows us to examine the influence of fire recurrence (field conditions) and soil heating recurrence (laboratory conditions) on the soil response to high temperature stress (comparison of the samples affected by the prescribed fire or wildfire and the corresponding unburned samples; comparison of the first and second thermal shock treatments, 1H and 2H). Different regression lines and therefore slope values (parameter “a” indicating the susceptibility of the soil to temperature) were exhibited by the soils samples depending on previous exposition to high temperatures; this is reflected by increased slope values in the samples subjected to previous soil heating under laboratory or field conditions (1H treatment: LU 0.158, LB 0.224; EU 0.165, EB 0.221; 2H treatment: LU 0.229, LB 0.240; EU 0.242, EB 0.259). The data clearly indicated that applying the same heating temperature to the soil, the burnt samples (prescribed fire or wildfire) reached higher degree-hours values than the corresponding unburned samples. The same tendency was observed for data obtained following soil heating recurrence; for the same soil heating temperature the DH or accumulated heat was higher in the samples after the second thermal shock (2H) than in the corresponding samples following the first soil heating event (1H).

The level of heat accumulated in the soil could be increased notably by fire/heating recurrence; the higher increases were detected at the higher soil heating temperature (e.g. increase up to 10-15 DH after 2 heating cycles at 200-300 ºC under laboratory conditions or after high severity wildfire). Furthermore, the differences observed between the heated samples at the surface and at 1 cm depth were attenuated as consequence of fires (field conditions) and thermal shock events (laboratory conditions). Although information on how the recurrence affects the soil response to a new heating event is scarce, our data are consistent with some investigations indicating that the thermal soil properties can vary as consequence of fires (Massman and Frank 2004; Verdes and Salgado 2011; Rubio et al. 2012) and that the maximum temperatures reached by the soil due to day-to-day thermal regimen were higher in the burned soils than in the unburned ones (Iverson and Hutchinson 2002; Massman et al. 2008). The results of these and other studies also indicated that moisture and bulk density (Campbell et al. 1995; Busse et al. 2005; Rein et al. 2008; Cancelo-González et al. 2012; Rubio et al. 2012) were the soil properties that have the greatest influence on soil heating dynamics (Tmax reached and heat transfer on depth). It should be noticed that in our experiment the moisture level was maintained constant (soils were rewetted after soil heating) and therefore did not affect data interpretation; other properties that govern the heat transport flow inside the soil could be involved.

The combined interpretation of the data obtained in the 128 temperature-time curves (Tmax, DH, slope) performed with the unburned and burned samples from both the low- and high-severity fires after thermal shock provides interesting information on heat transmission through the soil. One important consideration of the heating curves is the importance of the soil heating history as a decisive factor for interpreting the effects of forest fires on soil ecosystems (evaluation of impacts). It is very clear that differences exist among the thermal properties in the soil samples when the scenario changes; i.e. before and after soil heating/soil burning. Therefore, when the soil is burned its thermal properties and heat flow changed reaching in a shorter time higher Tmax values and affecting to a deeper soil layer. Another important aspect is the importance of low- and medium-severity burning as disturbance agent in forest ecosystems in relation to its negative accumulative effects; this should be taken into account in the process of evaluating the risks and reducing damages for the environment, particularly in Mediterranean countries where the frequency of wildfires is increasing and prescribed fires are used in some rural and forest areas as a management tool to prevent large fires. This is supported by investigations conducted in the eastern littoral of the Iberian Peninsula (Valencia, Cataluña) showing negative effects of recurrent prescribed fires evidenced by a loss of plant productivity and a reduced availability of soil nutrients content (Ferrán et al. 2005; Eugenio et al. 2006). Finally, another consideration of the present study is that temperature-time curves and degrees-hour methodologies are promising tools for examining the fire severity (temperature and residence time of soil heating). This aspect is of great interest for evaluating, under both laboratory and field conditions, the thermal shock effects on soils and to compare the results obtained in contrasting soils showing different fire regime (severity, recurrence) as well as those obtained for the same soil during a long time period (cumulative effects).

4. Conclusions

The results of this study indicated that the properties analyzed showed a different sensitivities to the impact of soil heating in forest ecosystems with different fire severity and recurrence. Physical and chemical properties can be used to detect the impact of high severity wildfires but not the impact of prescribed fires or thermal shocks at a low temperatures range (50-254 ºC) under laboratory conditions. In contrast, temperature-time curves and derived parameters (Tmax, DH) can be used to quantify the impact of soil heating at low temperatures (low severity) and to evaluate the effect of fire/heating recurrence. The results showed that the thermal response to a new heating event, measured in terms of Tmax reached and heat accumulated (DH), varied depending on previous soil exposure to high temperatures (fire, soil heating). Taking into account that information on the accumulative effect of fires and on how the recurrence affects the soil response to a new heating event is scarce, further studies are necessary in order to gain more insight on this topic. Work is in progress in our laboratory to evaluate the impact of fire regimen (severity, recurrence) on a wide range of soil biochemical and microbiological properties and to try to relate the observed changes with the heat accumulated into the soil.

5. Acknowledgements

This study was supported by the Ministerio Español de Economía y Competitividad (AGL2012-39686-C02-01) and by Fundación MAPFRE. A. Barreiro and A. Lombao are recipients of FPU grants from the Spanish Ministry of Education. We thank Rosario Basanta for the Portuguese translation.

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