ASSESSMENT ON THE RESPONSE OF THE THERMAL CONDUCTIVITY AS A FUNCTION OF WATER CONTENT OF A BURNT MEDITERRANEAN LOAM SOIL

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RESUMEN. La propuesta de este trabajo es explorar la variabilidad en la conductividad térmica -**λ**- de un suelo típico mediterráneo después de una quema prescrita, y evaluar los efectos de las cenizas en el transporte de calor una vez incorporadas a la matriz del suelo. La parcela de muestreo se localiza en el macizo de Montgrí (NE, de España). Se recogieron 42 muestras de suelo entre la superficie y los 5 centímetros de profundidad para los dos escenarios, antes y después de la quema. Se determinaron diferentes variables físicas y químicas para la caracterización del suelo. La variabilidad en la conductividad térmica se determinó a partir de curvas "dry-out" para cada escenario. Las curvas se construyeron a partir del método SoilRho® basado en ASTM D/5334-08 validado por LabFerrer. El contenido hídrico de cada muestra se calculó por gravimetría. Para la determinación de **λ** se utilizó el sensor térmico de doble aguja SH-1 junto con el data-logger KD2-Pro permitiendo realizar el seguimiento en continuo del sistema. El diseño experimental reveló cambios en los valores de la conductividad térmica del suelo que fueron menores para el suelo una vez quemado. Cuando las diferentes cantidades, en volumen de cenizas, se incorporaron a la matriz del suelo, el comportamiento térmico e hidrodinámico de éste, también presentó diferencias. Las muestras que incluían cenizas blancas mostraron una conductividad térmica más elevada que las muestras con cenizas negras. Los resultados en el análisis difractométrico revelaron diferencias mineralógicas entre ambos tipos de cenizas. En resumen, existieron diferencias en los valores de conductividad térmica cuando el escenario cambió (antes y después de la quema). Por otro lado, el volumen de cenizas incorporado al suelo incrementó las diferencias entre los dos tipos de muestras, mostrando incluso mejoras en el transporte del flujo térmico cuando los contenidos hídricos del medio afectaban en gran medida a este proceso.

ABSTRACT. The purpose of this research is to explore the variability on the soil thermal conductivity -λ- after a prescribe fire, and to assess the effects of the ashes on the heat transfer once its were incorporated into the soil matrix. Sampling plot was located in the Montgrí Massif (NE of Spain). A set of 42 soil samples between surface and 5 cm depth was collected before and after the fire. To characterize the soil chemical and physical variables were analyzed. To determine the variability on the soil **λ** a dry-out curve per scenario (before and after fire) was determined. SoilRho® method based on ASTM D-5334-08 which was validated by LabFerrer was used. Water content was calculated by dried sample in the oven. To determine the **λ** a SH-1 dual-needle sensor combined with KD2-Pro reader-logger were employed. The experimental set allowed to obtain a continuous large soil thermal data-set λ(θ) curve. Soil thermal conductivity shown changes in their values. Indeed, in all moisture scenarios the values of soil **λ** decreased after soil was burnt. The critical point in the relationship θ(λ) for the soil after fire always was stronger than soil before to be burnt. When several volume of different ashes were incorporated into the soil, thermal and hydrodynamic behaviour presented differences. Soil with "white" ashes showed a high thermal conductivity. An X-Ray difractometry analysis allowed to clarify and to verify these results. To sum up, we could say that thermal consuctivity presents changes when the scenario changes, i.e. before and after to be burnt. On the other hand, the volume of ashes incorporated on the soil increased the differences between no burnt and burnt soil, showing even some improvements on the heat transfer when water content started to govern the process.

1.- Introduction

The impact of fire on soils can vary between highly beneficial, when the fire is not too intense and soil heating brief, to irreversible damage, which occurs during deeply penetrating heat pulses and long-term exposures (DeBano et al. 1999, 2005). Prescribed fires are used in Catalonia since 1999 as a tool, among others, for managing forested areas with large amounts of fuel in order to prevent high intensity fires. The Montgrí prescribed fire main objective was reduced the shrubland in an ancient and abandoned pine plantation. On the whole of the literature, many researchers have studied the variations on the chemical and physical properties on or above burnt soils, but there are other physical properties as are thermal properties that govern the heat flow transport inside the soil, and affect the aspects mentioned above. Because of the severity of the soil heating during a prescribe burn the impacts can be significant and serious. They include the formation of a hydrophobic layer on the surface of or within the soil, destruction of most of the organic material in the upper few centimeters of soil and the concomitant loss of soil aggregate stability (Massman et al., 2008), changes in soil pH and soil chemistry, long-term differences in soil moisture amounts, increases in soil bulk density with accompanying decreases in soil porosity, therefore changes on soil structure (Huffman et al., 2001; Neary and Ffolliot, 2005). Thus, when biomass on or above a soil surface burns, a heat pulse penetrates the soil. The resulting high soil temperatures can alter soil properties and kill roots and soil microbes (Campbell et al., 1994).

On the other hand, changes in the soil thermal conductivity (λ, a measure of a soil's ability to conduct heat) is less obvious, but is not less significant because it is directly to many of the other fire included changes in the soil. Some of these changes would be changes in the structure, because soil thermal conductivity is strongly determined by soil structure (Farouki, 1986), and soil composition (e.g. De Vries, 1963; Campbell and Norman, 1998), that occur whenever soil organic matter is burned, therefore soil bulk density changes. Consequently, the purpose of this research is to explore the variability on the soil thermal conductivity -λ- after a prescribed burn for a natural and typical Mediterranean limestone soil to laboratory scale. For achieving the main goal, it was splited into up three operative objectives; (i) to observe the realtionship between soil thermal conductivity and water content, (ii) to evaluate the influence of several percentages of ashes on the soil thermal conductivity, and (iii) to determine which was the impact of the ashes on thermal conductivity when the ashes were incorporated into the soil matrix, taking account several moisture scenarios.

2.- Methodology

The study area is located in the north-eastern corner of the Iberian Peninsula in the coastal mountains of Catalonia, within the calcareous Montgrí massif. The vegetation of this area is typically Mediterranean, composed of Pinus plantation (*Pinus halepensis*) with shrubland of *Quercus coccifera, Cistus albidus, Rosmarinus officinalis* and *Pistacea lentiscus*. At the time of the fire, the air temperature was 12.5 ºC with a air relative moisture about 60%. In these conditions a prescribed fire was carried out. A set of 42 soil samples between surface and 5 cm depth was collected before and after the fire (UTM coordinates x: 514555 y: 4659552). The size of the plot is 18 x 4 meters (see Fig. 1). Soil samples were taken before, and just after the fire, from 42 points arranged in three transects and three crosses across the central transect.

The fire temperature was measured with a laser thermometer. In order to characterize the soil chemical and physical variables were analyzed. Particle-size distribution was determined using the wetting sieve method for 2000 to 50 μm and a device by dispersion laser beams (Malvern Mastersizer/E) for particles smaller than 50 μm. Bulk density and porosity were determined from undisturbed sample volume. Calcium carbonate was determined based on Bernard calcimeter (Skiner et al., 1959), whereas the hygroscopic water content was determined by weight differences after drying the samples at 105ºC during 24 hours The pH and conductivity was analysed following extraction with pure water (1:2.5), and measured with a pH-meter and conductimeter (MAPA, 1986). The organic matter was measured according to the sulfochromic oxidation method (Walkley and Black, 1934). To determine the variability on the soil thermal conductivity - **λ-** a dry-out curve (relationship between thermal properties and water content) was calculated (Rubio et al., 2008; 2009) using a target soil sample, which was a composed soil sample for each scenario, i.e. before and after prescribed burn, using a total of 42 soil samples. The samples were wetted up and packed until a target bulk density into a soil column devices. Water content was calculated by dried sample in the oven. To determine the thermal conductivity a SH-1 small dual-needle sensor was employed. The method is based on ASTM D-5334-08, which it is developed using the method and analysis described by Shiozawa and Campbell (1990). The SH-1 thermal sensor combined with the KD2-Pro reader-logger allowed us to obtain reliable and accurate soil thermal properties values and a continuous large soil thermal data-set.

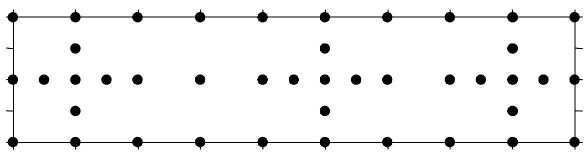

Fig. 1. Sampling plot designed. Black points are sampling points.

The experimental design with ashes was performed on soil column devices, as well. Several volumes of two types of ashes (white and black ashes) were used. The colour of ashes implies differences on the temperature reached on the soil surface; therefore; also imply differences in the composition of ashes. The ashes were mixed with burnt soil on the percentages 10%, 20%…, 90%.

For determining the dry-out curves with ashes, we only took into account the higher percentage of ashes (90%), because this would be the most critical case.

3.- Results

The soil from this plot in the Montgrí massif was classified according to USDA as loam textural class (SSS, 1998). Mean bulk density was around 1100 kg·m^{-3}. The chemical and physical properties values before and after prescribed burnt were, respectively: mean total organic carbon content were about 14.7% and 17.2%. The mean electric conductivity increased. On the other hand, the pH of the media did not show any change, and hygroscopic water content was similar, as well.

Table 1. Physical and chemical characteristics of the studied soil before and after fire. OM = organic matter content; CaCO3 = calcium carbonate content; EC = electrical conductivity and Hw =

hygroscopic water content.

Variables	Before Fire	After Fire
Sand (%)	39.3	41.7
Silt (%)	35.1	32.4
Clay (%)	25.6	25.9
E.C. ($\mu s \cdot cm^{-1}$)	330	520
pH	7.0	7.1
O.M (%)	11.2	10.9
CaCO3 (%)	<3	<3
Hw (%)	1.8	1.9

With respect to soil thermal conductivity -λ-, it showed changes in its values (Fig. 1). Indeed, in all cases the values of the dry out curve for soil λ decreased after soil was burnt than native soil. The critical point in the relationship θ(λ) always was stronger when soil samples were burnt than soil before prescribed fire, starting a critical reaction at 8% of water content for samples not burnt, and 6% of water content for burnt samples. Probably, this situation could be explained by the incorporation of burnt organic matter on the soil after prescribed fire, such that organic matter behaviour did not transmit well the heat pulse.

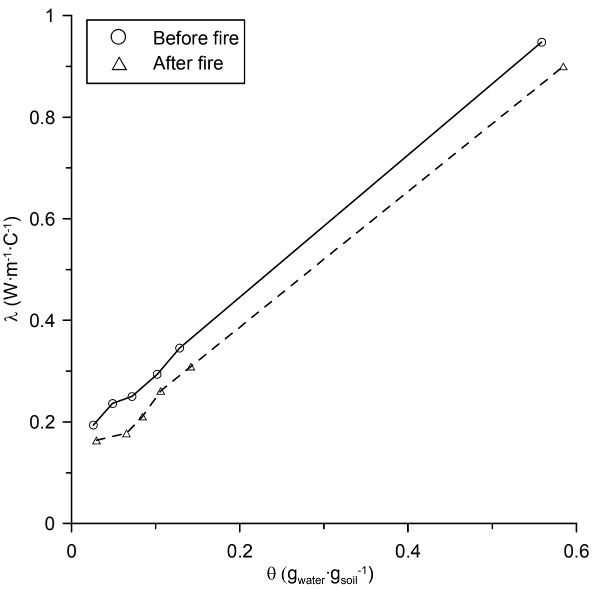

Fig. 2. Dry-out curves of the relationship between thermal conductivity and gravimetric water content.

Also, the mean temperature values for the soil samples before and after fire during the experiment were about 21.5ºC and 18.5ºC, respectively. The difference between both values did not affect the soil thermal properties measurements.

Finally, a new experiment using the black and white ashes found out over the soil surface after fire was carried out. After the prescribed fire a different quantity of ash patches were found out.

Some of the patches were black ashes where the temperature of the fire was lower, and other patches were white ashes where the temperature of the fire was higher (around 600ºC). The new test was used to find out differences out between two types of ashes. The soil samples after fire was used to amend and to repack with different quantities of black ashes in volume percentage of soil (0, 10, 20, 30,…, 100 %), and maintaining a similar bulk density. The same test was performed with white ashes.

The relationship between bulk density and porosity using fired soil and different ashes (black and white) is shown in Fig. 3. The linear relation between both variables means a well-compacted soil samples, and a decreasing pattern of the macro-porosity when bulk density increase, as well. In any case, two well-defined groups of samples were determined. The soil mixture with black ashes presented less bulk density values than soil with white ashes, which presented a lower porosity.

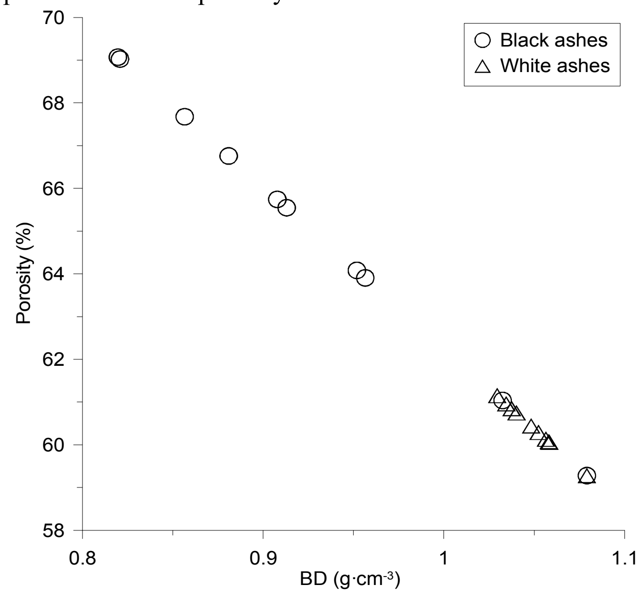

Fig. 3. Relationship between bulk Density and porosity for a burnt soil mixture with two different types of ashes.

Fig. 4 presents different volume percentages of two types of ashes mixture with a soil after fire, where soil thermal conductivity was measured. The white ashes (dot line) always shown a higher thermal conductivity, meanwhile soil with black ashes was a lower λ. Probably, this fact would be attributed by the large organic matter content that was not burned during the prescribed fire (Abu-Hamdeh and Reeder, 2000), such that the organic matter content has a low thermal conductivity. Hence, when organic matter content increases exhibit a decreasing thermal conductivity of the soil (Noborio and McInnes, 1993). However, the fine particle size of the white ashes improved the target bulk density, therefore it contributed to improve the soil thermal conductivity values.

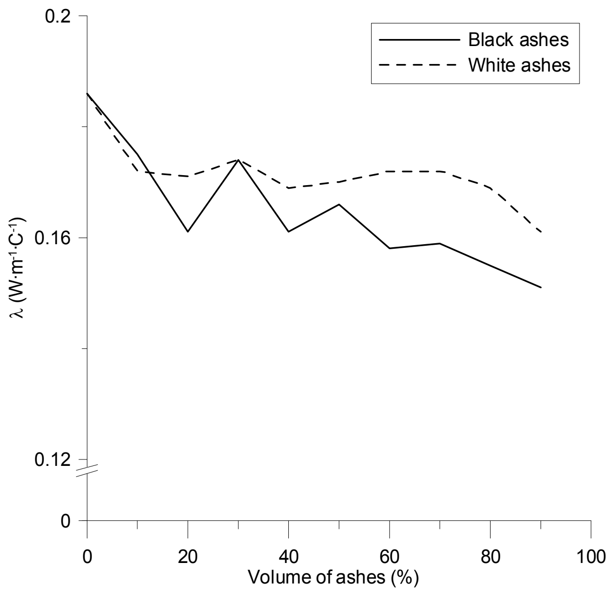

Fig. 4. Effects of the different ashes on soil thermal conductivity for a burnt soil.

To verify in detail the differences between both soil samples (before and after burning), a X-ray difractometry was performed. Fig. 5 shows the results of this analysis. The soil before burnt (black line) presented a less quarz than soil after fire, however, existed traces of mica musvovite, that it desappear when soil was burnt.

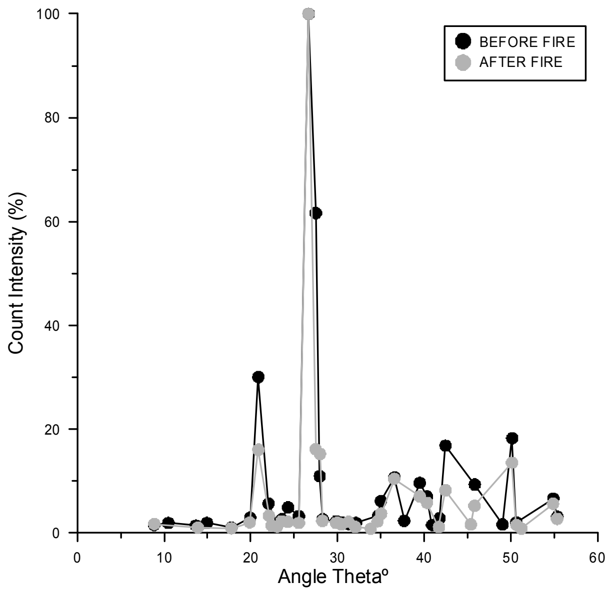

Fig. 5. X-Ray difractometry analysis for soil samples before and after prescribed fire.

The values of quarz element increased substantially after burnt, probably the plagioclase were unstructured when temperature rose over 500 ºC, releasing the quarz and some cations. In this case, the electrical conductivity of the soil would be increased, such as indicated the Table 1.

Eventually, in Fig. 5, can observe the relationship between thermal conductivity as a function of water content for a soil sample after burnt with 90% of volume of ashes (white and black ashes).

Clearly, existed differences between white and black ashes when these were incorporated into the soil matrix. In all cases, especially when the soil was closed to saturation the differences were higher. An acceptable explanation could be splited up; (i) white ashes presented a fine particle size, hence it increased the water film around the particle and increased the bulk density, as well. Therefore, a higher compaction than black ashes focused with a better heat transfer; (ii) mica muscovite presents dielectric properties, therefore it is a good resistivity material. When mica muscovite disappear, the thermal conductivity increased.

Finally, note that the particle size of the black ashes were large than white ashes, and also the organic carbon content did not work well when the heat flux transfer was necessary.

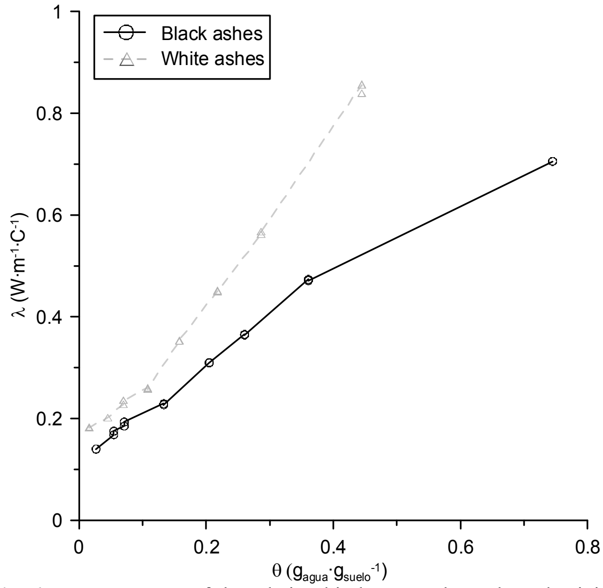

Fig. 6. Dry-out curves of the relationship between thermal conductivity and gravimetric water content, when different types of ashes (white and black) were incorporated into the soil matrix.

4.- Conclusions

As a summary, we could say that thermal properties can present changes when the scenario changes, i.e. before and after a prescribed fire. Soil after fire always presented a lower thermal conductivity, and therefore a lower thermal diffusivity, and volumetric specific heat capacity. On the other hand, when the ashes provoked by the fire were incorporated to the soil, the white ashes, which are poorer in organic carbon content, provided a better heat flow transfer. Also, the particle size was relevant in the retención water content. Therefore, when soil is burned its thermal properties change, and a natural or antropic addition of ashes, especially white ashes, could improve the conductance of the heat flux into the soil, improving the soil bulk density, and water retention content as well.

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