SJSS
SPANISH JOURNAL OF SOIL SCIENCE

Assessment of the impact of soil heating on soil cations using the degree-hours method

Evaluación del impacto del calentamiento del suelo en los cationes del suelo utilizando el método de los grados-hora
Avaliação do impacto do aquecimento térmico nos catiões do solo recorrendo ao método dos graus-hora

Received: 12.10.2012 | **Revised:** 09.11.2012 | **Accepted:** 11.11.2012

AUTHORS

Cancelo-González J. [@] [1]
javier.cancelo@usc.es

Rial-Rivas M.E. [2]

Barros N. [3]

Díaz-Fierros F. [1]

[@] Corresponding Author

[1] Departamento de Edafoloxía e Química Agrícola, Facultad de Farmacia, Campus Vida. Universidade de Santiago de Compostela. 15782 Santiago de Compostela (A Coruña), Spain.

[2] CESAM - Environment and Planning Department, Campus Universitario de Santiago. Universidade de Aveiro. PC 3810-193 Aveiro, Portugal.

[3] Departamento de Física Aplicada, Facultad de Física. Universidade de Santiago de Compostela. 15782 Santiago de Compostela (A Coruña), Spain.

ABSTRACT

Important factors in the evaluation of fire severity are the duration of the soil exposition to a certain temperature as well as the factors that determine the thermal transmissivity on the soil (moisture, texture, organic matter content, etc.). The aim of this work was to apply the degree-hours method (DH) to characterize the thermal impact of forest fires in soils. Thermal treatments in the laboratory were conducted using soil samples in order to study the effects in the soil exchange complex. The results showed the effect of the supplied degree-hour (DH) on the cation exchange capacity (CEC), which was expressed by a continuous exponential decrease in the CEC. This function may better explain the process of the decreasing of CEC than only the maximum temperature values. The sum of cations extracted in relation to the thermal treatment gradually increased with temperature or DH, and tended to stabilize at high values. The concentration of the different cations extracted increased gradually with the intensity of heating, and when related to the DH appeared to fit an equation of the type $y=a+bx^c$ with a high degree of confidence. Analyses of the results show that the measurement of the heat supplied to the soil is a useful parameter with which to interpret pedologic changes, especially when those changes happen continuously over time.

RESUMEN

Para la evaluación de la severidad de un incendio, tanto la duración de la exposición del suelo a una determinada temperatura como los factores que determinan la capacidad de transmisión térmica en el suelo (humedad, textura, contenido en materia orgánica, etc.) son parámetros importantes a tener en cuenta. El presente estudio tiene como objetivo la aplicación de la metodología de los grados-hora (DH) en la caracterización de los impactos térmicos de los incendios forestales en el suelo. Los tratamientos térmicos se realizaron en el laboratorio usando muestras de suelo recogidas en el campo sin alterar su estructura para estudiar su efecto en el complejo de cambio del suelo. Los resultados obtenidos muestran un claro efecto en la capacidad de intercambio catiónico (CIC) en función de los grados-hora (DH) suministrados, observándose un proceso de disminución continuo de carácter exponencial. Esta función podría explicar de forma más evidente el proceso de reducción de la CIC que los valores máximos de temperatura alcanzados. Analizando la suma de cationes extraíbles y su relación con el tratamiento térmico se observa como esta se incrementa gradualmente con la temperatura o los DH con una tendencia a la estabilización. Los diferentes cationes extraídos muestran un incremento progresivo con la intensidad del calentamiento, que cuando se relacionan con los DH pueden ajustarse a una función del tipo $y=a+bx^c$ *con un elevado grado de confianza. La utilización de los DH como medida del calor aportado al suelo puede ser un parámetro adecuado para establecer relaciones con los cambios edáficos que se pueden desencadenar en el mismo, sobre todo en el caso en el que los procesos varíen de forma continua en el tiempo.*

DOI: 10.3232/SJSS.2012.V2.N3.04

SJSS
SPANISH JOURNAL OF SOIL SCIENCE

RESUMO

Para a avaliação da severidade de um incêndio, tanto a duração da exposição do solo a determinada temperatura como os fatores que determinam a transmissão de calor no solo (humidade, textura, conteúdo em matéria orgânica, etc.) são parâmetros importantes a considerar. O presente estudo tem como objectivo a aplicação da metodologia dos graus-hora (DH) na caracterização dos impactos térmicos dos incêndios florestais nos solos. Os tratamentos térmicos foram realizados no laboratório utilizando amostras de solo recolhidas no campo com a estructura inalterada de modo a avaliar o efeito das mesmas no complexo de troca do solo. Os resultados obtidos mostram um claro efeito na capacidade de troca catiónica (CTC) em função dos graus-hora (DH) administrados, verificando-se um decréscimo contínuo de carácter exponencial. Esta função explica de forma mais evidente o processo de redução da CTC do que apenas os valores máximos de temperatura alcançados. Considerando a soma de catiões extraíveis em comparação com o tratamento térmico, o valor da soma aumenta gradualmente com a temperatura ou graus-hora com uma tendência a estabilizar para os valores mais elevados. A concentração dos diferentes catiões extraíveis aumentou progressivamente com a intensidade do aquecimento e relativamente aos DH, podendo ser ajustada por uma função do tipo $y=a+bx^c$ *com um alto grau de confiança. A partir dos resultados pode concluir-se que a medição do calor fornecido ao solo pode ser um parâmetro apropriado para interpretação das alterações edáficas produzidas, nomeadamente quando estas ocorrem de forma contínua.*

KEY WORDS
Fire severity, soil chemistry, soil exchange capacity

PALABRAS CLAVE
Severidad de un incendio, química del suelo, capacidad de cambio del suelo

PALAVRAS-CHAVE
Severidade do fogo, química do solo, capacidade de troca do solo

1. Introduction

Many studies of the effects of forest fires on soil and vegetation have been carried out since soil temperature thresholds were first defined. Significant changes in soil properties and vegetation are produced at temperatures above these thresholds. The initial study by Beadle (1940), which proposed a method for measuring the soil temperature reached in a fire, also reported the resistance of some types of seed to high soil temperatures. This study also highlighted the importance of soil moisture in transmitting heat and the consequent ecological effects of high temperatures. The concept of a critical temperature for determining the thresholds at which certain changes occur was established by DeBano et al. (1998), chemical synthesis studies to determine the impact of heating on soil chemical properties were carried out (Giovannini et al. 1990) (**Table 1**), and threshold temperatures for biological disruptions were established (Neary et al. 1999 from studies recompiled by DeBano et al. 1998). Subsequent studies and review papers established the impact of different threshold temperatures on soil properties (Nishita and Haug 1972; Boyer and Dell 1980; Wright and Bailey 1982; Mataix-Solera and Guerrero 2007; Úbeda et al. 2009; Varela et al. 2010; Mataix-Solera et al. 2011).

Table 1. Critical temperature thresholds at which some changes in soil properties occur (Giovannini et al. 1990)

Threshold temperatures (ºC)	Changes in soil properties
25 - 170	Dehydration of the composite sample
170 - 220	Dehydration of gel forms
220 - 460	Combustion of organic matter
550-700	Loss of OH groups from clay minerals
700-900	Decomposition of carbonates

When establishing the concept of fire severity (Hartford and Frandsen 1992), it was realised that the maximum temperature reached was not the only factor involved in the damage caused by forest fires. The duration of the temperatures, as well as factors determining the transmission of heat through the soil (moisture, texture, organic matter content, etc.) were all found to be important in evaluating fire severity. More recently, Certini (2005) stated that among all the previous factors, “duration is perhaps the component of the fire severity that results in the greatest belowground damage”.

Temperature-time curves (heating curves), which can be determined experimentally established or theoretically predicted, enable the effect of heat and heat duration on soil to be determined. Attempts have been made to define parameters of temperature-time curves (TTC) as a simple, indirect means of representing the information described by the curves. Hartford and Frandsen (1992) considered the duration temperatures above 100 ºC an important parameter, and Molina and Linares (2001) proposed others: peak temperature, total duration of heat, ascending slope, descending slope, duration of temperature increase, and duration of temperature decrease. Mercer and Weber (2001) developed a method of determining the total duration above a given temperature, which was applied by them to predict the mortality of trees affected by the temperatures reached during a fire.

Another approach used to determine the effects of forest fires on soil properties, which has a more valid physical basis, is the measurement of the transfer of heat energy to the soil. In a review paper of this topic, DeBano et al. 1998 concluded that the fundamental processes involved in heat transfer to soil are radiation, convection and conduction, the first two usually being the most important. Nevertheless, it is very difficult to characterize the heat transfer to soil because of the variability in combustion and soil conduction (Neary et al. 1999). Although different models have been developed to address this problem (Aston and Gill 1976; Hungerford and Campbell 1991; Campbell 1995) it remains to be determined whether these can be generally applied to the very varied conditions that affect forest fires.

Finally, Busse et al. (2005) proposed the use of degree hours above a given threshold as an alternative method to evaluate how lethal temperatures and their duration affect soil biological properties. These authors considered a lethal threshold temperature of 60 ºC (considered by many authors as the lethal level for soil biological processes) and proposed the accumulated degree hours above 60 ºC as an indicator of biological disruptions in the soil.

Measurement of degree hours or degree days, which is a common procedure in biometeorology (Munn 1970), is used to determine the combined influence of a given temperature threshold and of the duration of temperatures above this threshold. In lay terms, it can be considered as the “amount” or “degree” of heat provided. The use of the method is widely accepted in biological studies, particularly in phenological studies of plants and poikilothermic animals (Roltsch et al. 1999; Herms 2004). This method has been used in soils to characterize the pedoclimate from a biological point of view (Díaz-Fierros 1972) and to relate the heat provided to the decomposition and weathering of organic matter (Griffin and Honeycutt 2000; Ruffo and Bollero 2003). Different methods are used for simple and accurate measurement of the parameters required to calculate degree hours (Roltsch et al. 1999; Statewide IPM 2003; Coskun 2010).

The present study attempted to apply the degree-hours method to characterize the thermal impact of forest fires on soil. The study, which is the first carried out with large samples of soil subjected to thermal treatments under controlled laboratory conditions, aimed to evaluate the effect of thermal shock on the exchange complex (a basic chemical property).

2. Material and Methods

2.1. Soil sampling

The study area is located in the northwest of Spain (42º51´N, 9º06´W) at 12 meters above sea level. The soil sampling was carried out in a sparse *Pinus pinaster Ait.* stand, with a herbaceous understory consisting of graminaceous plants. The soil is Leptic Umbrisol (WRB 2007), with a 13.4% organic matter, pH in water of 5.64, a sandy-loam texture (USDA) and a soil depth from 20 to 30 cm, over granite and granodiorite bedrock. A total of six soil samples within an area of 4 m^2 without trees were collected and the natural structure of the soil was maintained by inserting a steel box of 20x40 cm (sides) and 15 cm deep into the ground (**Figure 1**) with the minimum disturbance in the soil structure.

2.2. Thermal shocks

In the laboratory, the samples were weighed and then heated with 8 infrared lamps (*Philips* IR375CH) situated 10 cm above the soil surface (**Figure 2**). The soil temperature was measured with thermocouples inserted at depths of 1 and 3 cm in the samples. In two of the samples (treatments A and B) heating was maintained until a temperature of 200 ºC at 1 cm depth, reaching a maximum temperature at that depth of 200 ºC and 220 ºC respectively. The other two samples (treatments B and C) were heated until a temperature of 400 ºC at 1 cm depth, reaching a maximum temperature of 434 ºC and 401 ºC respectively.

Figure 1. Soil sampling using steel boxes 20 x 40 x 15 cm to preserve soil structure.

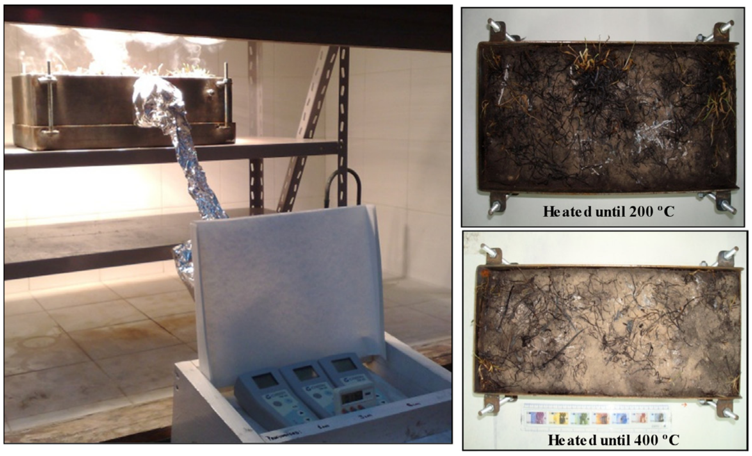

Figure 2. Experimental design for the heating treatments.

The soils were allowed to cool and were then reweighed to enable calculation of the water loss through heating (as the difference in weight of the soil before and after heating). Five subsamples of soil were taken from the burned surfaces, to a depth of 2 cm, and combined to make a composite sample of 10 g, which was homogenized and prepared for chemical analysis. The other two samples were not subjected to heating treatments and were used as controls.

2.3. Calculation of degree hours

The degree-hour method has been used in soils as a measure of the degree of heat supplied to the soil in relation to microbiological functions (Honeycutt et al. 1988; Griffin and Honeycutt 2000; Ruffo and Bollero 2003) as well in studies related to phenology of soil fauna (Pruess 1983; Zalom et al. 1983), or more recently about the thermal exchange of the materials used in construction (Coskun 2010). In the present work, the degree-hour method (DH) was modified for the specific case of study. Due to the fact that measurements were made every 5 minutes and the average temperature in the laboratory was 21 ºC, the following equation was used to calculate the degree hours (DH):

$$DH_{21} = \sum \frac{(T_{5(1cm)} - 21)}{12} \qquad \text{(Equation 1)}$$

To calculate the degree hours that affect the surface layer of the soil for each sample (DH_{sample}) the difference in temperatures at 1 and 3 cm depth were included adapting the equation as follows:

$$DH_{sample} = \sum \frac{(T_{5(1cm)} -(T_{5(3cm)})}{12} \text{(Equation 2)}$$

Where:
$T_{5\ (1cm)}$ = Temperature in ºC every 5 minutes at 1 cm depth.
$T_{5\ (3cm)}$ = Temperature in ºC every 5 minutes at 3 cm depth.

A good correlation between the two methods of calculating the degree hours was found ($r^2 = 0.964$), and the final equation used to relate both methodologies was as follows:

$$DH_{21} = 1.75\ (DH_{sample}) \qquad \text{(Equation 3)}$$

2.4. Determination of chemical changes in soil samples after heating

To assess the changes in the soil exchange complex due the heating treatments, the total cation exchange capacity (CEC) and the exchangeable bases (S) for the six samples (2 control samples and 4 heating treatments) were determined by the ammonium acetate method at pH 7.0 (Gillman et al. 1983; Sumner and Miller 1996; WRB 2007). The organic matter content was determined by oxidation with potassium dichromate and sulphuric acid (Guitián and Carballas 1976). For the treated samples all the parameters were also determined after each thermal shock treatment.

3. Results and Discussion

3.1. Time-temperature curves

The time-temperature curves (TTC) for the 1 and 3 cm depths are shown in **Figures 3A** and **3B**. The rates of increase and decrease in the temperatures in the pairs of soils heated to 200 ºC (Treatments A and B) and 400 ºC (Treatments C and D) were very different, particularly at 1 cm depth. A characteristic inflection point in the rate of heating was observed between 60 ºC and 100 ºC in the TTC of treatments B, C and D, but was not observed in the TTC of treatment A. This inflection may be attributed to the energy consumption required to evaporate the water contained in the soil (Campbell 1995). Soil water was lowest in treatment A as confirmed by the loss of water values for each treatment (**Table 3**). The plateau is also consistent with the endothermal peak that appears in thermograms for soils from NW Spain, which has been attributed to dehydration of the sample and loss of volatile compounds (Salgado et al. 1995).

The rate of heating is shown in **Table 3**, and is approximately described by the slope of the time-temperature rising curve. The rates and the maximum temperature reached during the heating distinguish the four thermal treatments. The TTC for the 3 cm depth shows lower maximum temperatures but over a longer duration. A delay in reaching the maximum temperature at both depths was observed for treatments A (10 min), C (45 min) and D (15 min), reaching the temperature peak first at 1 cm depth. Treatment B had a different behaviour and the temperature peak at 3 cm depth was reached 5 minutes before than at 1 cm depth.

According to the main soil heating models, moisture is the pedologic property that probably has the greatest influence on soil heating (De Vries 1963; Aston and Gill 1976; Campbell 1995). The relationship between the slope of the regression lines of the TTC (**Table 3**) and the loss of water from the soil (**Figure 4**) was therefore determined, and an excellent correlation between the variables was obtained ($r^2 = 0.968$).

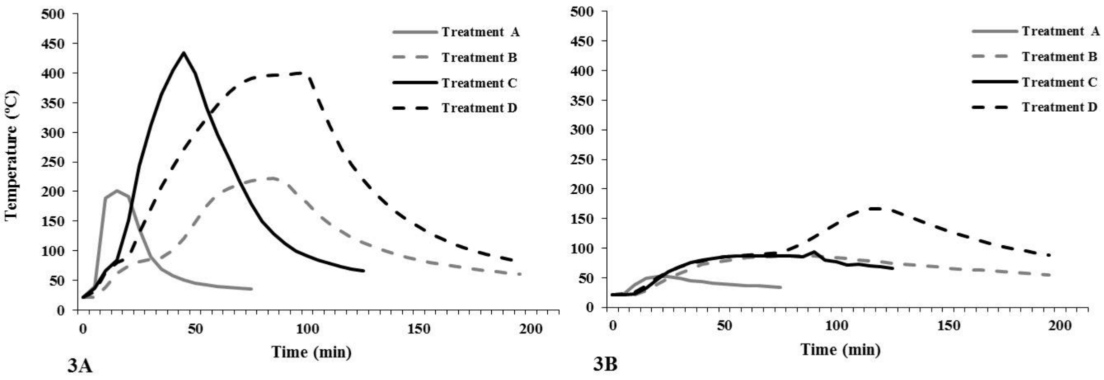

Figure 3. Time-temperature curves for 1 cm depth (**3A**) and 3 cm depth (**3B**).

Table 3. Regression lines for the rising phase of the time-temperature curves in the four thermal treatments studied. Maximum temperatures (Tmax) at 1 and 3 cm. Loss of water (w/w)

Thermal treatments	Tmax (ºC) (1 cm)	Tmax (ºC) (3 cm)	Regression line	r^2	Loss of water (kg)(w/w)
A	202	52	T=12.80 min+ 21	0.936	0.10 (0.009)
B	222	87	T=2.61 min+ 21	0.967	0.84 (0.075)
C	434	93	T=9.02 min+ 21	0.980	0.29 (0.026)
D	401	167	T=5.24 min+ 21	0.995	0.54 (0.048)

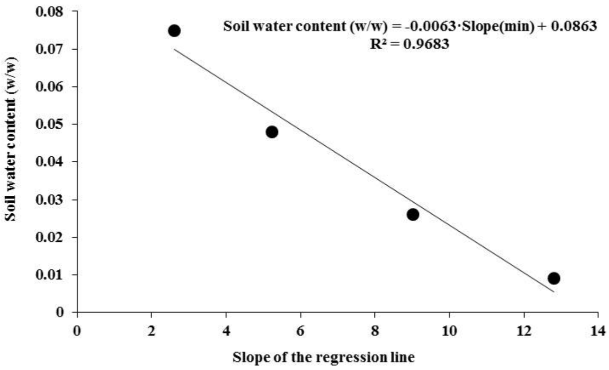

Figure 4. Relationship between the slope of the regression lines of the TTC and the loss of water from the soil.

The curve of the heating phase follows a sigmoidal pattern, and the mean slopes are different for each of the four soils samples. Besides other factors, the mean slope is proportional to the moisture content of the soil, with which is closely related. In general, the curve for the cooling phase is dependent on the duration and level of the temperature reached, and therefore the shape of the TTC would depend mainly on the maximum temperature reached (predetermined by the experimental conditions) and the soil moisture content.

The four heating curves could be grouped into pairs based on the temperature peak reached. This represents four different levels of heat supplied to the soil and is approximately determined by the area under the TTC and a given reference temperature. Taking the mean laboratory temperature (21 ºC) as the reference temperature, determination of the DH_{21} above this reference level may be a simple method for estimating the amount of heat supplied to the soil. The DH_{21} for the four thermal treatments were very different: A (79.05 DH_{21}), B (318.6 DH_{21}), C (351 DH_{21}) and D (643.9 DH_{21}), which indicated that this parameter may be more suitable than the temperature peak reached: A (202 ºC), B (222 ºC), C (434 ºC) and D (401 ºC), for studying the effect that thermal impacts have on soils or on pedologic ecosystems in general.

The calculation of the area under the TTC for depths 1 and 3 cm was considered as an alternative method for calculating the *DH* affecting the surface layer of the soil (DH_{sample}). This method also produced very different (although lower) values for each soil A (54.2 DH_{sample}), B (166.35 DH_{sample}), C (246.2 DH_{sample}) and D (373.2 DH_{sample}).

One important consideration that can be deduced from the curves is the importance of soil moisture as a decisive factor for interpreting the effects of forest fires on soils. In this case, the coefficient of variation of soil moisture (72%) for the four samples collected within a small area of soil is very high, possibly as a result of the heterogeneity of the soil, which was located in an old, unevenly spaced *Pinus pinaster Ait.* stand. Nonetheless, coefficients of variation closer to those cited in the literature may be equally important for interpreting the wide variability of responses of ecosystems to fires of apparently similar characteristics: Kachanoski et al. 1988, (42%); Nyberg 1996, (33-43%); Usowicz and Kosowski 2001, (14-21%); James et al. 2003, (20-30%); Jacobs et al. 2004, (40-60%); and Ersahin and Resit Brohi 2006, (14-20%).

3.2. Relationship between the degree-hours and the soil exchange cations

The degree hours that were calculated using the temperature data recorded at 1 and 3 cm depth (DH_{sample}) were considered to be a good indicator of the heat transfer within this soil layer. The DH_{sample} was related to the content of exchange cations in the soil subsamples under the different thermal treatments. The concentration of the different cations extracted with ammonium acetate increased gradually with the intensity of heating (**Figure 5**), and when related to the DH_{sample} appeared to fit an equation of the type $y=a+bx^c$ with a high degree of confidence (**Table 5**). Studies of the response of exchange cations to temperature when the soil is not affected by ash have reported a decrease in exchange cations with temperature (Nishita and Haug 1972), whereas in those cases when the ashes affect the soil, the response is positive (Christensen and Muller 1975; Khanna et al. 1994; Pereira et al. 2011). However, the release of cations such as calcium, which may be tightly bound to organic ligands (Allison 1973), should not be overlooked as these may move to exchange sites when organic matter is combusted.

The exponential fits to the DH_{sample} (**Table 5**) clearly show the continuous nature of the process, and also differentiate the monovalent cations (c >1) from the divalent cations (c <1). This difference may be explained by the increase in monovalent cations induced by the thermal shock, whereas the divalent cations tend to stabilize.

Table 5. Best fits to the straight line $y=a+bx^c$ for the relationship between the exchange cations from the thermal treatments and the DH_{sample}

Exchange cations (y)	a	b	c	R^2
Na	0.91	$3.4e^{-0.5}$	1.605	0.803
Na+K	2.13	$2.3e^{-0.5}$	1.929	0.928
Na+K+Ca	4.65	0.120	0.676	0.977
Na+K+Ca+Mg	5.76	0.124	0.678	0.966

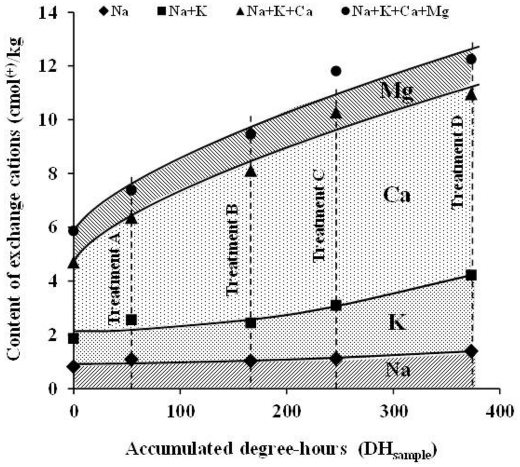

Figure 5. Family of curves showing the content of exchange cations in the soils subjected to the different thermal treatments.

This family of curves illustrate how the heating led to a continuous increase in the content of the exchange cations (area between curves). The increase tended to stabilize at the highest DH_{sample} values. The proportion of the different exchange cations observed in the control sample (Ca > Mg > K > Na) changed by the heating process to Ca > K > Na > Mg in treatment A. However, the increase in the concentration of Mg was greater than Na, and therefore the former was presented in a higher proportion at the end of the process. As regards the quantitative importance of the exchange sites, the sequence included in Table 6 was observed throughout the thermal shock treatments.

Calcium was the dominant cation in the exchange complex, followed by potassium. This sequence of cations is difficult to explain only in terms of additions via ashes, and suggests the involvement of other processes such as the release of cations from organic ligands or specific selectivity for exchange sites.

The relation between the DH_{sample} and the CEC (Figure 6) shows a continuous exponential decrease in the latter. This decrease was clearly observed from treatment A at 54 DH_{sample}. Comparison of the curve for CEC with the curve for the sum of the cations (S) revealed that the final portion of the sum of cations surpassed the value of the exchange capacity by 5 $cmol^{(+)}\ kg^{-1}$.

Table 6. Sequence of the quantitative importance of the exchange cations content after the different thermal treatments

No treatment (control)	Ca > Mg > K > Na
Treatment A	Ca > K > Na > Mg
Treatment B	Ca > K > Mg > Na
Treatment C	Ca > K > Mg > Na
Treatment D	Ca > K > Mg > Na

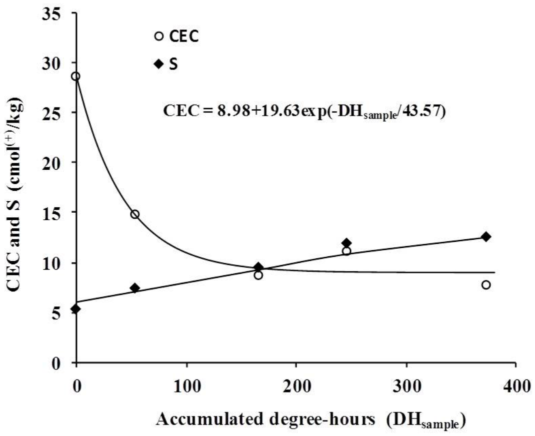

Figure 6. Relationship between the *DH*$_{sample}$, the soil exchange capacity (CEC), and the sum of cations (S).

Different authors have shown that soil heating generally leads to a loss of cation exchange sites in the soil. When these sites mainly depend on the type of organic matter in the soil, as in soils from NW Spain (Guitián 1964), the CEC begins to decrease above the threshold temperature of organic matter destruction. According to Giovannini et al. (1990), these processes begin above 220 ºC and are completed at around 460 ºC. In soils similar to those in the present study, Soto and Díaz-Fierros (1993) found that there was no decrease in the CEC at 170 ºC, whereas at 380 ºC the CEC had decreased by 76%. Nishita and Haug (1972) observed that the decrease in CEC began at 200 ºC in acid soils rich in organic matter. In these studies, the slopes of the curve describing the decrease in CEC with temperature vary from 36% (Soto and Díaz-Fierros 1993) to 15% (Nishita and Haug 1972) per 100 ºC. In the present study, the CEC decreased by 50% at 202 ºC, 70% at 220 ºC and by only slightly more (approximately 75%) at temperatures above 400 ºC. This response at the maximum temperatures may be considered normal in soils in which the CEC depends on the organic matter content.

Relating the CEC to the *DH*$_{sample}$ clearly defines a continuous exponential process (**Figure 6**). The equation: $CEC = 8.98+19.63exp(-DH_{sample}/43.67)$ ($r^2 = 0.977$) may provide a better explanation for the reduction in CEC than the maximum temperatures reached, as the reduction is not easily explained (e.g. the decrease of 20% between 202 and 220 ºC represents a slope of –110% per 100 ºC). Nonetheless, there is clearly a threshold temperature above which the CEC begins to decrease, and this part of the curve would be better defined by mean DH_{sample} values lower than 54.2 in treatment A.

Considering the sum of cations extracted with ammonium acetate in relation to the thermal treatment, the value of the sum increased gradually with temperature or DH_{sample} and then tended to stabilize. Such an increase in exchange cations has been reported in different studies (Grove et al. 1986; Raison and Stottlemyer 1990; Tomkins et al. 1991) and has been attributed to the inputs of cations via ashes due to effects of the heat released, by destruction of crystalline networks or, in particular, of organic radicals. The observed increase in **Figure 6** surpassed the maximum values of the CEC by some 5 $\mathrm{cmol^{(+)}kg^{-1}}$, and could be explained by the presence of cationic salts that would be added to the cations retained at the exchange sites (Nishita and Haug 1972; Soto and Díaz-Fierros 1993). The traditional method of determining exchange cations, which was used in the present study and is recommended for soil classification (Summer and Miller. 1996) involves extraction of the soil with 1M ammonium acetate without prior washing, and so the extract would also include hydrosoluble compounds that are not bound to the exchange complex.

4. Conclusions

The degree-hour method for measuring the heat supplied to soil by forest fires is suitable for studying the relationship between forest fires and the resulting effects on the soil. This particularly applies to cases in which the processes vary continually over time and allows the changes in the pedologic ecosystem to be interpreted. The degree-hours calculated using the temperatures recorded at 1 and 3 cm depth during the heating treatments were significantly related by exponential functions to the CEC and the content of exchange cations. In the case of the exchange cations a continuous increase was observed according to the degree of heat supplied, and tended to stabilize towards higher values of degree hours.

An important point to highlight in view of the results obtained in this and other studies is the importance of soil moisture data as a determining factor when interpreting the effects of forest fires. In general, the curve for the cooling phase is dependent on the duration temperature, soil moisture content and the maximum temperature reached, and these factors define the shape of the cooling curve.

REFERENCES

- Allison, F. 1973. Soil organic matter and its role in crop production. Amsterdam: Elsevier Scientific Publishing Company.

- Aston AR, Gill AM. 1976. Couples oil moisture, heat and water vapour transfers under simulated fire conditions. Aust J Soil Res. 14:55-66.

- Beadle NCW. 1940. Soil temperatures during forest fires and their effect on the survival of vegetation. J Ecol. 28:180-192.

- Boyer DE, Dell JD. 1980. Fire effects on Pacific Northwest forest soils. Northwest Region, Forest Serv., U.S. Dep. Agric. R6 WM 040. 59 p.

- Busse MD, Hubbert KR, Fiddler GO, Shestak CJ, Powers RF. 2005. Lethal soil temperatures during burning of masticated forest residues. Int J Wildland Fire 14:267-276.

- Campbell GS. 1995. Soil temperature and water beneath a surface fire. Soil Sci. 159(6):363-374.

- Certini G. 2005. Effects of fire on properties of forest soils: a review. Oecologia 143:1-10.

- Christensen NL, Muller CH. 1975. Effects of fire on factors controlling plant growth in Adenostoma chaparral. Ecol Monogr. 45:29-55.

- Coskun C. 2010. A novel approach to degree-hour calculation: indoor and outdoor reference temperature based degree-hour calculation. Energy 35:2455-2460.

- DeBano LF, Neary DG, Ffolliott PF. 1998. Fire's effects on ecosystems. New York: John Wiley and Sons.

- De Vries DA. 1963. Thermal properties of soil physics of plant environment. Amsterdam: W.R. Wijk.

- Díaz-Fierros F. 1972. Tipificación climática desde un punto de vista edafológico de la zona húmeda de la Provincia de León. P. Cent. pir. Biol. exp. 7:11-21.

- Ersahin S, Resit Brohi A. 2006. Spatial variation of soil water content in topsoil and subsoil of a Typic Ustifluvent. Agr Water Manag. 83(1-2):79-86.

- Gillman GP, Bruce RC, Davey BG, Kimble JM, Searle PL, Skjemstad JO. 1983. A comparison of methods used for determination of cation exchange capacity. Commun. Soil Sci and Plant Anal. 14:1005-1014.

- Giovannini G, Lucchesi L, Giachetti M. 1990. Beneficial and detrimental effects of heating on soil quality. In: Goldammer JG, Jenkins MJ, editors. Fire in ecosystem dynamics: Mediterranean and Northern perspectives. The Hague: Academic Publishing. p. 95-102.

- Griffin T, Honeycutt CW. 2000. Using growing degree days to predict nitrogen availability from livestock manures. Soil Sci Soc Am J. 64:1876-1882.

- Guitián F. 1964. Contribución a la caracterización química de las formas de humus. An Edafol Agrobiol. 23:521-531.

- Guitián F, Carballas T. 1976. Técnicas de análisis de suelos. Santiago de Compostela: Editorial Pico Sacro.

- Grove TS, O'Connell AM, Dimmock GM. 1986. Nutrient changes in surface soils after an intense fire in Jarrah (Eucalyptus marginata Donn ex Sm.) forest. Aust J Ecol. 11:303-17.

- Hartford EA, Frandsen WH. 1992. When It´s Hot, It´s Hot... or Maybe It´s Not! (Surface flaming may not portend extensive soil heating). Int J Wildland Fire 2(3):139-144.

- Herms DA. 2004. Using degree-days and plant phenology to predict pest activity. In: Krischik V, Davidson J, editors. IPM (Integrated Pest Management) of Midwest Landscapes. St. Paul, MN: Minnesota Agricultural Experiment Station Publication SB-07645. p. 49-59.

- Honeycutt C, Zibilske LM, Clapham WM. 1988. Heat units for describing carbon mineralization and predicting net nitrogen mineralization. Soil Sci Soc Am J. 52:1346-1350.

- Hungerford RD, Campbell GS. 1991. Evaluation of models predicting soil heating under fires. Bethesda, MD: Society of American Foresters.

- Jacobs JM, Mohanty BP, Hsu En-Ching, Miller D. 2004. SMEX02: Field scale variability, time stability and similarity of soil moisture. Remote Sens Environ. 92:436-446.

- James SE, Pärtel M, Wilson SD, Peltzer DA. 2003. Temporal heterogeneity of soil moisture in grassland and forest. J Ecol. 91:234-239.

- Kachanoski RG, Gregorich EG, Van Weswnbeeck IJ. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can J Soil Sci. 68:715-722.

- Khanna PK, Raison RJ, Falkiner RA. 1994. Chemical properties of ash derived from Eucalyptus litter and its effects on forest soils. Forest Ecol Manag. 66:107-125.

- Mataix-Solera J, Guerrero C. 2007. Efectos de los incendios forestales en las propiedades edáficas In: Mataix-Solera J, editor. Incendios forestales, suelos y erosión hídrica. Caja Mediterráneo CEMACAM Font Roja-Alcoi. p. 5-40.

- Mataix-Solera J, Cerdà A, Arcenegui V, Jordán A, Zavala LM. 2011. Fire effects on soil aggregation: a review. Earth-Science Reviews 109:44-60.

- Mercer GN, Weber RO. 2001. Fire plumes. In: Johnson EA, Miyanishi K, editors. Forest fires: behavior and ecological effects. San Diego: Academic Press. p. 225-255.
- Molina MJ, Llinares JV. 2001. Temperature-time curves at the soil surface in maquis summer fires. Int J Wildland Fire 10:45-52.
- Munn RE. 1970. Biometeorological methods. New York and London: Academic Press. 336 p.
- Neary DG, Klopatek CC, DeBano LF, Ffolliott PF. 1999. Fire effects on belowground sustainability: a review and synthesis. Forest Ecol Manag. 122:51-71.
- Nishita H, Haug RM. 1972. Some physical and chemical characteristics of heated soils. Soil Sci. 113:422-430.
- Nyberg L. 1996. Spatial variability of soil water content in the covered catchment at Gardsjön, Sweden. Hydrol Process. 10:89-103.
- Pereira P, Úbeda X, Martin D, Mataix-Solera J, Guerrero C. 2011. Effects of a low severity prescribed fire on water-soluble elements in ash from a Cork Oak (Quercus suber) forest located in the northeast of the iberian Peninsula. Environ Res. 111(2):237-247.
- Pruess K. 1983. Day-degree methods for pest management. Environ Entomol. 12:613-619.
- Raison RJ, Stottlemyer R. 1990. Considerations in modelling change in temperate forest nitrogen cycles. Tree Physiol. 9:209-225.
- Roltsch WJ, Zalom FG, Strawn AJ, Strand JF, Pitcairn MJ. 1999. Evaluation of several degree-day estimation methods in California climates. Int J Biometeorol. 42:169-176.
- Ruffo M, Bollero GA. 2003. Modelling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agron J. 95:900-907.
- Salgado J, González MI, Armada J, Paz-Andrade MI. 1995. Loss of organic matter in Atlantic forest soils due to wildfires. Calculation of the ignition temperature. Termochimica Acta 259:165-175.
- Soto B, Díaz-Fierros F. 1993. Interactions between plants ash leachates and soil. Int J Wildland Fire 3:207-216.
- Statewide IPM (Integrated Pest Management Program). 2003. Oakland: University of California, Division of Agriculture and Natural Resources.
- Sumner ME, Miller WP. 1996. Cation exchange capacity and exchange coefficients. In: Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Summer ME, editors. Methods of soil analysis. Madison, Wisconsin: Soil Science Society of America Book Series. American Society of Agronomy, Inc. p. 1201-1229.
- Tomkins IB, Kellas JD, Tolhurst KG, Oswin DA. 1991. Effects of fire intensity on soil chemistry in a Eucalipt forest. Aust J Soil Res. 29:25-47.
- Úbeda X, Pereira P, Outeiro L, Martin A. 2009. Effects of fire temperature on the physical and chemical characteristics of the ash from two plots of Cork Oak (Quercus suber). Land Degrad Dev. 20:589-608.
- Usowicz B, Kossowski J. 2001. Spatial variation of soil moisture and sampling strategy. International Conference Physical Methods in Agriculture.
- Varela ME, Benito E, Keizer J. 2010. Effects of wildfire and laboratory heating on soil aggregate stability of pine forest in Galicia: the role of lithology, soil organic matter content and water repellency. Catena 83:127-134.
- WRB 2007. World Reference Base for Soil Resources, first update 2007. IUSS Working Group. World Soil Resources Report Nº103. Rome: FAO.
- Wright HA, Bailey AW. 1982. Fire Ecology: United States and Southern Canada. New York: John Wiley & Sons.
- Zalom F, Goodell PB, Wilson LT, Barnett WW, Bentley WJ. 1983. Degree-days: the calculation and use of hear units in pest management. University of California, Division of Agriculture and Natural Resources, Leaflet 21373. 10 p.