J Therm Anal Calorim (2011) 104:177–186
DOI 10.1007/s10973-010-1173-2

Changes induced in the thermal properties of Galizian soils by the heating in laboratory conditions

Estimation of the soil temperature during a wildfire

P. V. Verdes · J. Salgado

ISBC XVI Conference Special Issue

Abstract The soil properties can be strongly affected by wildfires, causing direct effects on ecosystem productivity and sustainability. These effects depend, among other things, on the soil type and on the temperature reached during the fire. The variations of thermal properties of several Galizian soils heated in an oven in laboratory conditions at different temperatures (200–500 °C) during 15 min have been examined in this study. The measured properties are heat of combustion of soil organic matter, ignition temperature, specific heat and mass loss, determined using DSC 2920 TA Instruments and a TGA 7 Perkin Elmer under dry air gas flow. In agreement with other authors, this study establishes three temperature intervals with different effects on the soil: up to 200 °C, low intensity heating, with no significant changes in thermal properties; between 200 and 350 °C, medium intensity heating, with losses of organic matter up to 50%; and high intensity heating to temperature higher than 350 °C, with harmful effects on the soil organic matter. On the other hand and taking into account that the sampled soils had been affected by forest fires, the variations of thermal soil properties with the laboratory heating temperatures allowed for an estimation of the temperature reached by the soil in the real fire.

P. V. Verdes
Departamento de Física Aplicada, Facultade de Física, Campus Vida, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain

J. Salgado (✉)
Departamento de Física Aplicada, Escola Politécnica Superior, Universidade de Santiago de Compostela, 27002 Lugo, Spain
e-mail: j.salgado.carballo@usc.es

Keywords Forest fires · Enthalpy of combustion · Ignition temperature · Maximum temperature · Organic matter content · Soil specific heat

Introduction

Galicia is one of the most affected regions by wildfires in Spain. During the period between 1996 and 2005, this region accounted for 54% of the total number of forest fires in Spain leaving more than 312,000 ha of land being burnt. Most of these fires have taken place in summer months, when the damages would be predictably higher due to the conditions of humidity and temperature of the vegetation, soil and environment [1, 2].

Soil is an integral component of all the terrestrial ecosystems and plays a central role in the functioning and productivity of ecosystems. Heat radiated downwards in the soil is the driving mechanism for increasing the soil temperature and initiating a wide range of responses in the soil physical, chemical and biological systems [3, 4].

Effects of fire on soil physical, chemical and biological properties are complex. However, general relationships describing response of soil properties to soil heating can be established [4]. These relationships are as follows:

- Biological properties of soils are most sensitive to soil heating, with fatal temperatures for most of the living organisms, occurring below 100 °C.
- Complete dehydration of soil occurs when the temperature reaches 220 °C, although it does not significantly affect the physical or chemical properties of the soil.
- Heating between 220 and 460 °C combusts soil organic matter and affects soil properties. Although the destruction of the organic matter can destroy soil

structure, it could be beneficial in some cases, because it provides large amount of readily available plant nutrients.
– Heating above 460 °C can drive off hydroxyl groups from clays, thereby disrupting carbonate structures. These irreversible changes produce a soil that is less porous, less elastic and highly erodible.

Fire affects soil physical properties mainly destroying organic matter. It provokes the soil structure destruction and reduces bulk density and porosity, which decreases infiltration and increases runoff and erosion. The magnitude of the change in physical properties depends largely on the severity of fire, the amount of vegetation destroyed, forest floor consumed, heating of the soil, area burned and length of fire intervals. The duff and soil temperatures are the ultimate gauges of the changes that can be expected in postfire soil properties. Unfortunately, fire temperatures are difficult to quantify because the soil heating depends on soil conditions and the time of burning.

Fire intensity is an important factor to be considered while quantifying fire severity, and it can be measured in terms of temperature and heat released, which factors, however, depend on the type and characteristics of the fuel (loading, size, and moisture), climate conditions (temperature, relative humidity, rainfall and wind) and topographic conditions (slope and altitude) [4]. Obviously, these parameters have considerable influences on the fire duration, and therefore in the fire intensity.

The impacts on soils do not finish when the fire is extinguished; sometimes, even after the flames have disappeared, a heat transfer between the vegetable rests and the soils continues for long time, especially in high intensity fires. The duration and quality of this heat transfer determine the severity of the impact on the soil system [4]. The transferred heat makes the temperature of the soil increase. Soil temperature, which is highly related with the soil's physical properties such as colour and texture [5], is a factor of primary importance in determining the rates and directions of soil physical processes, and of energy and mass exchanges with the atmosphere [4, 6, 7]. Temperature also governs the types and rates of chemical reactions taking place in the soil, and has influence on biological processes, such as seed germination, root development and microbial activity [4, 8].

The effect of fire of high intensity on the soil is doubled, because of the heating effects and the ashes input [9], provoking the destruction of organic matter in soil surface layers, with an alteration on physical, physicochemical, chemical and biological characteristics of soil, especially permeability, porosity, aggregation stability, as well as pH, electrical conductivity, nutrients available and biological activity [10–13]. The residual effects of forest fires may be extremely negative due to the destruction or composition alteration of soil organic matter. This is particularly evident in the upper 5 cm of soil, since the temperature rarely surpasses 150 °C below this depth [14, 15].

As has been mentioned above, many parameters have influence on the fire intensity and temperature. This fact could explain the variability of scientific results found in vegetation and soil [4, 16–18]. Giovannini et al. [19] present a review of the great variability of temperature levels reached at the soil surface: 120 and 330 °C during incomplete and complete burning, respectively, of wheat stubble; 338–442 °C during the burning of straw; 555 °C during grassland fires; 700–800 °C during savannah vegetation burns; and 850 °C during burning of chaparral forest soils. On the other hand, Neary et al. [4] show that the maximum ground temperatures are typically in the range of 200–300 °C, and, with heavy fuel loads, the temperature can reach more than 500 °C.

In order to make recovery possible, it is necessary to avoid the erosion and to act rapidly to improve the quality of the soils after a forest wildfire, by assessing the fire impact as soon as possible. In this sense, several researchers have introduced different parameters to determine this impact. Varela et al. [20] propose the soil water repellency as a simple test for quantifying indirectly the intensity level reached on the soil surface during a fire. The determination of the temperature reached by the soils during the fire would be an important step, as it is another possible parameter to help us quantify the impact of the fire on the soil.

Direct measurement of the maximum temperature reached in the soil surface during the uncontrolled fires is an impossible task. Therefore, the aim of this study is to propose a new method to determine indirectly, and after the fire, this burnt soil parameter, basing on the knowledge of the variation with the temperature of several soil properties, such as specific heat, enthalpy of combustion of the organic matter, ignition temperature and soil organic matter content. By comparing the values of the same physical properties of the burnt soil in the field, the maximum temperature reached due to the fire can be calculated.

In previous studies, calorimetric methods that are employed to determine the loss of the organic matter of various soils affected by fires have been described [21, 22]. Their validity remained demonstrated since other authors have also found similar results using conventional methods. Till now, however, the specific heat of soil has not been used, which is but an important parameter as it is a key property controlling the diurnal and seasonal temperature variations in planetary surface material [23]. Relevant references in the literature have not been found regarding specific heat in burnt soils.

Materials and methods

Three Galician forest soils (NW Spain), namely, Humic, Cambisols over granite and under *Pinus* spp., affected by wildfires of different intensities, were selected for study. These soils, which were representative of the main forest ecosystems affected by wildfires in the Galicia region, were located at Villestro (province of A Coruña), Retortas (province of Pontevedra) and Cervantes (province of Lugo). Villestro soil, which was affected by a fire in summer, presented, at the moment of the sampling, two zones with morphological signs of different burning; therefore, it was sampling in both zones: Villestro I, at the top of the hill, and Villestro II at the bottom of the hill. Retortas soil, affected also by a fire in summer, presented morphological signs of a high intensity fire with white ashes on the surface, whereas Cervantes soil, which was affected by the fire in winter, presented black ashes on the surface—a sign of low intensity burning [14].

Samples for this study were collected at random, immediately after the fire, from the top (0–2-cm depth) of the A horizon of the burnt soils. Leaves, branches and vegetable rests were removed by hand. The soil was sieved at 4 mm, and the fraction less than 4 mm was air-dried, grinded and homogenized [24]. Unburnt samples from the same zone, located close to the burnt soils but not affected by the fire, were also collected at random at the same depth. They were sieved at 4 mm, prepared as above and used as controls.

It was assumed that the properties of the unburnt soils were the same as those of the corresponding burnt soils before being affected by the fires because the unburnt

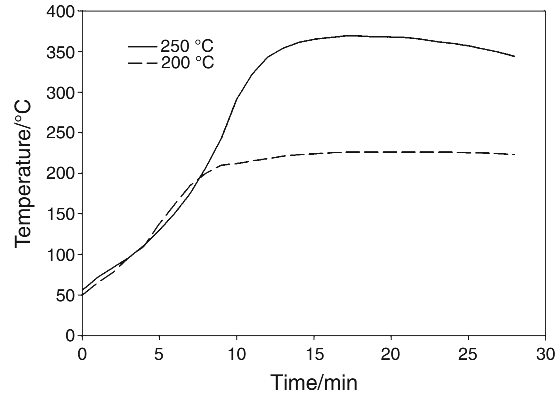


Fig. 3 Temperature of the soil during the heating of two Retortas samples. Oven temperature was 200 and 250 °C

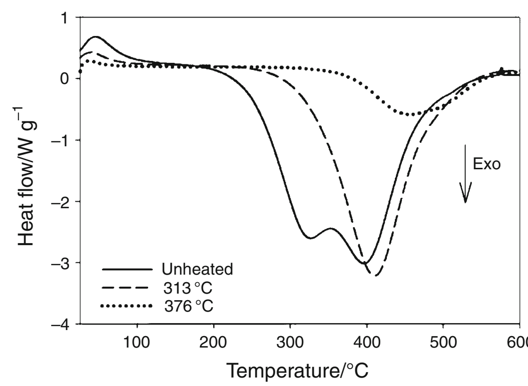


Fig. 4 DSC curves of Villestro I unheated and laboratory heated soil at 313 and 376 °C

Fig. 1 DSC curves of Retortas and Cervantes burnt and unburnt soils

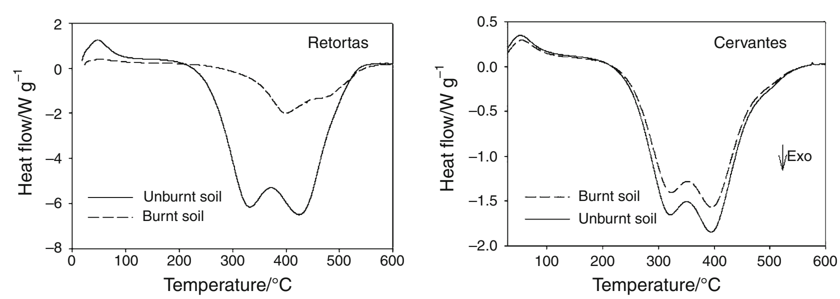
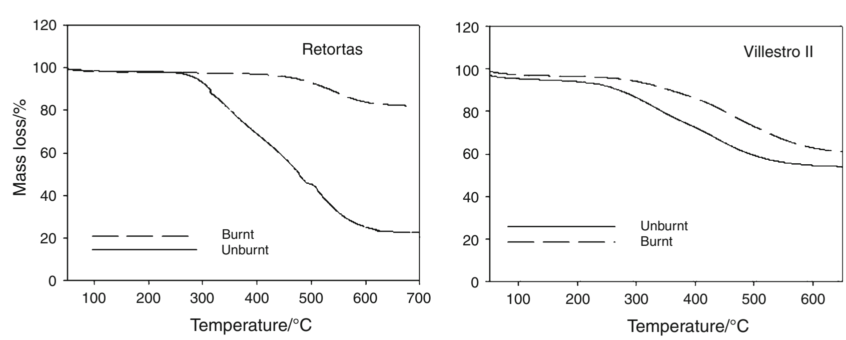


Fig. 2 Thermogravimetric curves of Retortas and Villestro II unburnt and burnt soils



corresponding zone belonged to the same geomorphologic and edaphic formation with the same type of vegetation. The unburnt samples were divided in two parts: one part was subjected to heat treatments and used as a heated soil, and the other part was not heated and used as control.

Heated soils

Samples of every unburnt soil, with masses ranging between 5 and 10 g, were placed in a tray and heated in an oven at different temperatures of range between 175 and 350 °C. The sample thickness was selected to be less than

Table 1 Values of the enthalpy of combustion of the organic matter, ignition temperature, mass loss and specific heat of samples of Villestro I, Villestro II, Retortas and Cervantes soils heated at different temperatures

Soil	Heating temperature/°C	Heat of combustion/kJ g^{-1}	Ignition temperature/°C	Mass loss/%	Specific heat/ J kg^{-1} $°C^{-1}$
Villestro I	225	−6.13	233	51	1.03
	232	−5.62	240	44	0.93
	275	−4.80	270	31	0.89
	302	−4.25	293	28	0.85
	313	−2.79	304	24	0.83
	345	−2.40	338	21	0.81
	376	−0.92	362	8	0.82
	407	–	–	–	0.79
Villestro II	210	−4.59	237	25	0.90
	238	−2.89	269	24	0.87
	273	−2.15	277	18	0.85
	298	−1.61	297	10	0.83
	318	−0.89	348	7	0.84
	337	−0.66	350	6	–
	373	−0.5	388	5	0.79
	403	–	–	3	0.80
Retortas	205	−8.1	256	61	1.09
	222	−7.8	263	58	0.99
	253	−7.8	268	60	0.95
	257	−8.1	270	62	0.95
	277	−7.6	294	57	0.92
	303	−6.8	300	50	0.87
	325	−5.4	307	40	0.84
	355	−5.0	316	37	0.84
	370	−4.2	320	31	0.79
	396	−2.5	325	19	0.85
	410	−2.5	338	15	0.86
	436	−1.1	334	8	0.86
	476	−0.3	–	2	0.81
Cervantes	166	−2.2	223	20	1.48
	189	−2.0	230	19	1.37
	199	−1.7	242	16	1.34
	227	−1.3	271	12	1.23
	248	−1.1	307	10	1.19
	298	−0.7	345	7	1.14
	320	−0.3	425	3	1.11
	350	−0.2	435	2	0.98
	385	–	–	–	0.93

1 cm to avoid a temperature gradient. The lower temperature of this interval has been chosen to be slightly lower than the ignition temperature [21] to ensure that the effects of low intensity fires were included in this study and also the temperature interval is wide enough to include the effects of fires of different intensities [14, 19].

The temperature of the soil during the heating was controlled by a thermocouple located within the sample. After reaching the selected heating temperature, the soil samples were maintained at a constant temperature for 15 min inside the oven. Afterwards, they were withdrawn and kept at room temperature.

Unburnt, laboratory-heated and burnt soil samples were analysed in a Differential Scanning Calorimeter (DSC 2920 TA) and a Thermogravimetric Analyser (TGA 7 Perkin Elmer). Heat of combustion of organic matter, ignition temperature and mass loss were obtained following the procedure explained in previous studies [21, 22]. The specific heat at 25 °C of every sample was also determined.

Specific heat determination

The specific heat at 25 °C of every heated soil sample was measured using a Differential Scanning Calorimeter (DSC-7, Perkin Elmer). All the DSC curves were carried out using 30–40 mg soil samples, which were encapsulated in aluminium crucibles of 50 µl under a dry air flow of 2.1 kg cm^{-2}. The scanning rate was 10 °C min^{-1} and the temperature interval between 20 and 30 °C. Samples of Indium (mp = 156.6 °C) and Zinc (mp = 419.47 °C) were used to calibrate the calorimeter [21, 22], and sapphire was used as a patron of specific heat [25].

Maximum temperature reached during the fire

The lineal and non-lineal parameter estimation procedures described in SPSS 11.5 with LSD test at the 95% probability level were used to fit the experimental data of the thermal properties of the heated samples. The values of these parameters corresponding to those of the burnt samples were interpolated in the fit equations to determine the temperature reached by the soil during the forest fire.

Results and discussion

Figure 1 shows the DSC curves of Retortas and Cervantes soils burnt and unburnt. Taking into account the reduction in the area of combustion peak between unburnt and burnt soils, Retortas seems to be the most affected soil after fire and Cervantes the least, which is expected because it has been a winter fire.

Figure 2 shows the TG curves of Retortas and Villestro II unburnt and burnt soils. Because the mass loss between 200 and 600 °C is proportional to the organic matter content [22], it can be observed that the unburnt Retortas soil has high organic matter content, and its reduction after fire is high, and therefore its recovery will be much difficult. Unburnt Villestro II soil has an organic matter content lower than Retortas, and its reduction, as a consequence of fire, is also lower, indicating less intensity fire and an expected lower temperature rise during the fire.

The combustion of organic matter causes a significant increase in the heat released, provoking an uncontrollable increase in the sample temperature, especially if programmed temperature is higher than ignition temperature of unburnt soil (ITUS). Typical values of ITUS in Galician soils are between 220 and 230 °C [21]. Figure 3 illustrates, as example, the recording of temperature during the heating of two Retortas' soil samples, programming the oven at 200 °C (lower than ITUS) and 250 °C (higher than ITUS). The rise of maximum temperatures by these samples was entirely different in these two cases: lower than 230 °C and higher than 350 °C, respectively.

Figure 4 shows the DSC curves of the unheated and heated Villestro I soil. A reduction in the area of combustion peak and an increase in the ignition point with the heating temperature are observed.

Table 1 shows the values of heat of combustion, ignition temperature, mass loss and specific heat of the heated samples soils, as well as the temperature rise in the sample during the heating, measured with a thermocouple inside the sample. Heat of combustion and ignition temperature of Villestro I, Villestro II and Cervantes soils heated at temperatures higher than or about 400 °C could not be determined because the heating provoked a complete destruction of the organic matter. This fact was reflected in the DSC curves which exhibited a straight line practically coincidental with the baseline of the apparatus, Fig. 5, and

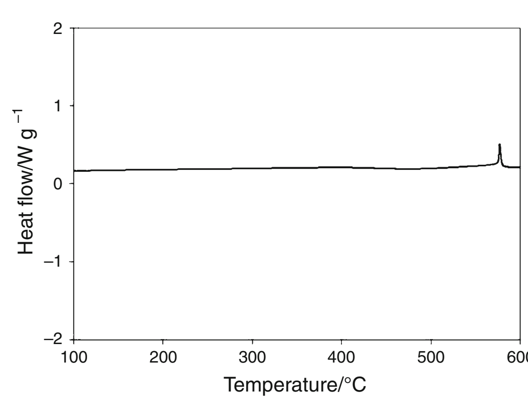


Fig. 5 DSC curve of Villestro II soil heated at 403 °C for 15 min

the organic matter content, proportional to the mass loss, was practically zero. However, Retortas soil, the most organic soil, had to be heated at superior temperatures, to destroy the organic matter, above 476 °C. These results seem to suggest that the thermal resistance of organic matter depends on its content and composition, in line with results of Fernandez et al. [15].

Figures 6, 7, 8 and 9 show the properties determined from thermal analysis as a function of the temperature for Villestro I, Villestro II, Retortas and Cervantes soils, respectively.

As was exposed above, the values of all the calculated parameters of the heated samples were correlated with the maximum temperature rises in the sample during the heating, using the SPSS computer program. Table 2 presents the best model found for every measured magnitude in the studied soils. Two simple models have been used, lineal and exponential, to fit all the measured parameters with the

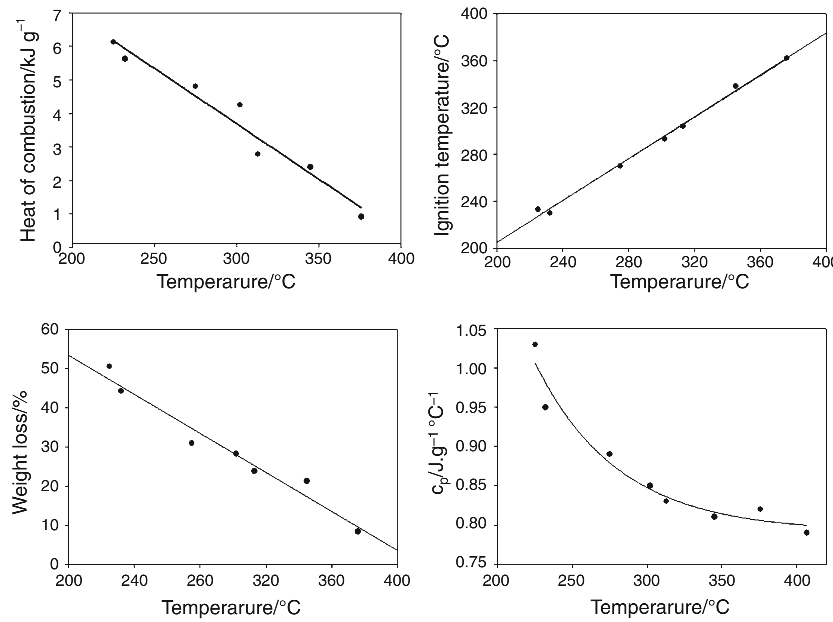


Fig. 6 Results of Villestro I soil

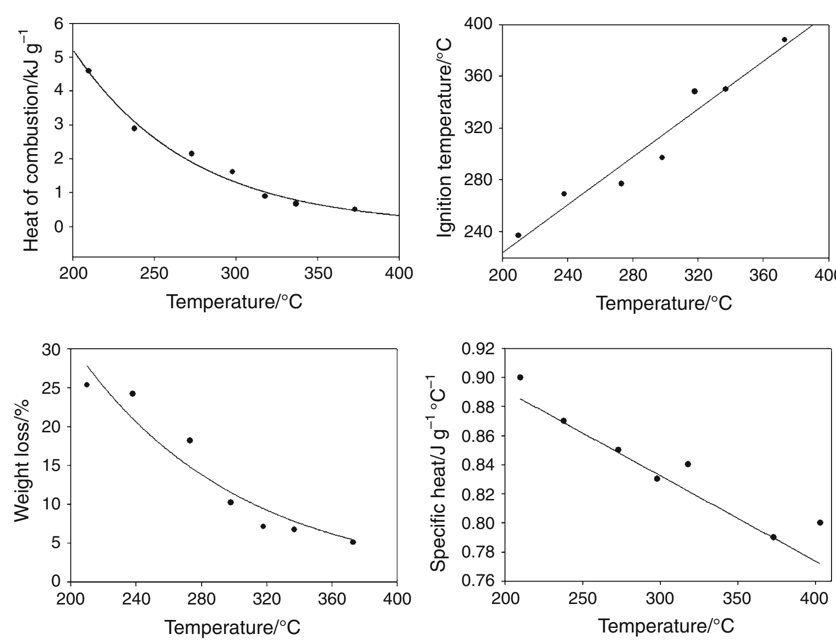


Fig. 7 Results of Villestro II soil

Fig. 8 Results of Retortas soil

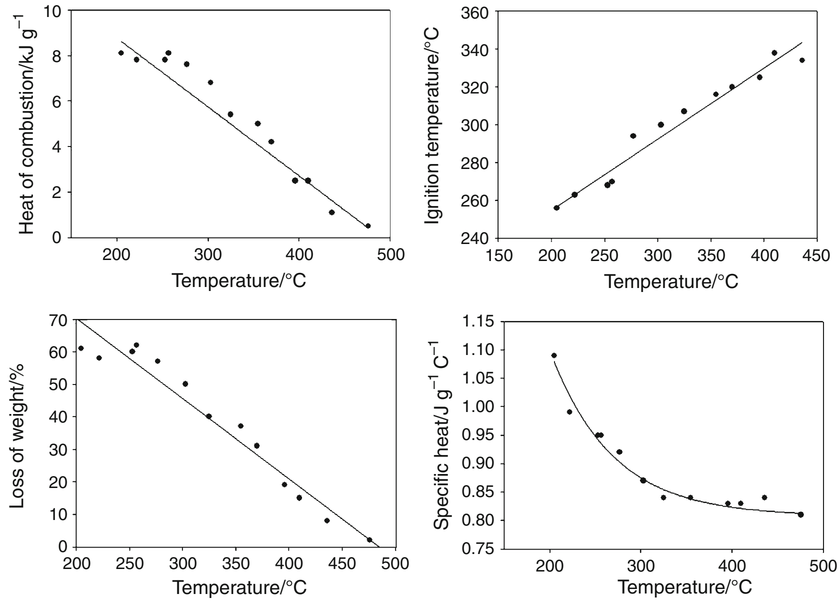
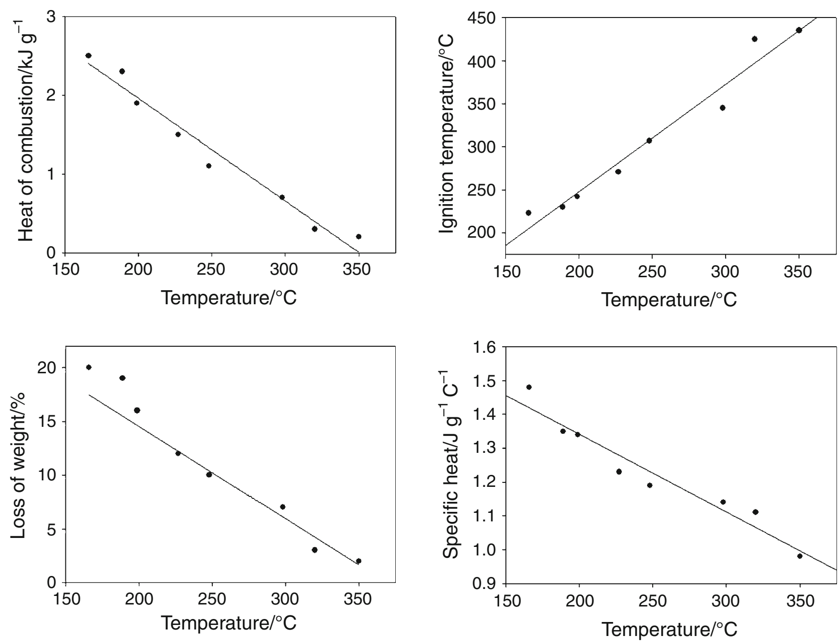


Fig. 9 Results of Cervantes soil



maximum temperature (T_{max}). Later, the values of these parameters in the soils burnt in the forest wildfires (Table 3) were interpolated in these models to obtain indirectly the maximum temperatures reached in the field during the fire. Table 4 presents the values of the maximum temperatures, reached by the soils, calculated from each model.

An important similarity between the results obtained from each model has been found, indicative of the close relationships among these soils properties.

Of all the measured physical properties, specific heat is the one with less variation with temperature. It has been observed that during the combustion, which takes place from 200 °C, the specific heat changes are 0.24, 0.10, 0.19 and 0.30 J g^{-1} °C^{-1} in Villestro I, Villestro II, Retorts and Cervantes soils, respectively. This fact complicates the determination of the maximum temperature from the variation of specific heat, its calculation being only possible in the last soil, which presents the major variation. It is important to note that the values of specific heat are similar in all the soils heated at the highest temperatures, and similar to specific heat of granite (0.8118 J g^{-1} °C^{-1}) [26], an important component in Galician soils.

Taking into account that the Villestro I and Villestro II soils were collected with apparent different morphological

Table 2 Best models obtained for every measured magnitude, heat of combustion of organic matter (Q), ignition temperature (T_{ign}), % mass loss (%Loss) and specific heat (C_p) in all the soils heated in this study, with the statistical results

Soil	Model	*a* error	*b* error	*c* error	R^2	Sig.
Villestro I	$Q = -0.0329\ T_{max} + 13.578$ kJ g^{-1}[a]	3×10^{-3}	0.9	–	0.9785	0.000
	$T_{ign} = 0.8842\ T_{max} + 28.669$ °C[a]	0.03	8	–	0.9968	0.000
	% Loss $= -0.25\ T_{max} + 104.418$[a]	0.02	7	–	0.9847	0.000
	$C_p = 0.791 + 12.131 \exp(-0.018\ T_{max})$ J g^{-1} °C^{-1}[b]	0.022	1.506	0.006	0.981	0.001
Villestro II	$Q = 84.279 \exp(-0.0139\ T_{max})$ kJ g^{-1}[b]	–	2.096	0.001	0.9905	0.000
	$T_{ign} = 0.9253\ T_{max} + 38.836$ °C[a]	0.095	8.218	–	0.975	0.001
	% Loss $= 227.71 \exp(-0.010\ T_{max})$[b]	–	8.736	0.002	0.913	0.000
	$C_p = -0.0006\ T_{max} + 1.0085$ J g^{-1} °C^{-1}[a]	0.0005	0.54	–	0.8334	0.05
Retortas	$Q = -0.0303\ T_{max} + 14.821$ kJ g^{-1}[a]	2×10^{-3}	0.8	–	0.974	0.000
	$T_{ign} = 0.3756\ T_{max} + 179.843$ °C[a]	0.02	8	–	0.980	0.000
	% Loss $= -0.2326\ T_{max} + 112.55$[a]	0.02	6	–	0.9826	0.000
	$C_p = 0.815 + 5.533 \exp(-0.0149\ T_{max})$ J g^{-1} °C^{-1}[b]	0.011	2.457	0.002	0.986	0.000
Cervantes	$Q = -0.0112\ T_{max} + 3.975$ kJ g^{-1}[a]	0.178	0.001	–	0.989	0.000
	$T_{ign} = 1.187\ T_{max} + 1.1871$ °C[a]	–	0.8	–	0.980	0.000
	% Loss $= -0.0861\ T_{max} + 31.7392$[a]	0.047	15.478	–	0.962	0.001
	$C_p = -0.002\ T_{max} + 1.802$ J g^{-1} °C^{-1}[a]	0.000	0.06	–	0.969	0.000

R^2 correlation coefficient corrected, *Sig* significance

[a] Model $y = ax + b$

[b] Model $y = a + b \exp(cx)$

Table 3 Measured parameters corresponding to burnt soil

Soil	Enthalpy of combustion/kJ g^{-1}	Ignition temperature/°C	Mass loss/%	Specific heat/ J g^{-1} °C^{-1}
Villestro I	−4.9 ± 0.4	250 ± 2	40 ± 1	–
Villestro II	−2.8 ± 0.5	256 ± 4	15 ± 1	–
Retortas	−3.0 ± 0.2	323 ± 7	20 ± 2	0.83 ± 0.10
Cervantes	−2.5 ± 0.3	231 ± 5	26 ± 1	1.39 ± 0.03

Table 4 Values of maximum temperature reached by the soils during the wildfires

Soil	Villestro I/°C	Villestro II/°C	Retortas/°C	Cervantes/°C
Enthalpy model	264	245	390	132
Ignition model	250	235	380	185
Mass loss model	254	272	398	–
C_p model	–	–	–	179

characteristics of the burning, the maximum temperature reached in the soils was not as different as could be expected from the temperature at the moment of the sampling. An explanation of this discrepancy could be the different compositions of the soils. The different values of the TG analysis of the unburnt Villestro I (52.0 ± 3.3% mass loss) and Villestro II (29.0 ± 0.2% mass loss) soils are indicative of this fact.

The maximum temperature rise experienced by Retortas soil during the fire was the highest, being approximately 400 °C, with this soil being seriously damaged by the wildfire. Almost all the organic matter was destroyed [21, 22] and, therefore, a long duration will be necessary to effect the recovery of the initial properties of the soil [27], and even a recovery may be impossible if the soil is exposed to phenomena associated with such impacts as the erosion.

Although Cervantes is the soil that presents the biggest differences between the obtained maximum temperatures, in all the cases, the values are lower than ignition temperature of the unburnt soil, 230 ± 3 °C. This indicates a low intensity fire [14], and the burning probably did not damage the soil irreversibly. This result was expected because this soil had been affected by a winter fire, and during this season, the temperature, the weather and the vegetation are not in the best conditions for the soil to reach high temperatures [27, 28].

The results of this study showed that Retortas soil was affected by a high intensity fire (maximum temperature between 380 and 398 °C); Villestro I and Villestro II soils affected by a medium intensity fire (maximum temperature between 235 and 272 °C) and Cervantes soil affected by a low intensity fire (maximum temperature lower than ITUS). Maximum temperature standard deviations are less than 15%. Although these results are obtained in laboratory conditions, they agree with those obtained by Gimeno-García et al. [29] during experimental fires.

Conclusions

A new indirect method has been designed to determine the maximum temperatures reached by the soil during a forest fire based on the variation with the temperature of different physical properties. Four soils were analysed using this method, obtaining different maximum temperature values due to the different climatic conditions and the different states of the vegetation and soil.

The variations of the specific heat, the enthalpy of combustion of the organic matter, the ignition temperature and the organic matter content generally showed a lineal relationship with the temperature during the burning in the laboratory.

The results obtained from every model are similar for every soil, indicative of the validity of the method used to determine the maximum temperature reached by the burnt soil.

The soil that reaches a low temperature during the fire is Cervantes soil, which was burnt in winter, whereas the soil that reaches high temperatures is Retortas soil, which corresponds to a summer fire. Retortas soil was the most affected by the fire, despite it being regarded as the most thermal resistant, showing its control soil the major value of organic matter content.

References

1. MMA 2006. Los incendios forestales en España: 1996–2005.
2. Rodríguez Trejo DA. Incendios forestales. Mundi-Prensa México; 1996.
3. Porrero Rodríguez MA. Incendios forestales. Investigación de causas, Mundi-Prensa Madrid; 2001.
4. Neary NG, Klopatek CC, DeBano LF, Folliot PF. Fire effects on belowground sustainability: a review and synthesis. For Ecol Manag. 1999;122:51–71.
5. Ulery L, Graham RC. Forest fire effects on soil color and texture. Soil Sci Soc Am J. 1993;57:135–40.
6. Agren GI, Bosatta E. Reconciling differences in predictions of temperature response of soil organic matter. Soil Biol Biochem. 2001;34:129–32.
7. Gavito ME, Curtis PS, Mikkelsen TN, Jakobsen I. Interactive effects of soil temperature, atmospheric carbon dioxide and soil N on root development, biomass and nutrient uptake of winter wheat during vegetative growth. J Exp Bot. 2001;52: 1913–23.
8. Reyes O, Casal M. Regeneration models and plant regenerative types related to the intensity of fire in Atlantic shrubland and woodland species. J Veg Sci. 2008;19:575–83.
9. García-Oliva F, Sanford RL, Kelly E. Effect of burning of tropical deciduous forest soil in Mexico on the microbial degradation of organic matter. Plant Soil. 1998;206:29–36.
10. Solari P, Siccardi F. Soil degradation and erosion in small Mediterranean watersheds: non-lineal interaction between forest fires and extreme rainfall processes. In: Proceedings of III International Conference on Forest Fire Research, vol. II, Luso, Portugal; 1998. p. 1333.
11. Carballas M, Acea MJ, Cabaneiro A, Trasar MC, Villar MC, Díaz-Raviña M, Fernández I, Prieto A, Saa A, Vázquez FJ, Zëhner R, Carballas T. Organic matter, nitrogen, phosphorus and microbial population evolution in forest humiferous acid soils after wildfires. In: Trabaud L, Prodon P, editors. Fire in Mediterranean ecosystems. Commission of the European Countries, Ecosystems Research Series, Report 5. Brussels, Belgium; 1994. p. 379–85.
12. Díaz-Raviña M, Prieto A, Bäth E. Bacterial activity in a forest soil after soil heating and organic amendments measured by the thymidine and leucine incorporation techniques. Soil Biol Biochem. 1996;28:419–26.
13. Fernández I, Cabaneiro A, Carballas T. Organic matter changes immediately after a wildfire in an Atlantic forest soil and comparison with laboratory soil heating. Soil Biol Biochem. 1997;29:1–11.
14. Chandler C, Cheney P, Thomas P, Trabaud L, Williams D. Fire in forestry. Forest fire management and organizations. New York: Wiley; 1991.
15. Fernández I, Cabaneiro A, Carballas T. Thermal resistance to high temperatures of different organic fractions from soils under pine forests. Geoderma. 2001;104:281–98.
16. Marcos E, Tárrega R, Luis E. Changes in a Humic Cambisol heated (100–500°C) under laboratory conditions: the significance of heating time. Geoderma. 2007;138:237–43.
17. Valette JC, Gomendy V, Marechal J, Houssard C, Gillon D. Heat-transfer in the soil during very low-intensity experimental fires—the role of duff and soil-moisture content. Int J Wildland Fire. 1994;4:225–37.
18. Karischke ES, Johnstone JF. Variation in postfire organic layer thickness in a black spruce forest complex in interior Alaska and its effects on soil temperature and moisture. Can J For Res. 2005;35:2164–77.
19. Giovannini G, Lucchesi S, Giachetti M. Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Sci. 1998;146:255–61.
20. Varela ME, Benito E, de Blas E. Impact of wildfires on surface water repellency in soils of northwest Spain. Hydrol Process. 2005;19:3649–57.
21. Salgado J, González MI, Armada J, Paz Andrade MI, Carballas M, Carballas T. Loss of organic matter in Atlantic forest soils due

to wildfires. Calculation of the ignition temperature. Thermochim Acta. 1995;259:165–75.
22. Salgado J, Mato MM, Vázquez-Galiñanes A, Paz-Andrade MI, Carballas T. Comparison of two calorimetric methods to determine the loss of organic matter in Galician soils (NW Spain) due to forest wildfires. Thermochim Acta. 2004;410:141–8.
23. Lu L, Qin Z, Zhao C, Li W, Gao M. Effects of vegetation indices to the spatial changes of desert environment using EOS/MODIS data: a case study of Sangong inland arid ecosystem. Proc SPIE. 2006. doi:10.1117/12.689413.
24. Guitián Ojea F, Carballas Fernández T. Técnicas de Análisis de Suelos. Ed. Pico Sacro. Santiago de Compostela, Spain; 1976.
25. Dodd JW, Tonge K. Thermal methods. Chaps 2 and 4. London: Wiley-Interscience; 1987.
26. Waples DW, Waples JS. A review and evaluation of specific heat capacities of rocks, minerals and substances fluids. Nat Resour Res. 2004;13:97–122.
27. Giovannini G, Luchesi S, Giachetti M. Beneficial and detrimental effects of heating on soil quality. In: Fire in ecosystem dynamics: Mediterranean and northern perspectives. Proceedings of the Third International Symposium on Fire Ecology, Freiburg. The Hague, Netherlands: Academic Publishing; 1990.
28. Giovannini G, Luchesi S, Giachetti M. Effects of heating on some chemical parameters related to soil fertility and plant growth. Soil Sci. 1990;149:344–50.
29. Gimeno-García E, Andreu V, Rubio JL. Spatial patterns of soil temperatures during experimental fires. Geoderma. 2004;118: 17–38.