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A new method for performing smouldering combustion field experiments in peatlands and rich-organic soils

E. Pastor[A,F], *I. Oliveras*[B], *E. Urquiaga-Flores*[C], *J. A. Quintano-Loayza*[D], *M. I. Manta*[E] *and E. Planas*[A]

[A]Department of Chemical Engineering, Centre for Technological Risk Studies, Universitat Politècnica de Catalunya·BarcelonaTech, Eduard Maristany 10-14, E-08019 Barcelona, Catalonia, Spain.

[B]Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX13QY, UK.

[C]Departament of Systematic and Evolutionary Botany, University of Zurich, Zollikerstrasse 107, CH-8088 Zurich, Switzerland.

[D]Departament of Botany, Universidad de San Antonio Abad del Cusco, Avenida Cultura 733, Cusco, Perú.

[E]Forest Management Department, Universidad Nacional Agraria La Molina, Avenida La Universidad S/N, , Apartado 12-056, Lima, Perú.

[F]Corresponding author. Email: elsa.pastor@upc.edu

Smouldering ground fires have severe environmental implications. Their main effects are the release of large amounts of carbon to the atmosphere with loses of organic soil and its biota. Quantitative data on the behaviour of smouldering wildfires are very scarce and are needed to understand its ecological effects, to validate fuel consumption and smouldering propagation models and to develop danger-rating systems. We present, for the first time, a methodology for conducting smouldering experiments in field conditions. This method provides key data to investigate smouldering combustion dynamics, acquire fire behaviour metrics and obtain indicators for ecological effects of smouldering fires. It is to be applied in all types of undisturbed soils. The experimental protocol is based on a non-electric ignition source and the monitoring system relies on combining both point and surface specific temperature measurements. The methodology has been developed and applied by means of large series of replicate experiments in highly organic soils at the forest–grassland treeline of the Peruvian Andes. The soil tested exhibited weak ignition conditions. However, transition to oxidation phase was observed, with smouldering combustion during 9 h at 15-cm depth and residence times at temperatures above dehydration of ~22 h.

Additional keywords: carbon emission, charcoal combustion, ground fires, infrared imagery, Peruvian Andes, thermal damage.

We present a method for conducting smouldering experiments in field conditions by which data on fire behaviour and ecological effects of ground fires are obtained at real scale. The methodology is tested at the forest–grassland treeline of the Peruvian Andes. We observe smouldering during 9 h at 15-cm depth.

Introduction

Peatlands are a key component of the global carbon pool. They cover only 2–3% of the global terrestrial surface but store over 25% of the world's soil carbon (Yu 2012). Despite their importance, peatlands are being rapidly depleted because of land use changes (e.g. drainage for oil palm plantation in Indonesia and Malaysia, Moore *et al*. 2013) and fires (Page *et al*. 2002; Turetsky *et al*. 2014). Peat fires are characterised by smouldering combustion, a slow, flameless and low-temperature combustion of the organic matter in porous form (Ohlemiller 1985; Rein 2009). The controlling mechanisms of soil smouldering fires are still scarcely known (Rein 2009), although there is plenty evidence of their daunting effects on certain ecosystems (Page *et al*. 2002; Rein 2009; Davies *et al*. 2013). Smouldering fires can persist for long periods (months to years), totally consuming the soil and thus creating a devastated landscape. For example, during October and November 2015, more than 10 000 forest fires destroyed large peatland regions across Kalimantan (Indonesian Borneo) and Sumatra (Carrington 2015). These events matched at least the fires of 1997, the worst year on record on peatland fires, which released between 0.98 and 2.6 Gt of carbon to the atmosphere (Page *et al*. 2002). Temperate peatlands are also increasingly being affected by smouldering fires even in managed systems like in the UK (Davies *et al*. 2013), as well as are boreal systems – for example, it has been estimated that Russian boreal forest fires accounted to 15–20% of the annual global carbon emissions from forest fires in 1998 (Conard *et al*. 2002).

The most common triggering events of extensive smouldering combustion are wildfires, either natural or, most frequently, human-induced. In tropical regions, fires from deforestation and land clearing are usually the starting point for smouldering combustion, especially in El Niño years (Page *et al*. 2009). In temperate regions, management prescribed burnings are often the cause of these fires (Davies *et al*. 2016). The effects of ground fires are the release of very large amounts of carbon to the atmosphere with the consequent loses of organic soil, complete mortality of soil biota and all vegetation existing in that landscape.

Smouldering combustion in organic soils propagates laterally and downwards by an overall exothermic process composed by three stages (Fig. 1). First, the smouldering front preheats gradually the medium ahead at dehydration temperatures ~50–100°C (Filkov *et al*. 2012).

Once dehydrated, the dry medium experiences endothermic reactions of pyrolysis at temperatures above 150°C (Phase 2) (Chen *et al*. 2011), in which the chemical breakdown of the solid fuel yields char (carbon-enriched solid material), pyrolysate gases and ash. In smouldering combustion, *in situ* char oxidation dominates gas-phase oxidation. Last (Phase 3), char oxidation reactions take place once ignition temperatures (above 210°C) are reached (Babrauskas 2003) and sufficient transfer of oxygen is guaranteed, giving heat, CO_2, CO and water vapour as main combustion products.

The intensity and rate of spread of a smouldering subsurface wildfire front is primarily controlled by the heat losses to the environment and by the oxygen transfer to the combustion zone (Ohlemiller 1985). The soil properties that allow for a sustained smouldering ignition and propagation are soil moisture, mineral content, bulk density, soil depth, porosity, permeability and organic composition of the different subsurface layers involved (Rein 2009). Although it is well known that all of these factors may play a certain role in the overall smouldering combustion processes, the relative importance of each, their interaction and effects on smouldering fire behaviour (e.g. spread rate, residence time, heat released, fuel consumption) in different types of soils and ecosystems are still poorly understood (Rein 2013).

Smouldering evidences of real wildfires (e.g. depth of burn) have been quantified in the literature (e.g. de Groot *et al.* 2009; Turetsky *et al.* 2011). However, quantitative data on the actual behaviour of smouldering wildfires are very scarce (Usup *et al*. 2004), because the stochastic and unforeseen nature of these events makes the development of systematic and reliable sampling methodologies in real wildfire scenarios a very challenging task. Data on smouldering fires related variables are needed to better understand its ecological effects and positive feedbacks to climate change (Bertschi *et al*. 2003; Davies *et al*. 2013), and to validate fuel consumption and smouldering propagation models (Grishin *et al*. 2009) and danger rating systems (Reardon *et al*. 2009). However, despite the ideal environment to study smouldering would be a field scenario (Frandsen 1987), smouldering field experiments have never been reported in the peer-reviewed literature. To the best of our knowledge, there were some limited attempts of ignition field tests in Engelman spruce duff in 1995 (Lawson *et al*. 1997), but those authors did not report any combustion metrics nor a well described methodology.

Because of these challenges, smouldering combustion in ground fuels has so far only been studied in laboratory conditions (or more recently, using computational models to recreate laboratory set ups as in Huang *et al*. 2015). Most of these experiments have provided valuable insights defining ignition and sustained combustion thresholds associated to soil moisture, inorganic content, fuel depth and density. These studies have used different approaches to induce combustion – the most common is an electrically heated coil (e.g. Frandsen 1987; Miyanishi and Johnson 2002; Garlough and Keyes 2011), as well as different soil substrates – whereas some have used commercial disaggregated peat-moss to emulate real natural fuels (Frandsen 1987, 1998; Hartford 1989; Miyanishi and Johnson 2002; Prat *et al.* 2015), some others have used field samples (Frandsen 1991, 1997; Reardon *et al.* 2007; Rein *et al.* 2008; Benscoter *et al.* 2011; Garlough and Keyes 2011). All these studies have artificially varied some of the sample properties to meet specific research objectives, being the most common manipulations moisture (by moistening and/or drying samples – e.g. Garlough and Keyes 2011), addition of inorganic substrate (inorganic content manipulation – e.g. Frandsen 1987) and/or mechanical compaction (soil density manipulation – e.g. Miyanishi and Johnson 2002; Garlough and Keyes 2011). Laboratory studies usually use punctual temperature measurements to monitor combustion and fire behaviour (e.g. Rein *et al.* 2008; Benscoter *et al.* 2011) with only few studies using continuous monitoring such as infrared (IR) imagery systems to extract quantitative data (Prat-Guitart *et al.* 2015, 2016; Huang *et al.* 2016). These controlled laboratory studies have provided a clear step forward on our current understanding of smouldering fire behaviour. However, they barely replicate natural conditions. For example, the majority of laboratory studies published so far have suggested that the ignition limit of organic soil horizons is at moisture content (on wet base) of 150% or less (Garlough and Keyes 2011). However, smouldering in peat wildfires has been reported to be sustained at higher moisture contents (e.g. average values of 252 and 273% (dry base) found in Davies *et al.* 2013) and recent simulation studies (250% dry base, Huang and Rein 2015; Thompson *et al.* 2015) and laboratory studies (Watts 2013 also finds a 250% dry base moisture content threshold) also suggest so. In addition, the inability of laboratory methods to reproduce real smouldering downward propagation patterns has already been noted (Watts 2013).

Moisture is a key factor when determining whether smouldering combustion is sustained and is highly influenced by inorganic content, soil density and soil depth (Frandsen 1987; Miyanishi and Johnson 2002; Reardon *et al.* 2007; Garlough and Keyes 2011). In most laboratory experiments, moisture content has been manipulated to be homogeneous within the samples. However, natural ground fuel is heterogeneous, with moisture, inorganic content and soil density varying laterally and vertically (e.g. Bridge and Johnson 2000; Zoltai *et al.* 2000; Benscoter *et al.* 2005). Frandsen (1987) already highlighted the importance of natural moisture gradients in controlling the ignition and propagation of smouldering fronts. In fact, assumptions of homogeneity have already been considered invalid for thick organic soils (Benscoter *et al.* 2011) and some authors have already stressed that the validity of their results depends on real moisture and mineral content distributions (Reardon *et al.* 2007; Garlough and Keyes 2011).

This study presents, for the first time, a novel methodology for conducting smouldering experiments in field conditions. The methodology is envisaged to provide data to: (i) analyse the transition of the several combustion stages at different depths and locations; (ii) extract smouldering fire behaviour metrics; and (iii) obtain indicators for ecological effects of smouldering fires. Our proposed methodology can potentially be applied to study any type of subsurface organic layer and environment. It is particularly suitable for systems with difficult properties for being replicated at laboratory scale (high density soils, colloidal soils, soils with wide ranges on characteristic properties, etc.). The paper is organised as follows: we first present the methodology rationale giving details on the main assumptions regarding the aim and scope of the methodology, the experimental layout and the ignition source and smouldering monitoring. Next, we provide extensive information on the methodology development and testing through a study case conducted to investigate smouldering combustion on the humic layers of high-latitude Andean grassland soils exposed to real weather conditions. We then discuss the suitability of our method and the significance of the experimental results obtained in our study case, by comparing our protocol with laboratory procedures, by presenting some insights on how ground fires are sustained and by estimating the final fire behaviour and ecological effects metrics regarding our experiments. Finally, we provide some concluding remarks and outline further work.

Methodology rationale

An experimental method for studying smouldering combustion on field conditions requires a careful design taking into account several aspects about its applicability and operability. The underlying assumptions considered when developing the method are detailed as follows.

Scope and objectives

The final aim of the method is to provide quantitative data on smouldering fire behaviour metrics and indicators under field conditions (e.g. rate of spread, smouldering transition thresholds, fire residence time, carbon lost) to be mainly used for ecological effects analysis and models validation (fuel consumption, fire propagation, danger rating, etc.). The methodology is not foreseen to be used as a procedure to analyse the particular involvement of a certain soil property on the smouldering ignition and propagation phenomena. Rather, the method is intended to provide a detailed picture in terms of smouldering fire behaviour and related parameters under realistic conditions. The methodology should be applicable and generalisable to all sorts of smouldering-prone soils, regardless its eco-zone and location, respecting the nature of the organic horizons, preserving soil natural variations and hence assuring a realistic scenario.

Experimental layout

The protocol should take into account the natural soil heterogeneity, the eventually variable weather conditions and should allow large series of experiments with multiple replications. For this reason, it should consider a layout with different experimental blocks covering different areas of the selected study site. Within each block, several plots should be designed to account for true replicates (to be burnt at the same time) and for control plots (to monitor soil properties). The number of blocks and plots should reflect a good compromise between results significance and experimental program complexity and effort.

Ignition source and smouldering monitoring

The ignition procedure should be quantifiable, easy to replicate, realistic, independent of external energy sources and easy to implement in isolated areas. The monitoring system should have a positive trade-off between monitoring effort and quality/quantity of the data needed. Ideally, it should contemplate a combination of point (thermocouples) and surface specific (infrared imagery) temperature measurements. Thermocouples disposed in a spatial and soil-depth array in the study area should provide the temperature–time evolution of the smouldering front to analyse smouldering dynamics and compute fire behaviour and fire effects metrics. Processing temperature–time curves should enable to obtain data on the smouldering transition thresholds, on the rate of spread of the smouldering front and on the residence times of the heat front at different temperatures (e.g. Usup *et al*. 2004; Rein *et al*. 2008). Moreover, time-integrated temperatures above certain temperature thresholds should provide an indicator of the accumulated heat that the medium experiences over time, containing valuable information to analyse fire severity and other ecological effects (e.g. Kennard *et al*. 2005; Bova and Dickinson 2008). The optimum thermocouples layout should consider several sensors at different depths (according to the soil moisture content profile) and should be evenly distributed through the plots surface. In contrast, infrared imagery should allow surface temperature surveys at certain periods, and should provide information about the overall area affected by combustion activity (e.g. Plucinski and Pastor 2013; Prat-Guitart *et al*. 2015). This type of data should be useful to control the course of the experiments, to assess fuel consumption and, provided carbon content is known, to estimate carbon lost during smouldering.

Methodology development and testing: study case in Andean Puna organic soil

Experimental site

The study was carried out in the high-altitude Andean grasslands of the south-eastern Peruvian Andes (Fig. 2), at ~3300 m above sea level (ASL) in the south-western buffer area of Manu National Park (13°10′50.28″S, 71°35′19.95″W). These grasslands are characterised by tussock-forming grasses. Dominant species include *Calamagrostis longearistata*, *Ageratina sternbergiana*, *Juncus bufonius* and *Scirpus rigidus* (Oliveras *et al.* 2014*a*). Average annual rainfall ranges from 1900 to 2500 mm, with a wet season spanning from October to April. Mean annual temperature were ~11°C at 3600 m ASL (Gibbon *et al.* 2010). Soils are composed of a thick organic-rich A-layer, stony B/C-layers, and a thin or no Oh-layer (Zimmermann *et al.* 2010; Oliveras *et al.* 2014*b*). At the study site, the organic rich layer varied between 60 and 110 cm. One of the key aspects of fires in the region is the occurrence of smouldering (Román-Cuesta *et al.* 2011; Oliveras *et al.* 2013) and we aimed to study the conditions that would enable ignition and sustained combustion of the soil organic layers. The study was developed within the framework of a larger project aimed at characterising the dynamics of forest fires at the forest-grassland treeline of the Peruvian Andes (Oliveras *et al.* 2014*a*, 2014*b*, 2014*c*; Román-Cuesta *et al.* 2014).

Experimental design

The experimental set up consisted of a randomised block design of two blocks, 500 m apart located in a relatively flat area with no grazing, with 20 plots (0.5 × 0.5 m) each (see Fig. 2). Plots dimensions were established according to typical smouldering front propagation values (Rein (2009) provides typical front rate of spread values of 1– 3 cm h^{-1} meaning that a 50 × 50-cm plot should be burned between 16 h and 50 h hence ensuring a long monitoring period). At each block (named W1 and W2), five plots were randomly selected as control plots (to be left unburned and to control soil moisture content), and excepting on these, metal plates were inserted in all plots up to 0.5 m soil deep in order to avoid any eventual smouldering front to propagate out of the plot (in deeper regions, according to preliminary soil-moisture content measurements and according to visual inspections, we assumed that the soil was too moist and dense to sustain smouldering combustion). We initially set a planning consisting on five experimental days, burning each day six plots (three at every block, randomly selected and acting as true replicates), but bad meteorological conditions only allowed us to perform burns on 3 days (Table 1). Therefore, burns were performed on eighteen plots on 7, 10 and 11 July 2012, starting between 1030 and 1430 hours local time. All experiments were left to burn for 48 h.

Ignition procedure

We established an ignition procedure that consisted on introducing 1 kg of smouldering charcoal in a 30 cm long × 10 cm wide × 20 cm deep hole dug at one of the ends of the plot. Charcoal was preliminary activated with a portable gas burner outside the plot. The hole had the back side protected with firebricks against an eventual undesired spread direction, enabling our design smouldering propagation forwards only (Fig. 3).

An estimate of the power supply of the ignition source was made based on charcoal burning properties. Instantaneous charcoal burning rate ($\dot{M}_i$, kg s^{-1}) depends, according to D. Andreatta (pers. comm., 30 May 2013), on the mass of charcoal remaining at each time instant *i* (M_{ri}, kg) and can be approximated by the following equation:

$$\dot{M}_i = 16.617 \times 10^{-8} \cdot M_{ri} \quad (1)$$

Ignition heat flux at each instant (I, kW m^{-2}) can be expressed (Eqn 2) assuming that the heat generated by the charcoal combustion is homogeneously transmitted through all the transferring area of the charcoal volume:

$$I = \frac{\dot{q}_i}{A} = \frac{\dot{M}_i \cdot H_c}{A} \quad (2)$$

where $\dot{q}_i$ is the energy released by time (kW) and A is the heat transferring area (0.16 m^2 corresponding to 5 out of 6 faces of the charcoal volume; there was a 20 × 30-cm section protected by firebreaks acting as insulation).

H_c is the heat of combustion of the charcoal (MJ kg^{-1} of charcoal). Composition of 75% of fixed carbon content (%C) and 20% of volatile matter (%VM) – being the rest 5% ash and moisture content– can be expected for typical charcoal (Food and Agriculture Organization of the United Nations 1984), hence H_c can be obtained by considering the contribution of both heat of char smouldering combustion and heat content of volatile matter as follows:

$$H_c = 10^{-2}\left(\%C \cdot H_{ch} + \%VM \cdot H_{vm}\right) \quad (3)$$

where H_{ch} is the heat of char smouldering combustion (MJ kg^{-1} of C), and H_{vm} is the heat content of volatile matter (MJ kg^{-1} of VM). H_{ch} depends on the efficiency of C oxidation, and can be estimated by the products of combustion CO/CO_2 ratio (de Souza Costa and Sandberg 2004). According to this, H_{ch} will vary between 21.8 and 29.1 MJ kg^{-1} of C if a wide range (e.g. 1/3–3) of CO/CO_2 proportion is considered (note that typical values of CO/CO_2 ratios in smouldering combustion are around unity (Rein 2009)). In contrast, heat content of volatile matter (H_{vm}) is mostly comprised between 12.8 and 17.2 MJ kg^{-1} for most forest fuels (Susott *et al*. 1975; Susott 1982). Thus, with the charcoal composition considered and following Eqn 3, a maximum value of H_c of 25.3 MJ kg^{-1} of charcoal will be expected if all the C and the VM react and upper bounds of H_{ch} and of H_{vm} are considered. By contrast, taking the lower H_{ch} bound and considering that volatiles might also exit the smouldering surface without reacting (no contribution of H_{vm} in Eqn 3), H_c can have a minimum value of 16.4 MJ kg^{-1}. Therefore, given these H_c limits, a mean value of 20.85 MJ kg^{-1} was assumed for H_c in this study.

Smouldering combustion monitoring

An array of K-type metal-sheathed thermocouples of 0.5-mm diameter, 30-cm length connected to HOBO Onset U12–014 data loggers was used to monitor soil temperatures. The thermocouples distribution was set (i) according to the sensors availability; (ii) considering two different depths (5 and 15 cm) *a priori* set by analysing preliminary soil moisture content measurements; (iii) depicting a homogenous layout (see Fig. 3). The final array was designed to detect ignition (by observing the temperature evolution of the thermocouple placed 5 cm apart from the ignition source) and to identify any possible heat front spreading laterally and/or downwards (by observing the temperature evolution provided by the rest of the sensors). The loggers were set before the start of the experiments, to acquire temperatures at a frequency of one datum per minute.

In addition to the thermocouples, the experiments were monitored with an IR camera (AGEMA Thermovision 570-Pro, FSI-FLIR Systems) operating at the 7.5–13-µm range. We surveyed the plots at regular time intervals saving nadir viewing images approximately every 24 h. The monitoring frequency was determined according to the smouldering activity observed (i.e. low intensity) and according to the overall logistics of the experiments (the study site was located in a remote area). Burning candles were placed at the plot corners and used as hot control points for IR imagery sizing. IR images were analysed using ThermaCAM Researcher software and AutoCAD software. Both the charcoal and the plot surface were modelled as black bodies (Prat-Guitart *et al*. 2015), with emissivity equal to 0.97

Environmental variables

Weather conditions (air temperature, relative humidity 2-m wind speed and direction) were continuously recorded at a frequency of 30 s with a portable weather station (Kestrel 4500) that was placed between the two blocks of plots.

Soil moisture content (on dry base) was measured with a Hydrosense Soil Water Measurement System (Campbell Scientific, Inc.) at 12- and 20-cm soil depth. At each block, two points were measured every day just before ignition, one in the corresponding control plot of that burning day and another one outside the block. Two soil samples of 10 × 10 × 25 cm (one from each block) were used to calibrate the Hydrosense for the local soil conditions (Supplementary information). The calibration was performed by using a natural dry-down method, measuring the moisture and weighting the soil every 4 h for 4 days. After the 4 days, soil was oven-dried at 80°C until constant weight. Significant differences between days, blocks and soil depth moistures were evaluated using a multifactorial ANOVA.

Five soil cores of known volume (62.5 cm^3) were extracted with a core sampler of 50-mm diameter and 10-cm depth sampled at each experimental block for calculating bulk density, soil carbon content and mineral content. Samples were taken to the laboratory and oven-dried at 80°C until constant weight. The samples were crushed and sieved to 2 mm to remove stones, and the remaining fine roots were removed manually. Bulk density was calculated as the free-stone and free-roots mass fraction per cubic centimetre. A sub-sample was grounded and analysed for organic carbon with a mass spectrometer coupled to an elemental analyser (Isotope Ratio Mass Spectrometry) Finnigan Delta plus XP at the University of Saint Andrews (UK). Soil inorganic content was determined by weighting the remaining material after burning a 10-g soil subsample on a muffle furnace (1807 FLIBL CM) at 1300°C. Soil properties between sites (bulk density, organic carbon and mineral content) were tested for significant differences using a *t*-test for independent samples.

Statistical analyses were used using R software (R Foundation for Statistical Computing, Vienna, Austria, see https://www.R-project.org).

Experimental results

(i) Weather variables and soil properties

Weather variables showed the same daily pattern during all burning days. During daytime (i.e. between 7 and 17 h), ambient conditions showed rapid fluctuations in temperature, wind speed and relative humidity (Fig. 4). At night time, weather was more stable, with temperature ~8°C, relative humidity above 85% and wind speed between 5 and 9 km h^{-1} for the whole experimental period (Fig. 4).

At the study sites, soil had 66% of sand, 22% of silt, and 12% of clay. Soil properties at the sites presented some degree of heterogeneity (Table 2), but there were not significant differences between sites in either soil bulk density (*t*-test parameters: $t = 3.18$, d.f. = 8, $P = 0.86$), organic carbon (*t*-test parameters: $t = 2.17$, d.f. = 7, $P = 0.39$) and inorganic content (*t*-test parameters: $t = 2.23$, d.f. = 8, $P = 0.55$). These three variables had 34%, 39% and 16% coefficient of variation respectively. Soil moisture content was also relatively constant at the experimental site with no significant differences between days (*F*-test parameters: $F = 1.575$, d.f. = 3, $P = 2.52$) or blocks (*F*-test parameters: $F = 1.28$, d.f. = 1, $P = 2.81$), but soil moisture at 20 cm was significantly lower than soil moisture at 12-cm depth (*F*-test parameters: $F = 10.9$, d.f. = 1, $P = 0.003$).

(ii) Ignition source and smouldering monitoring

At the beginning of the test, the initial charcoal ignition power was ~22 kW m^{-2}, and mean temperature ~434°C (Fig. 5), which translated to a radiative heat flux of 14 kW m^{-2} (following Stefan–Boltzmann Law), that is 60% of the total power initially supplied. According to Eqns 1 and 2 and to empirical evidence, charcoal was totally consumed (98%) through smouldering combustion 6.5 h after ignition. During the first 120 min (in which 70% of the charcoal was consumed), average ignition power reached 13 kW m^{-2}, and then decreased to 7 kW m^{-2} with an exponential decay of the burning rate from 10 to 3 g min^{-1}. The remaining fuel was then slowly consumed at a mean burning rate of 1 g min^{-1} supplying 2.28 kW m^{-2} of mean heat flux.

Twelve out of the eighteen tests registered temperatures above 60°C at the first thermocouple located 15-cm depth (i.e. TC1 at 3) (Table 3). The time needed for TC1 thermocouples to reach this temperature varied from 8 to 16 h after ignition, depending on the plot. Slightly less than half of these TC1 thermocouples reached 80°C, and three of them registered temperatures above 100°C. One TC1 thermocouple registered peak temperatures above 400°C. Three of the thermocouples located at 10 cm from the ignition source (named TC2 or TC3 in Fig. 3) recorded temperatures above 60°C and only in one of these peak temperature reached 80°C.

These results show that under our experimental conditions, there was a 6% chance for a weak ground fire ignition (i.e. a ground fire that may propagate less than 10 cm from the ignition point tending to self-extinguish). Furthermore, there was 17% chance of developing a heat front with an average temperature of 60°C that would travel less than 15 cm.

From all tests, test B1 in block W1 (i.e. W1B1) registered the highest temperature for the longest sustained period of time (Fig. 6). In that test, soil surrounding TC1 experienced temperatures above 400°C for more than 5 h, reaching a maximum temperature of 463°C at 15 h after ignition, and sustained temperatures exceeding 200°C for 16 h. Other selected TC1 thermocouples also registered high temperatures over long periods of time (Fig. 6). For example, test W2D4 registered temperatures above 60°C for more than 45 h, and exhibited a plateau at 80–100°C (corresponding to soil moisture evaporation) for ~12 h. Test W2A3 TC1 registered temperatures above 60°C for ~15 h. Finally, test W1D1 provides a clear example of an unsuccessful ignition, i.e. although TC1 surpassed the lower dehydration threshold, it registered a clear temperature drop 11 h after ignition.

We obtained an indicator of the heat accumulated over time in the soil (referred here as 'thermal dose', and elsewhere as 'integrated area over a 60°C threshold' (Kennard *et al*. 2005; Bova and Dickinson 2008) for the 15 thermocouples that registered temperatures above 60°C, by integrating their temperature function within the time range for which temperature was above

60°C (Fig. 6*c*). There was a good linear relationship (R^2 = 0.978) between thermal dose and time above 60°C on those plots where the minimum temperature for triggering the smouldering process was not reached, whereas the points of plots that reached smouldering fell outside the linear regression line.

Infrared imagery allowed us to control the course of the experiments and to gather information about other smouldering activity not detected by the thermocouples, revealing smouldering combustion in the soil subsurface layers. For instance, in the left lower corner of W1B1 (a section not monitored by thermocouples) a 6.8 cm-long 21.7 cm wide area (49 cm^2) with aboveground minimum temperatures of 60°C (maximum value of 78°C) was observed, providing evidence of the existence of a smouldering front located at a certain depth within the plot (Fig. 7). After visual inspection of the soil, we located the affected zone 2.5 cm below the surface and we estimated a mean burnt depth of 2 cm. With this figures we estimated that the solid volume burnt by smouldering was of 98 cm^3.

Discussion

This study presents, for the first time, a systematic methodology for smouldering combustion field experimentation, by which data on the different phases that characterise smouldering fires on organic soils can be gathered. With our method, we were able to identify the transition to the oxidation phase and observed continuous smouldering combustion during ~9 h at 15-cm depth, in a 260-kg m^{-3} dense soil with mean moisture values of 114.5% in Andean grasslands soils exposed to real weather conditions.

Ignition source suitability

The heat flux supplied for ignition in smouldering tests is a key aspect when designing a smouldering experimental method. The ignition limit depends both on the amount of energy transferred from the ignition source to the fuel and on the duration of this heat transfer process. Increasing the power of the ignition source (both in terms of energy or exposure time) may allow starting smouldering at increasing moisture contents (Hawkes 1993; Huang *et al*. 2015). This is particularly important on small-scale laboratory experiments, where the smouldering front spread is physically limited and therefore there must be an ignition method powerful enough for generating sustained smouldering combustion but not too powerful as to interfere with the natural heat transfer process in the sample. To date, this issue has received little attention among the scientific literature, with none or very limited information about ignition power supplied in many studies (Frandsen 1987, 1991; 1997; Reardon *et al*. 2007; Miyanishi and Johnson 2002). The ignition heat flux can be estimated in other studies, (Garlough and Keyes 2011; Rein *et al*. 2008; Prat *et al*. 2015) but to the authors' knowledge, only a few studies report directly on this key parameter (Hawkes 1993; Benscoter *et al*. 2011; Hadden *et al*. 2013; Huang *et al*. 2015).

The ignition method presented by here represents a natural ignition scenario, as many ground fires start with an element burning in a soil fissure (e.g. stumps, burning piles of slash, thick trunks, etc.). Ignition power supply has been estimated considering typical values of charcoal composition, CO/CO_2 ratio and heat of oxidation of char and volatiles. The method used to calculate ignition power supply is simple and hence has some uncertainty, mainly related to the hypothesis of assuming that the heat generated by the charcoal combustion is homogeneously transmitted through all the transferring area of the charcoal volume. Our ignition protocol allows to easily estimate total and radiative heat flux, and can be applicable to other soil conditions (e.g. different soil types, bulk density, fuel moisture content). Ohlemiller (2002) established a power limit of 10 $kW{\cdot}m^{-2}$ for achieving sustained smouldering combustion in solid wood, and our method had higher heat fluxes than this threshold for the first 2 h of combustion. At laboratory scale, the most commonly used ignition source is an electrically heated element running along one side of the sample and buried in it to some extent (Frandsen 1987, 1991; 1997; Reardon *et al*. 2007; Rein *et al*. 2008; Garlough and Keyes 2011). With the information provided in these studies, we estimate that typical ignition heat flux values in laboratory-based studies range between 1.7 to 20 kW m^{-2} with time exposures ranging from 2 to 50 min. Our ignition method therefore provides a longer more accumulated heat flux than laboratory tests.

Field experimentation allows working with larger plots than in laboratory, hence minimising possible interferences by the ignition source to the heat transfer process in the smouldering front. Here, we used 0.25-m^2 experimental plots, while sample dimension values on laboratory experiments range between 2.5×10^{-3} m^2 and 0.04 m^2. Furthermore, field scale avoids extra concerns regarding the border effect, which conversely has to be considered at laboratory scale, by using non-combustible insulating materials of similar thermal properties to the ones of the fuel tested.

Smouldering monitoring by thermocouples and IR imagery

Our combined smouldering monitoring system (i.e. temperature measurements by thermocouples and ground surface thermal imagery), provided to be satisfactory because both systems delivered complementary information needed for a comprehensive study on smouldering combustion.

The use of punctual temperature measurements allowed us to observe the different smouldering stages in selected locations of the soil. For example, looking at data from thermocouple TC1 (located 5 cm apart from the ignition source and 15-cm soil depth), we got information about the first phase of the smouldering combustion. Looking at TC1-W1B1, we observed that the dehydration front arrived rapidly at this point (less than 1 h after ignition) and dried the soil for ~2.5 h, which corresponds to the time span of the plateau observed ~80°C. This pre-heating process lasted longer in TC1-W2D4, where a plateau at ~70°C was not observed until 12 h after ignition and the soil did not experience a pronounced temperature increase until 20 h after the beginning of the test. Because the time spans of the temperature plateaus around dehydration temperatures are proportional to moisture content (Rein *et al.* 2008), these plateaus in our study likely reflect evidence of differences on moisture content between plots. However, in our experiment the soil moisture of every burned plot was not measured to avoid disturbance of the soil properties. Therefore, further research is needed to corroborate this prediction.

Pyrolysis and ignition temperatures of the combustion products (i.e. volatiles and char) depend on the chemical composition and state of the biomass and on the soil heating rate (Miyanishi 2001; Usup *et al.* 2004; Chen *et al.* 2011). Pyrolysis has been reported to start above 150°C in mountain forest peat (Chen *et al.* 2011). According to this threshold (looking at TC1 behaviour, Fig. 6*a*) pyrolysis in W1B1 started 4.5 h after the beginning of the test at the TC1 spot, whereas it would not have been triggered in W2D4 (maximum temperature registered by TC1-W2D4 was 138°C 24.7 h after the beginning of the test). Ignition reflects the transition between endothermic to exothermic processes (Frandsen 1997) and, as such, ignition temperature can be thought of as the point between both (Usup *et al.* 2004). Usup *et al.* (2004) found ignition temperatures of volatiles in smouldering experiments of tropical peatlands between 250 and 280°C and ignition temperatures of char between 340 and 370°C. In W1B1 ignition occurred ~10 h after the beginning of the test when TC1 registered the local minimum of 285°C and temperature increased abruptly immediately afterwards, as a result of the exothermic oxidation of the pyrolysis products (Fig. 6*c*). If we consider this instant as the smouldering front characteristic arrival time, we can estimate that the smouldering front covered 5 cm at ~5 mm h^{-1}. This value corresponds to a self-extinguishing ground fire front and is below the typical ranges for smouldering fronts of 10–30 mm h^{-1} (Rein 2009).

In smouldering peat fires, heat is transferred to the surface soil layer over periods of time of the order of 1 h, which can lead to soil sterilisation (Grishin *et al.* 2009). With our thermocouples readings, we have observed residence times of temperatures above 80–100°C of ~22 h, in both ignited and non-ignited plots, at 15-cm depth. In compacted soils and deep layers heat losses are minimised, and as such residence times are significantly higher. Those values, however, have never been reported before in laboratory studies. Such high temperatures can have important ecological effects on the soil, such a microbial biota death, protein degradation and soil disaggregation (Cerdà and Robichaud 2009).

The large series of experiments with multiple replications at the Puna soil revealed weak ignition conditions (only the first few thermocouples registered heat transfer processes signals), which probably indicates that ground fires have very low incidence and mild consequences in Andean Puna under conditions similar to that of the experiments. Nevertheless, having densely monitored experiments (i.e. 7 thermocouples in a 375-cm^2 area at two different depths) would have allowed us to eventually detect the lateral as well as the downward propagation edge in a volume of 5600 cm^3 of soil in each plot. The optimum thermocouples layout depends on the organic horizon depth and on the soil properties governing ignition and spread of the smouldering front. Most of this information is *a priori* unknown, so there is not a definitive sensor arrangement that will suit all types of soils. However, distances of 5–10 cm between thermocouples at representative depths might be adequate to have a clear representation of the smouldering edge spread in most type of soils.

The use of IR imagery allowed controlling the experimentation. Monitoring frequency (every 24 h) was enough to observe the course of the experiments (a higher frequency would be recommended in case more intense activity was observed). Moreover, it allowed detecting the existence of smouldering subsurface activity in areas not covered by the thermocouples and thus complemented the information given by these. Thermocouples provide point-specific temperature–time evolution and, because of their nature, they cannot cover (and it is not practically feasible) the overall experimental volume. In contrast, IR imagery is surface specific and can be used to assess the overall smouldering activity up to a certain depth. The analysis of IR images coupled with simple visual inspections provided us estimation in an easy and precise way of areas and volumes affected by smouldering in experimental plots, which in turn, permits assessing key parameters related to fuel consumption. Surface radiative temperatures just above 60°C depicted in thermal images revealed the presence and the morphology of a smouldering solid volume of 98 cm^3 in one of our plots, which would have remained undetected otherwise. Therefore, considering a mean soil organic carbon content of 22.6% in our plots, we can estimate a maximum amount of carbon released in the mentioned solid volume of 5.8 g. This is a conservative figure as combustion efficiency has not been taken into account in this simple calculation.

Note that thermal IR imagery can eventually also be used to obtain more detailed smouldering dynamics provided a set of images recorded at an adequate frequency is available. Our experiments did not allow performing such analysis as they were surveyed once every 24 h.

Nonetheless, with self-sustained smouldering activity captured in IR images, propagation vectors can be calculated at a fine scale (Prat-Guitart *et al*. 2015, 2016).

Conclusions

This study provides an experimental methodology that represents an important advance for obtaining ground fire behaviour and effects metrics under realistic scenarios. The method provides a detailed picture in terms of smouldering fire combustion dynamics and related parameters under field conditions and can be a good complement to laboratory studies aimed at analysing the particular involvement of a certain soil property on the smouldering ignition and propagation phenomena.

The method is to be applied in undisturbed soil under field conditions. The applicability of such a method should comprise many types of subsurface organic layers (i.e. duff, organic rich soils, peatlands), regardless their locations (tropical, temperate or boreal) and is particularly indicated for soils with high densities (difficult to reproduce at laboratory scale), for soils difficult to sample without disturbances, and particularly for soils in remote areas.

The experimental protocol is based on a realistic non-electric ignition source whose power supply can be easily estimated. The monitoring system relies on combining both punctual and superficial temperature measurements by which data on smouldering combustion phases and fire behaviour basic descriptors (such as rate of spread or carbon consumed) can be obtained.

The methodology presented applied to Andean Puna soils represent a novel contribution, since studies of organic soil consumption by smouldering in the tropical eco-zone are limited. The soil was tested (mean density of 260 kg m^{-3} and mean moisture of 114.5%) by means of large series of replicate experiments which exhibited weak ignition conditions, hence indicating that smouldering fires may have little effect in these type of ecosystems. However, we could observe transition to oxidation phase with smouldering combustion during ~9 h at 15-cm depth and residence times at temperatures above dehydration of ~22 h. This behaviour has never been reported in peer-reviewed laboratory studies.

Further work is required to follow-up methodology robustness. Efforts in this regard should be 2-fold; in one hand, method's sensitivity on the ignition source main variables (i.e. charcoal type and mass) should be assessed, and on the other, different soil conditions (i.e. density, moisture and inorganic content) should be also tested using our experimental protocol to confirm its global applicability.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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Table 1. Tested plots during the three burning days of the experimental campaign

Tested plots	Day 1 (7-Jul-2012)	Day 2 (11-Jul-2012)	Day 3 (12-Jul-2012)
Plots in block W1	A1, B2, D1	A4, B4, B5	B1, D3, D5
Plots in block W2	B1, C1, C2	B4, D4, C5	A1, A3, A5

Table 2. Range (minimum–maximum) values of the environmental variables associated with the ground fire tests

; DB: dry basis; WB; wet basis.

Variable	Measures
Mean midday[A] temperature (°C)	10.7–18.3
Mean midday windspeed (km h^{-1})	6.1–7.9
Mean midday relative humidity (%)	37.7–95.9
Soil moisture content at 12 cm (DB, %)	90.89–130.76
Soil moisture content at 20 cm (DB, %)	83.29–122.96
Mean soil moisture content[B] (DB, %)	114.5
Soil mineral content (%)	6.0–10.6
Soil bulk density (DB, kg m^{-3})	188–355
Mean soil bulk density (ρ_{WB}, WB, kg m^{-3})	260
Soil organic carbon (%)	21.1–24.02

[A]Midday is considered to be the time interval between 1100 and 1400 hours. [B] Considering measures at all depths

Table 3. Temperature response summary of the tests

TC1 are located at 15-cm depth, 5 cm from the ignition source. TC2 and TC3 are located at 5-cm depth, 10 cm from the ignition source

Thresholds	Number of tests	Occurrence
TC1 at t >60°C	12/18	67%
TC1 at t >80°C	5/18	28%
TC1 at t >100°C	3/18	17%
TC1 at t >400°C	1/18	6%
TC2/TC3 at t >60°C	3/18	17%
TC2/TC3 at t >80°C	1/18	6%

Fig. 1. Smouldering stages

Fig. 2. Study area location and sketch of the experimental site. CP1-CP5 are control plots.

Fig. 3. Scheme of an individual plot showing the ignition procedure. (*a*) Schematic top view. (*b*) Schematic side view and (*c*) picture showing a plot arrangement.

Fig. 4. Evolution of the weather variables during 24 h of the burning tests (from 1100 hours of 12 July to 1100 hours of 13 July)

Fig. 5. (*a*) Ignition source behaviour: fuel consumption, mass loss rate and ignition power; (*b*) Temperature distribution of burning charcoal at the beginning of test (randomly selected W2_B4). Dashed line delimits the 30 × 10-cm surface area occupied by charcoal. Mean temperature of the delimited area is 434°C (s.d. is 95.3°C)

Fig. 6. (*a*) Temperature evolution of TC1 thermocouples at four selected tests; (*b*) thermal severity registered by the same TC1 thermocouples; (*c*) thermal dose above 60°C, experienced by TC1, TC2 or TC3 thermocouples in all tests.

Fig. 7. W1B1 thermal image 24 h after ignition, superimposed on a plot and thermocouples layout.

Table 1. Tested plots during the three burning days of the experimental campaign

Tested plots	**Day 1 (07/07/2012)**	**Day 2 (07/11/2012)**	**Day 3 (07/12/2012)**
Plots in block W1	A1, B2, D1	A4, B4, B5	B1, D3, D5
Plots in block W2	B1, C1, C2	B4, D4, C5	A1, A3, A5

Table **2**. Range (min – max) values of the environmental variables associated with the ground fire tests**.** (1) midday is considered to be the time interval between 11.00h and 14.00h; (2) Considering measures at all depths; d.b.: dry basis; w.b.; wet basis.

Variable	**Measures**
Mean midday(1) temperature (ºC)	10.7 – 18.3
Mean midday windspeed (km·h^{-1})	6.1 – 7.9
Mean midday relative humidity (%)	37.7 – 95.9
Soil moisture content at 12 cm (d.b.%)	90.89 – 130.76
Soil moisture content at 20 cm (d.b.%)	83.29 – 122.96
Mean soil moisture content(2) (d.b.%)	114.5
Soil mineral content (%)	6.0-10.6
Soil bulk density (d.b. kg·m^{-3})	188-355
Mean soil bulk density ($\boldsymbol{\rho_{w.b}}$, w.b. kg·m^{-3})	260
Soil organic carbon (%)	21.1 – 24.02

Table 3. Temperature response summary of the tests. TC1 are located at 15 cm depth, 5 cm from the ignition source. TC2 and TC3 are located at 5 cm depth, 10 cm from the ignition source.

Temperature Thresholds	**Number of tests**	**Occurrence**
TC1 at T > 60ºC	12/18	67%
TC1 at T > 80ºC	5/18	28%
TC1 at T > 100ºC	3/18	17%
TC1 at T > 400ºC	1/18	6%
TC2/TC3 at T > 60ºC	3/18	17%
TC2/TC3 at T > 80ºC	1/18	6%

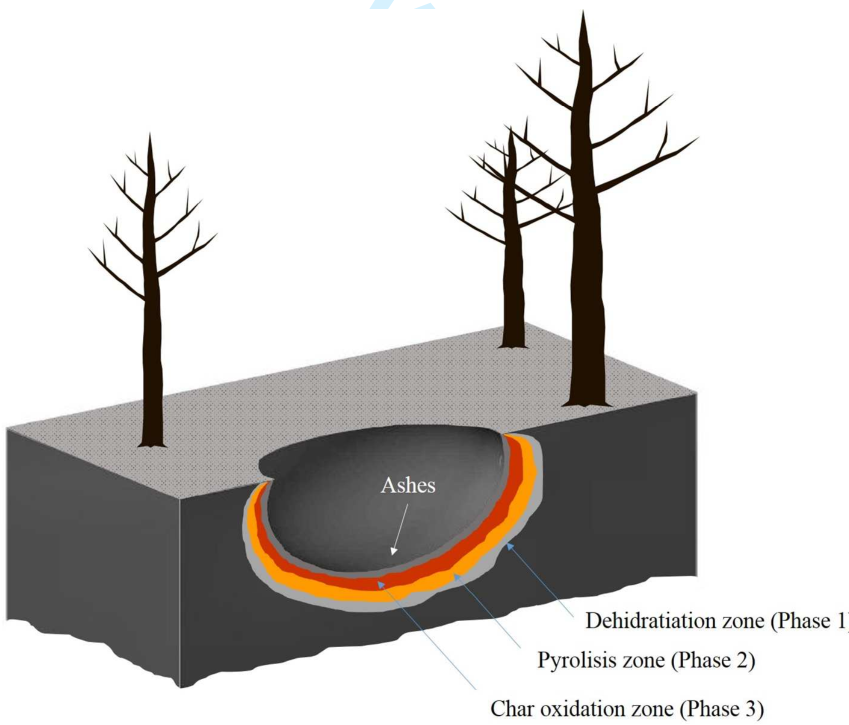


Fig. 1. Smouldering stages

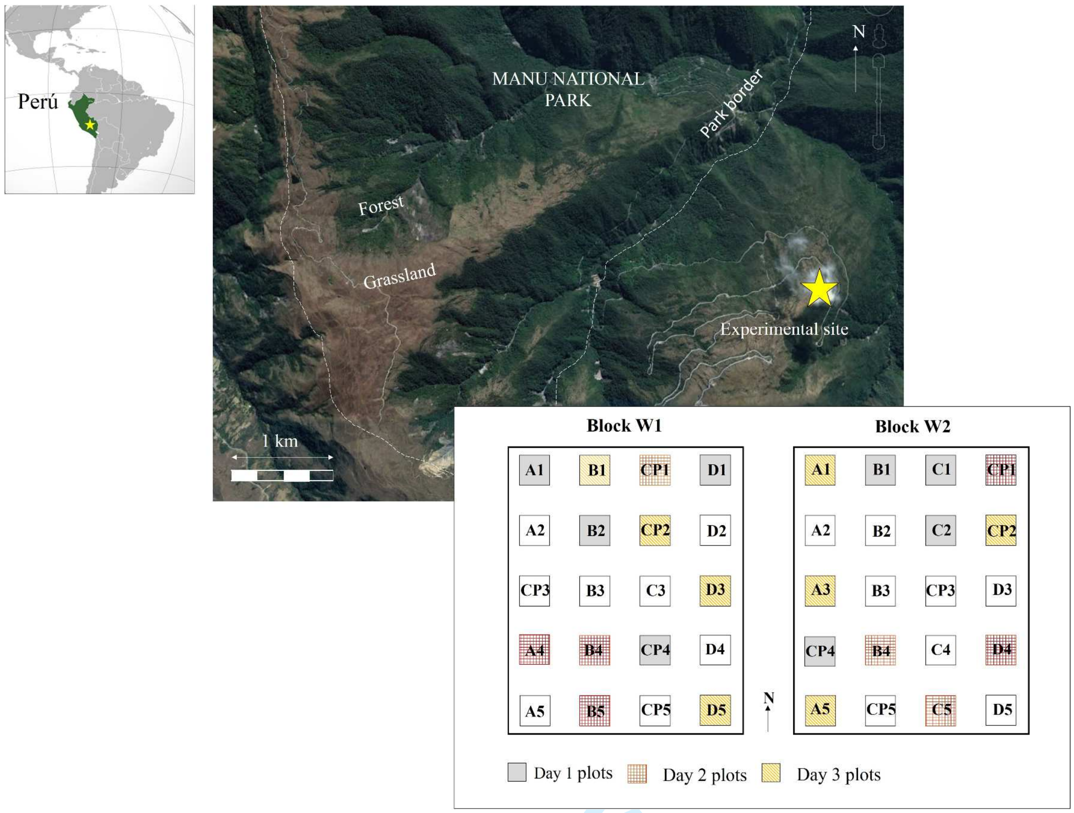


Fig. 2. Study area location and sketch of the experimental site. CP1-CP5 are control plots.

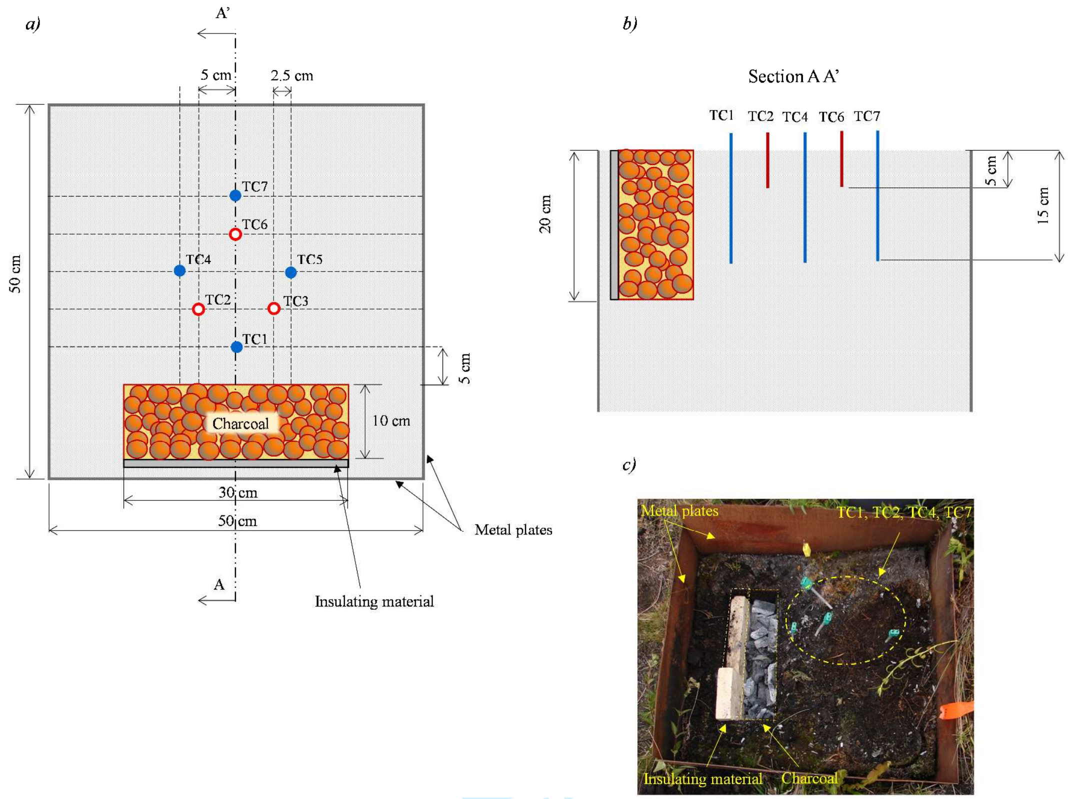


Fig. 3. Scheme of an individual plot showing the ignition procedure. a) Schematic top view. b) Schematic side view and c) picture showing a plot arrangement.

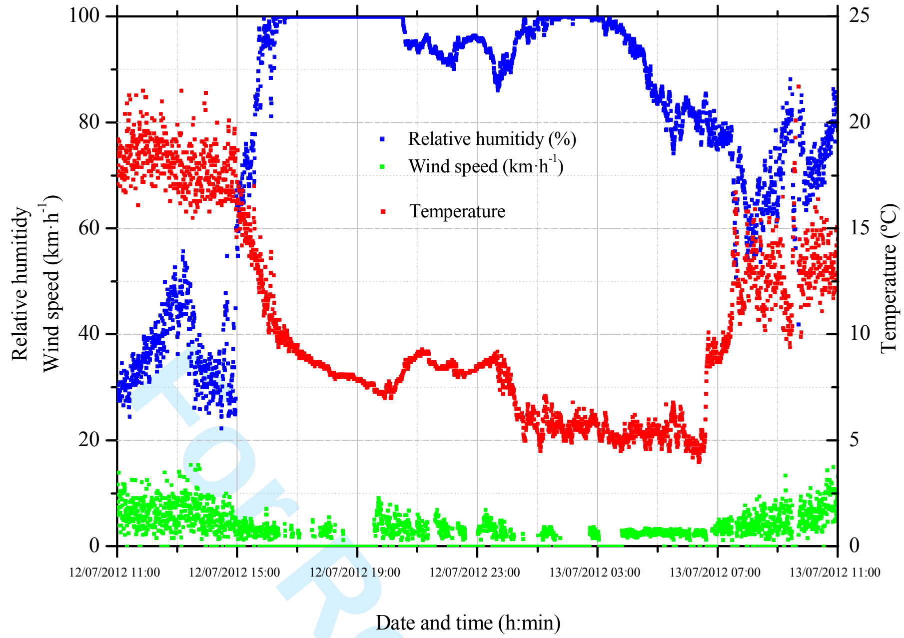
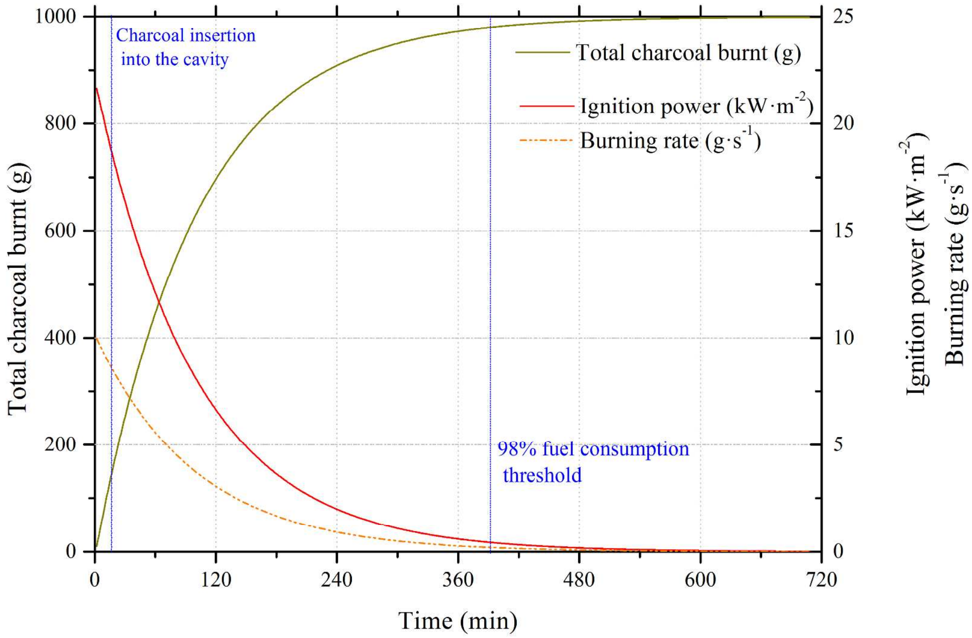


Fig. 4. Evolution of the weather variables during 24h of the burning tests (from 11.00h of July 12th to 11h of July 13th)

a)



b)

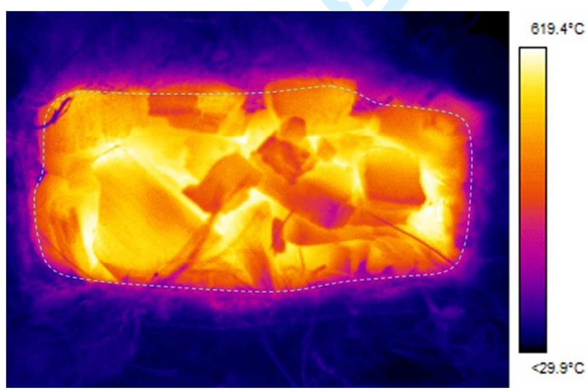


Fig. 5. a) Ignition source behaviour: fuel consumption, mass loss rate and ignition power; b) Temperature distribution of burning charcoal at the beginning of test (randomly selected W2_B4). Blue dashed line delimits the 30 cm x 10 cm surface area occupied by charcoal. Mean temperature of the delimited area is 434ºC (st.dv is 95.3ºC)

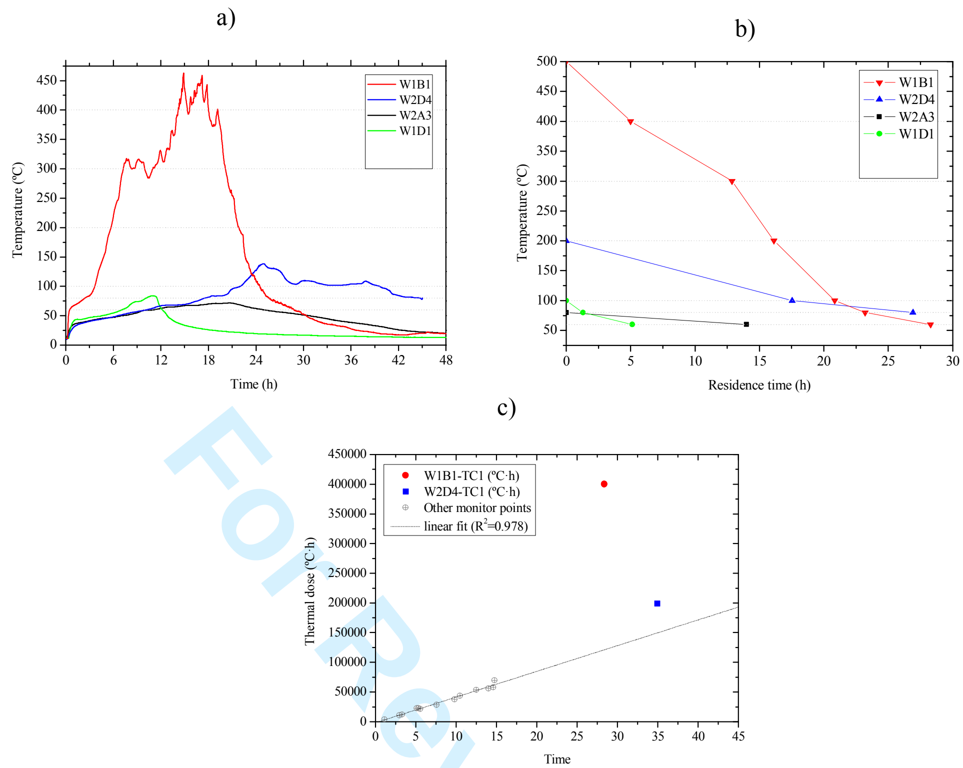


Fig. 6. a) Temperature evolution of TC1 thermocouples at four selected tests; b) thermal severity registered by the same TC1 thermocouples; c) Thermal dose above 60ºC, experienced by TC1, TC2 or TC3 thermocouples in all tests.

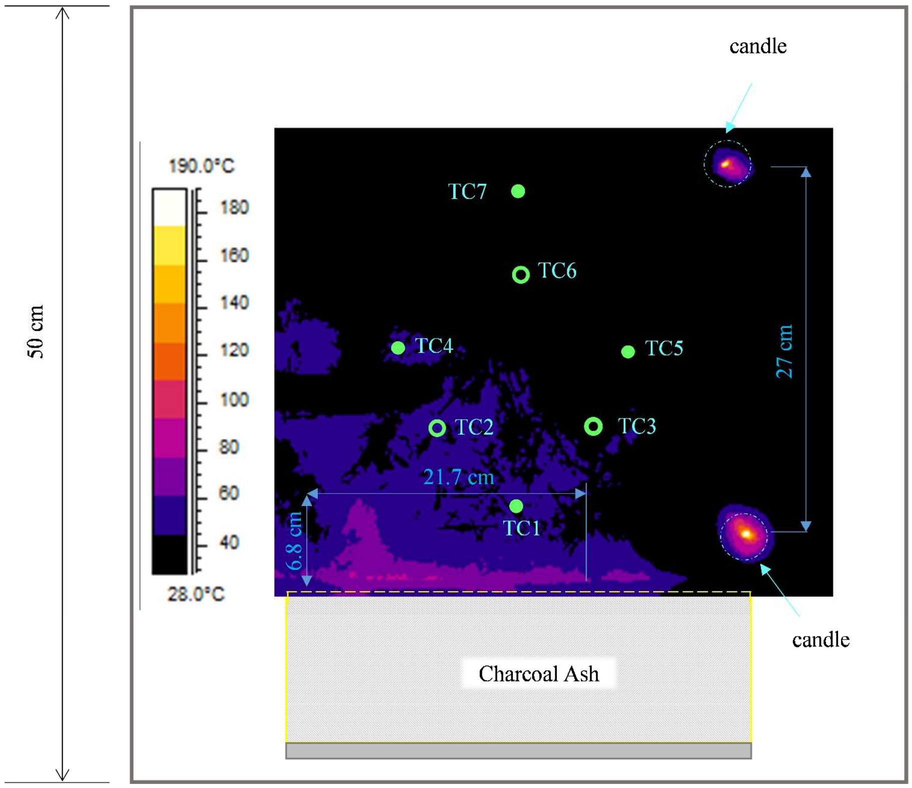


Fig. 7. W1B1 thermal image 24h after ignition, superimposed on a plot and thermocouples layout.

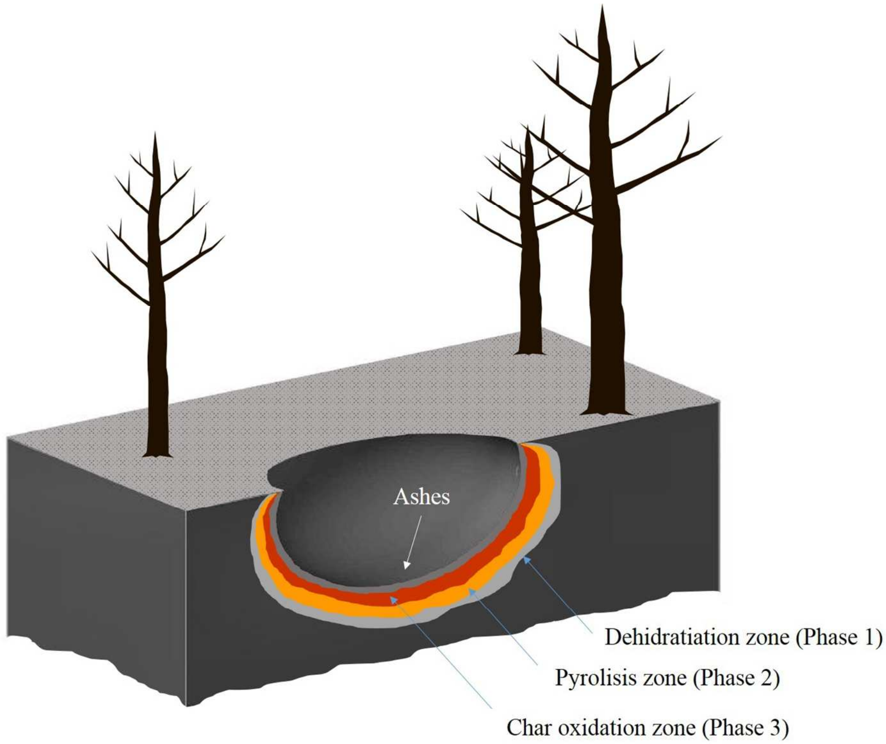
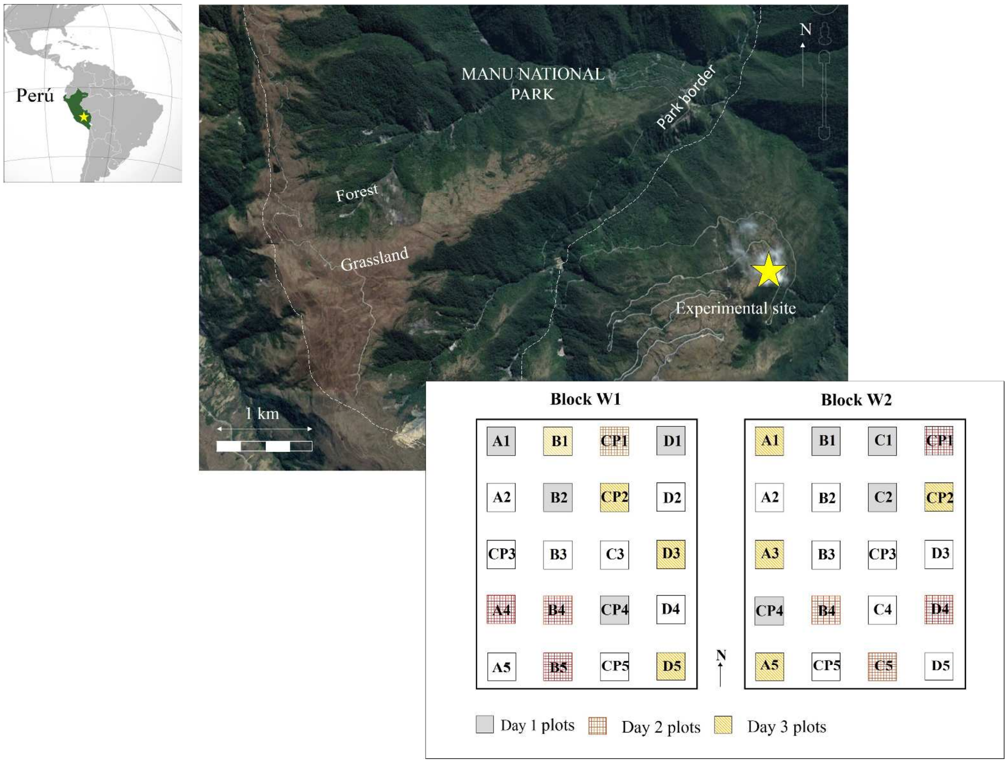


Fig.1. Smouldering stages

272x218mm (150 x 150 DPI)



Study area location and sketch of the experimental site. CP1-CP5 are control plots.

740x558mm (150 x 150 DPI)

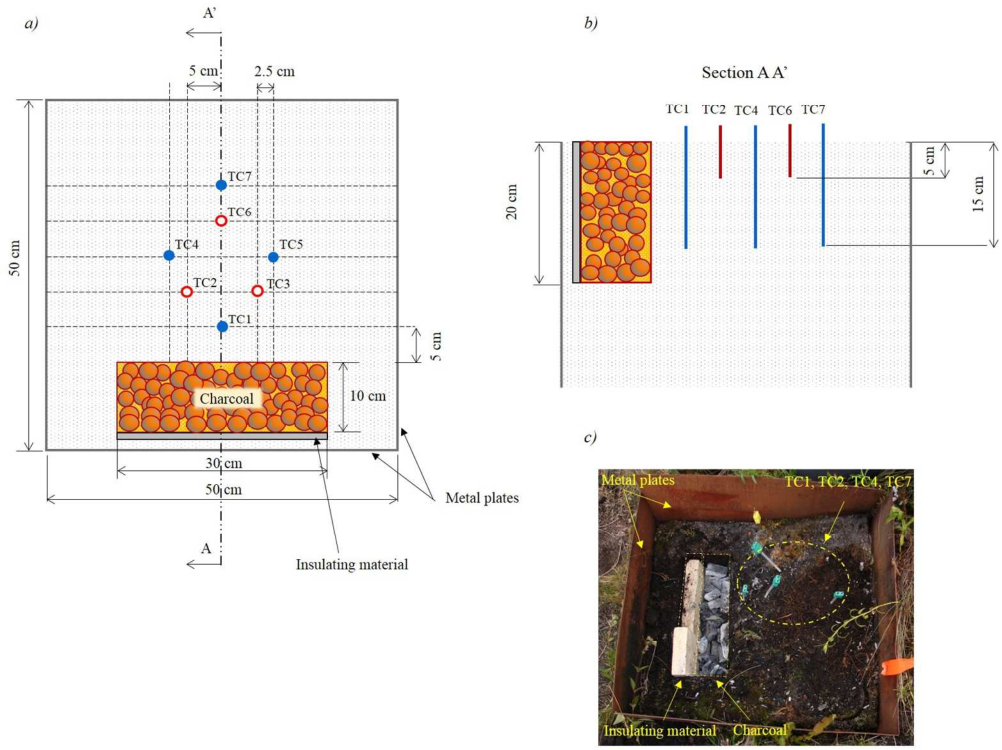


Fig. 3. Scheme of an individual plot showing the ignition procedure. a) Schematic top view. b) Schematic side view and c) picture showing a plot arrangement.

285x213mm (150 x 150 DPI)

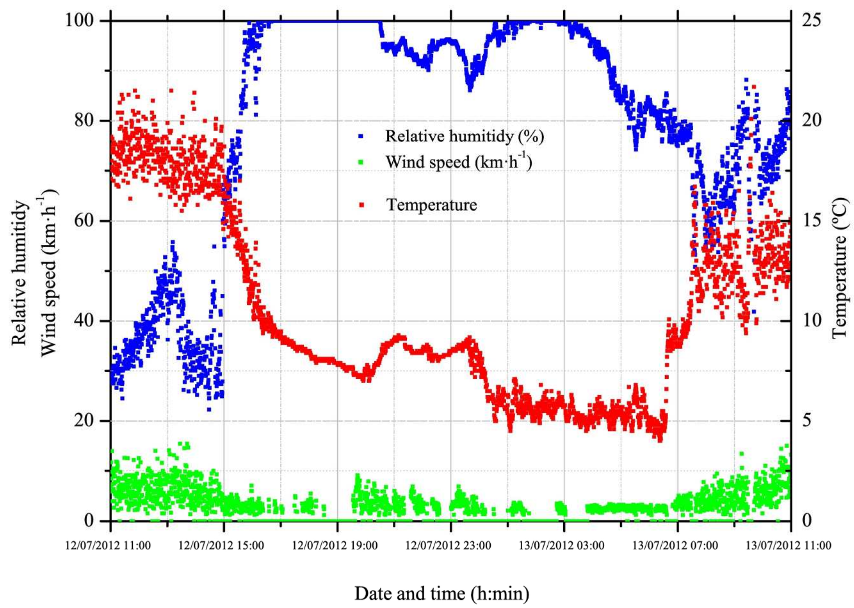
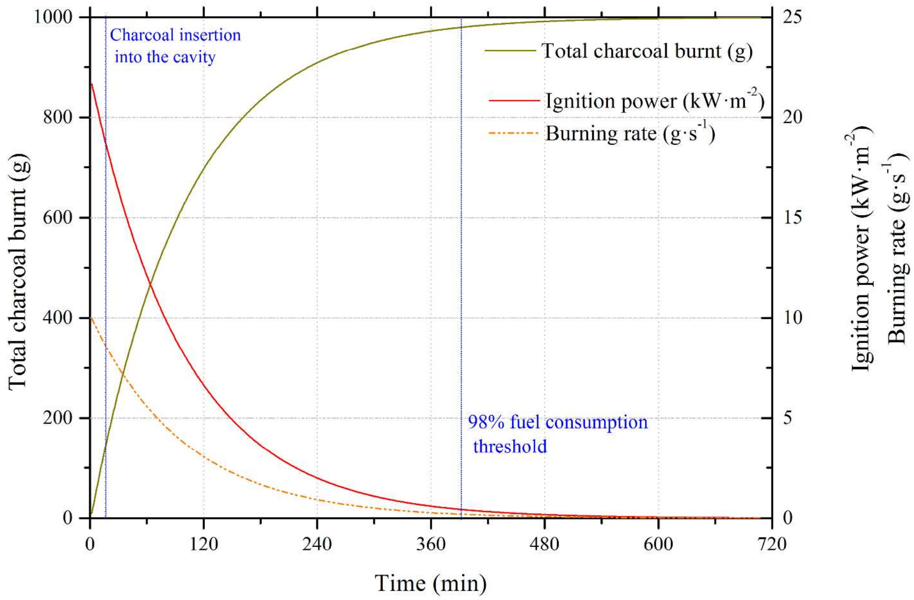


Fig. 4. Evolution of the weather variables during 24h of the burning tests (from 11.00h of July 12th to 11h of July 13th)

201x141mm (300 x 300 DPI)



a) Ignition source behaviour: fuel consumption, mass loss rate and ignition power

288x201mm (300 x 300 DPI)

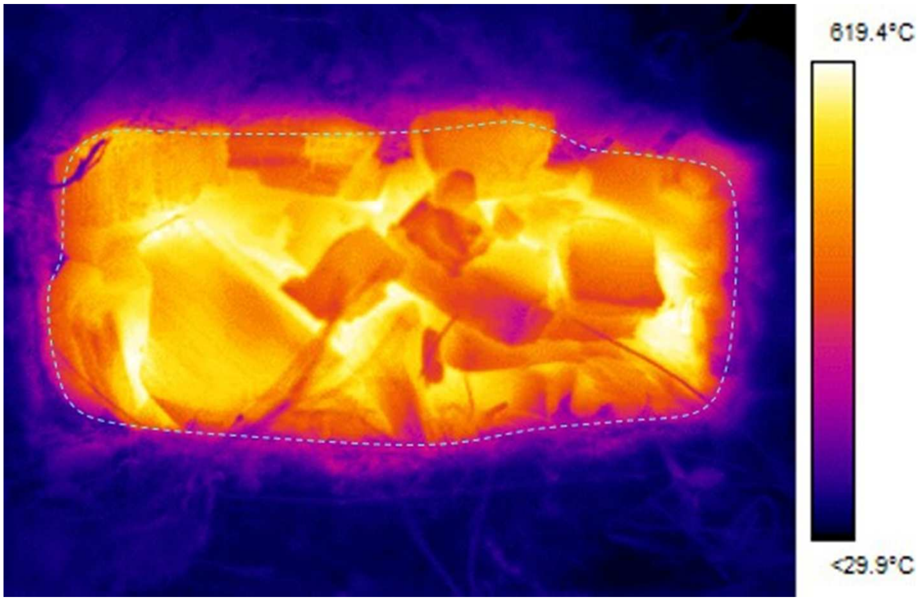


Fig. 5. b) Temperature distribution of burning charcoal at the beginning of test (randomly selected W2_B4). Blue dashed line delimits the 30 cm x 10 cm surface area occupied by charcoal. Mean temperature of the delimited area is 434ºC (st.dv is 95.3ºC)

107x63mm (150 x 150 DPI)

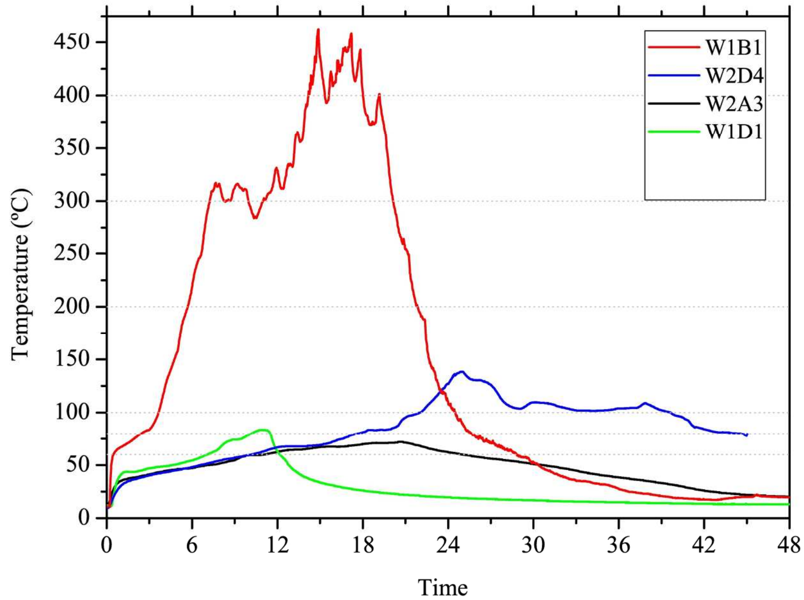


Fig. 6. a) Temperature evolution of TC1 thermocouples at four selected tests.

202x141mm (300 x 300 DPI)

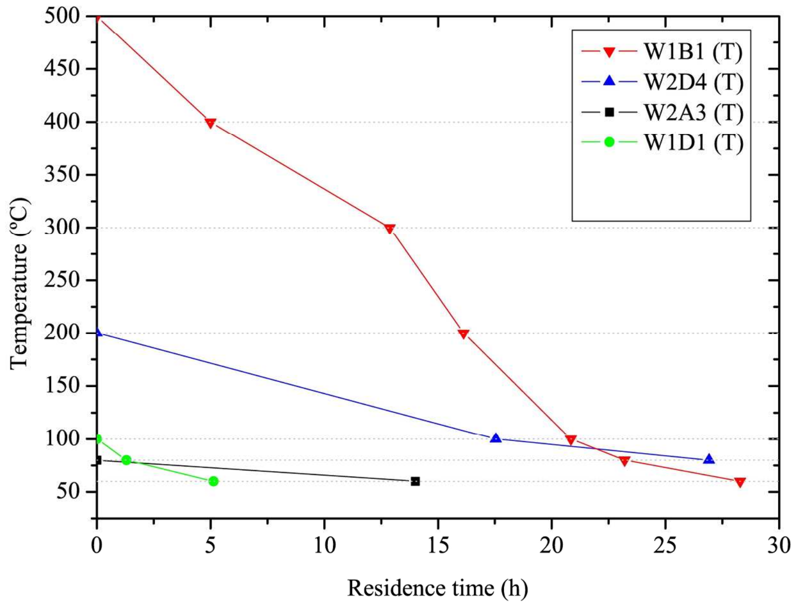


Fig. 6. b) thermal severity registered by the same TC1 thermocouples.

202x141mm (300 x 300 DPI)

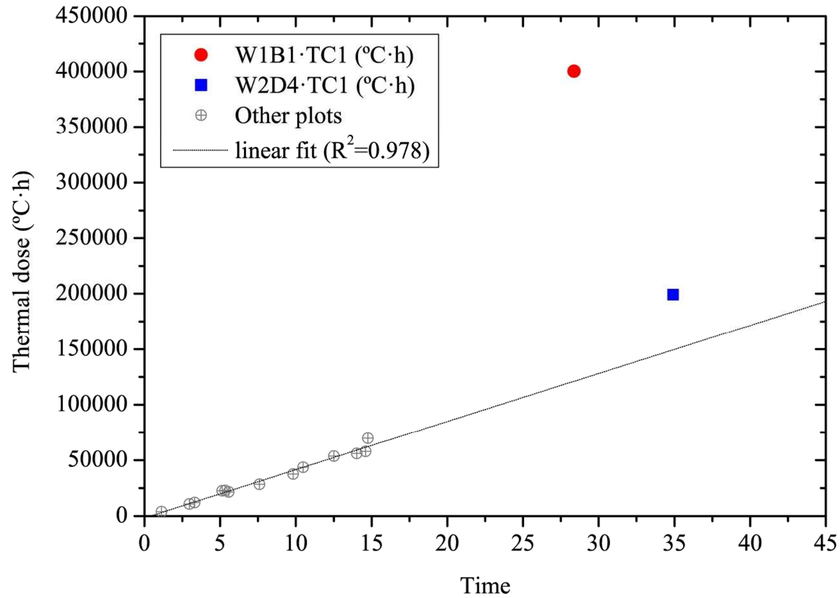


Fig. 6. c) Thermal dose above 60ºC, experienced by TC1, TC2 or TC3 thermocouples in all tests.

201x141mm (300 x 300 DPI)

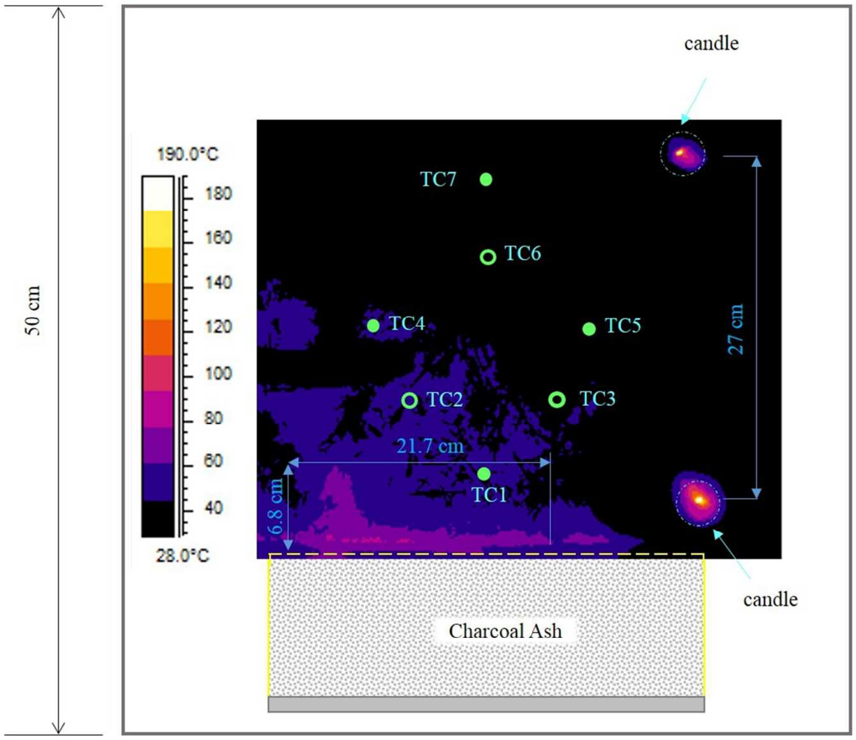


Fig. 7. W1B1 thermal image 24h after ignition, superimposed on a plot and thermocouples layout.

203x151mm (150 x 150 DPI)

Supplementary Information. Relationship between the measured soil moisture with the Hydrosense® probes and the real soil moisture (calculated by natural dry down soil, see Methods section) at each measured soil depth (12 cm, 20 cm).