Chapter XVII: Fire severity assessments in both the laboratory and the field

Moya D.*[1], Madrigal J.[2,3], Fontúrbel T.[4], Marino E.[5], Hernando C.[2,3], Guijarro M.[2,3], Fernández C. [4], Jiménez E. [4], Lucas-Borja M.[1], Vega J.A.[4], de las Heras J.[1]

[1] Higher Technical School of Agricultural and Forestry Engineering. University of Castilla-La Mancha – UCLM. Campus Universitario. 02071, Albacete, Spain

[2] INIA, Forest Research Centre, Department of Silviculture and Forest Management, Forest Fire Laboratory. Ctra. Coruña Km 7,5 28040 Madrid, Spain.

[3] iuFOR, University Institute for Sustainable Forest Management, uVA-INIA.

[4] Forest Research Center of Lourizán. Xunta de Galicia. 36080 Pontevedra, Spain.

[5] AGRESTA Sociedad Cooperativa, c/ Duque de Fernán Núñez 2, 28012 Madrid, Spain

*Corresponding author: Daniel.Moya@uclm.es

1 INTRODUCTION AND KEY CONCEPTS

Fire severity and burn severity are used indistinctly because their recording is often based on similar metrics related to loss of, or change in, organic matter aboveground (vegetation) and belowground (soil) (Keeley 2009). Fire severity describes how fire intensity affects ecosystems, and has been defined as the degree to which a site has been altered or disrupted by fire as a result of fire intensity and residence time (NWCG 2006). Burn severity qualitatively assesses how the heat pulse directed toward the ground during a fire, is related to soil heating, large fuel and duff consumption, consumption of the litter and organic layer beneath trees and isolated shrubs, and the mortality of buried plant parts (NWCG 2006).

Fire impact strongly depends on ecosystem type and fire severity as regards vulnerability/resistance and resilience, mainly at the plant-soil interphase and in the short term (Vallejo *et al.* 2012; Moya *et al.* 2017). Variation in severity can influence post-fire vegetation regeneration due to the mechanisms that occur during the fire itself, e.g. thermal damage to plant structure, soil seed banks and germination cues (Legg *et al.* 1992; Maia *et al.* 2012), and because of altered post-fire environmental conditions, e.g. loss of nutrients and changes in soil microclimate, microbiota, water repellency (Neary *et al.* 1999; DeBano *et al.* 2000; Fonturbel *et al.* 2016; Grau-André *et al.* 2017). A reduction in both ecosystemic and social goods and services after a fire is temporary, but the recovery pattern and time needed to restore the provision (flow) of goods and services can vary depending on ecosystem resilience, fire characteristics (mainly size recurrence and severity), type of damaged goods/services, and the implementation of post-fire management techniques (Mavsar *et al.* 2012); i.e., the negative impacts of high burn severity on the regeneration of plant and soil in semiarid Mediterranean forests was concentrated during the short-term period (Gonzalez-de Vega *et al.* 2016).

Adaptive forest management should consider the vulnerability and resistance of managed ecosystems to increasing fire severity, and also the effects on prevention and post-fire management and restoration, including climate change trends (changing fire regimes) to preserve plant diversity and soil properties (Doblas-Miranda *et al.* 2017). Tools to reduce fire severity in future fire events should also be considered, such as burning prescription and proper rehabilitation after wildfires, and mainly in areas that are at high desertification risk (Doblas-Miranda *et al.* 2015; Moya *et al.* 2017). It is important to include a monitoring and evaluation framework to quantify the success rate of those tools that allow any changes in the resistance, vulnerability and resilience of ecosystems.

The planning and implementation of restoration actions in burned areas should be mapped to account for stand-level variability, including ecosystem response and fire severity levels (Figure 1). Fire damage depends on fire characteristics, where fire severity is the main key variable to assess how a given ecosystem responds to fire (Vallejo *et al.* 2012). Therefore to develop fire severity assessments, it is important to implement proper post-fire actions as quickly as possible after a wildfire. The combined use of remote sensing and field sampling (before the first rainfall, if at all possible) allows a rough visual assessment to be made of severity, and provides spatial information to identify the areas that require emergency action (Vega *et al.* 2013a). Erosion modeling can be obtained by overlapping ecosystem type, fire severity and terrain characteristics, such as slope, soil type and amount of exposed soil and rock (Parsons *et al.* 2010). The spatial and temporal "snapshot" of burn severity is also a baseline for monitoring changes in soil, plant community and vegetation recovery, which can be used to create other useful tools to assess different issues; e.g., post-fire tree mortality, post-fire slope stability, effects on watersheds, effect of aerial seeding or mulching, cultural resources and other at-risk resources (Parsons *et al.* 2010).

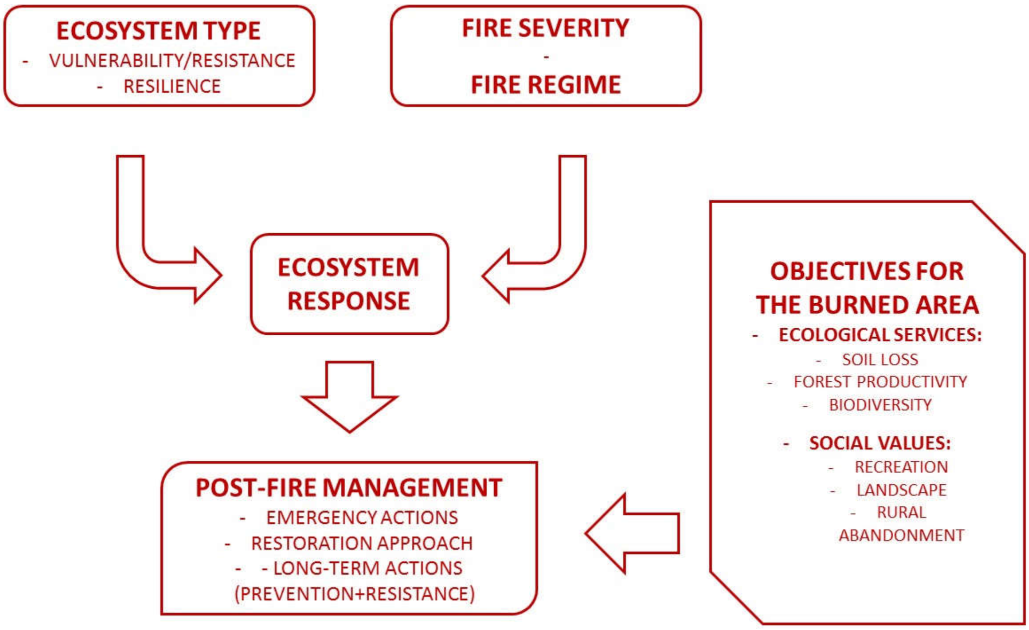

Figure 1. Post-fire restoration depends on fire damage and ecosystem response, linked to the adaptive traits developed by the plant community and soil characteristics (ecosystem resilience), the current situation of the soil-plant interphase (resistance or vulnerability to disturbances) and fire characteristics (mainly size, recurrence and burn severity) (adapted from Vallejo *et al.* 2012).

2 FIRE REGIMES AND FIRE BEHAVIOR

The behavior and characteristics of wildfires depend on several factors: vegetation (fuel) composition and structure, succession stage, previous disturbances, forest management, climate and weather patterns, terrain and landscape patterns (Flannigan 2000). The "fire regime" concept provides an integrated way of classifying patterns of wildfires and their impacts in both ecosystem or landscape terms, which have been linked to vulnerability, resistance and resilience concepts (Enright *et al*. 2014). Climate change also promotes an increasing climatic fire risk by modifying the fire regime to a set of large, frequent, intense and severe wildfires, and this poses a challenge to ecosystems' resistance and resilience in different ways (Doblas-Miranda *et al*. 2017). Knowledge of the historical fire regime in ecosystems, apart from the factors that alter them, will help to understand the interactions that link fuel, fire and climate change and effects on ecosystems, mainly in fire-prone areas, which affect more arid conditions (Doblas-Miranda *et al*. 2015). Following the multipartner LANDFIRE Project (Rollins 2009), there are five fire regime groups according to the fire return interval and severity:

- Non-Fire regimes
- Fire Regime Group I: <35 Year Fire Return Interval + Low/Mixed Severity
- Fire Regime Group II: <35 Year Fire Return Interval + Replacement Severity
- Fire Regime Group III: 35-200 Year Fire Return Interval + Low/Mixed Severity
- Fire Regime Group IV: 35-200 Year Fire Return Interval+ Replacement Severity
- Fire Regime Group V: >200 Year Fire Return Interval+ Any Severity

On a local scale, fire behavior is influenced by terrain, slope, exposure, vegetation/fuel, land management and ignitions, and can be classified according to different fire characteristics; e.g., propagation type (surface, crown or ground fire), size, intensity and severity, seasonality, recurrence, etc. (Agee 1996). In the past, the fire intensity term has been used to represent and describe fire effects on the ecosystem rather than a meaning linked to fire behavior (energy released per length unit of a fire front per time unit). Nowadays, fire intensity is more usually associated with the fire behavior properties characterized by measuring physical factors, such as heat transfer (temperature), depth and duration of soil heating, smoldering and parameters that describe the flaming front (flame length and depth, residence time, spread rate) combined with a fire-line geometry description (Sommers *et al*. 2011). Keeley (2009) also differentiated the terms “fire severity” and “burn severity” from “fire intensity” described by fuel consumption, vegetation mortality and soil organic matter consumption (Sommers *et al*. 2011).

Forest management for fire prevention and suppression purposes is an anthropogenic activity that directly alters fire regimes, and aims to reduce fire damage by decreasing fire number, frequency, size and severity. However, success may occur only in the short term since long-term intense fire suppression increases large fires (>500 ha) because of fuel build-up (Brotons *et al.* 2013). In historically anthropogenic regions, and in those where fire suppression policies are successful, fire regimes differ from historical ones and model future projections. Future estimations on the landscape scale based on models of fire effects should include the understanding of the short-term fire regime changes influenced by fire suppression, and changes due to climate conditions and land use (Brotons *et al.* 2013).

3 FIRE SEVERITY

Thanks to Keeley (2009), the fire severity term describes how fire intensity affects ecosystems and indicates the magnitude of wildfire effects, which are variable depending on the vulnerability, considered as the fire severity interaction, and the resistance and resilience of ecosystems. Fire severity measurements focus on loss or decomposition of organic matter both above- and belowground. A first approach was simplified to propose a fire severity classification and has five fire severity categories according to the degree of consumed organic matter (Ryan & Noste 1985):

- Unburned: unaltered
- Scorched: unburned, but radiated
- Light: scorched tree stems that maintain green leaves; no deep soil affects
- Moderate or severe surface burn: trees show canopy damage, but fine parts are not consumed; charred or consumed understory plants; largely consumed pre-fire soil organic layer
- Deep burning or crown fire: canopy trees consumed; surface litter of all sizes and soil organic layer consumed; white ash deposition and charred organic matter to a depth of several centimeters

More recent methodologies have suggested recording fire severity as a continuous measure, including the burn severity term, which sometimes refers to not only fire severity, but also to ecosystem responses. According to Keeley (2009), both terms include different concepts and should be assessed independently. The metrics that combine burn severity and plant-soil recovery characteristics may provide misinformation, and recommendations suggest including an assessment of organic matter loss separately from the ecosystem response (Keeley *et al.* 2012).
Therefore, fire severity is one of the most widely used variables to characterize wildfires. Its importance is related to fire damage as it influences the ecosystem’s response, and is a key

aspect in planning management strategies that aim to integrate fire protection: prevention, extinction and restoration, and their interrelationships. Consequently, the intention is to develop a common methodology by implementing available tools and technologies to assess this important variable for landscape management. This chapter reviews some research works that have focused on achieving this objective, which range from terminology and concepts to quantitative or qualitative measurements of fire severity, and include some references to remote sensing assessments that are further developed in Chapter XXII: Remote sensing techniques to estimate burning severity and fire impacts on soil.

4 FIELD ASSESSMENT OF FIRE SEVERITY

There is a no standardized method available that measures fire severity, although the most widely used indices and methods have been included in this chapter. Improving the approach by Ryan and Noste (1985), and that by Neary *et al.* (2005), provides guidance for making comparisons to two-dimensional severity ratings, including the spatial scale of the stand or community (sampling the spatial distribution of fire severity classes):

- ***Low severity burn:*** < %2 severely burned and <15% moderately burned. Remainder of the area burned at low severity or unburned
- ***Moderate severity burn:*** <10% severely burned and >15% burned moderately. Remainder is burned at low severity or unburned
- ***High severity burn:*** >10% burned at high severity and >80% moderately or severely burned. Remainder is burned at low severity

According to fire size, the number of plots that should be surveyed (distributed in a regular sampling grid) to characterize the fire severity area varies depending on the extent of the burned area. If wildfire burned under 500 ha, Alloza *et al.* (2014) propose 6 to 15 plots, while Vega *et al.* (2013a) recommend at least one plot every 5-10 burned ha. For those wildfires that have burned 500 to 5000 ha, they respectively recommend 15-50 plots, or one plot for each burned 10-50 ha. For wildfires that have burned more than 5000 ha, they respectively recommend more than 50 plots, and at least one plot every 50-100 ha. In all plots, the burn assessment has to be made to include soil conditions, affected leaf litter, and the condition of trees and shrubland damage (Ryan & Noste 1985; Alloza *et al.* 2014; Vega *et al.* 2013a).

4 1 Visual Field Assessment

One direct measure of burn severity is the direct Visual Field Assessment. The operator evaluates the degree of loss or decomposition of the organic matter contained in both vegetation and soil.

Larson & Franklin (2005) propose Percent Basal Area Mortality. Fire severity is calculated as a percentage based on the difference in the basal area measured between the pre- and post-fire periods in relation to the pre-fire value (1). Some authors argue that this method can underestimate fire severity if it is monitored in the first year after fire because of delayed fire-induced mortality, which occurs several years following the fire.

$$Fire\ severity = \frac{prefireBasalArea - postfireBasalArea}{prefireBasalArea} \times 100 \qquad (1)$$

Based on the method to record the minimum diameter of burned branches (Moreno & Oechel 1989; Pérez & Moreno 1998), increasing fire severity has been related to the decreasing diameter of any remaining burned branches in vegetation samples (1 m^2) according to the mean Minimum Diameter of Branches per square Meter (MDBM) (2). Maia *et al.* (2012) propose a similar method, the Twig Diameter Index (TDI), obtained by recording the diameter of the three thinnest remaining twigs on ten burnt shrubs, randomly selected in a square plot (25 m^2). Diameter values are averaged per plot, and the results are then re-scaled by dividing by the maximum diameter measured in the burned area (to obtain values that range from 0 to 1 to describe lower to higher fire severity).

$$MDBM = \frac{a_1 MDBP_1 + \cdots + a_n MDBP_n}{a_1 + \cdots + a_n} \tag{2}$$

a_i = number of stems in each recorded plant

MDBP = Minimum diameter of the upper ten remaining branches (>1 cm length).

Chafer *et al.* (2004) and Chafer (2008) proposed a rapid field assessment method of fire severity to validate and correct the satellite imagery results obtained from SPOT or LANDSAT (see Section 4.2.). Six plant damage levels are developed (including some descriptive pictures) for arbitrary visual fire severity classifications:

- UNBURNED: no significant fire damage
- LOW: ground fuel+ grasses, herbs and low shrubs burned
- MODERATE: ground fuel+ shrubs to 4 m burned
- HIGH: ground fuel+ shrubs incinerated, lower canopy scorched
- VERY HIGH: ground fuel+ shrubs incinerated and canopy completely burned
- EXTREME: all green vegetation burnt and incinerated <10 mm-thick stems

Burn severity also refers to the level of fire damage in soil, including effects on physical, chemical and biological soil characteristics, such as the index water drop penetration time (WDPT) or the infiltration rate recorded with a minidisk infiltrometer (Cerdá & Robichaud 2009; Robichaud *et al.* 2008; Jordan *et al.* 2010). Some research has also developed a fire damage assessment in soil according to the different temperatures reached (Mataix-Solera *et al.* 2011). The temperature regime is measured in a laboratory by the spectral responses of red band (RED), near Infrared (NIR), shorter and longer infrared (SWIR) bands (Arcenegui *et al.* 2010; Schepers *et al.* 2014), or those based on structural changes in soil organic matter (González-Pérez *et al.* 2004). However, the burn severity term includes soil heating (and time of residence), and is related to the fire damage of soil (De Bano *et al.* 1998; Certini 2005). It may, therefore, be included for a proper burn severity assessment of fire in soil. Depending on the pre- and post-fire characteristics of soil and vegetation, burn severity is characterized and defined according to ground cover, surface color and ash depth, soil structure, root damage and soil water repellency (Parsons *et al.* 2010). Vega et al. (2013b) categorize burn severity as five levels depending on different indicators: changes in organic cover, litter (Oi horizon) and duff (Oe+Oa horizons), and soil surface (Mineral soil (Ah horizon):

- Very low severity: Oa partially or totally intact + Ah undisturbed
- Low severity: Oa totally charred and possible ash occurrence + Ah undisturbed
- Medium severity: Bare soil and possible ash occurrence + Ah undisturbed
- High severity: Bare soil and thick layer of ash + Ah disturbed: SOM and surface fine roots consumed; soil color turns to grey
- Very high severity: Bare soil and no charred residue + Ah disturbed: SOM and surface fine roots consumed; soil color turns reddish

To provide a quantitative method to measure burn severity, some authors have developed indices that combine different metrics. One of the most widely applied methods is the Composite Burn Index (CBI) (Key & Benson 2005). Fire severity is estimated from a set of parametrized variables that are organized hierarchically into five vertical strata to obtain averaged values at the ground level, two shrub levels (<1 m and 1-5 m tall) and two tree levels (subcanopy and dominant trees). A value is found for each stratum that is added to obtain a CBI value for the understory, the overstory and the total (Figure 2). The Composite Burn Index (CBI) is designed to define burn severity ecologically, and to measure ground effects, which could be related to a signal detected by satellite imagery, by visually assessing conditions (giving scores) of the burned plant community by vegetative strata, physical properties and the distribution of traits within sampling plots across broad geographic regions (Key & Benson 2003). The methodology can be used when remote sensing data are lacking to describe and evaluate localized burn sites for several purposes (Parks *et al.* 2014). The CBI estimates the percentage of change in relation to the pre-fire scenario, but does not include information about its spatial extent. Therefore, De Santis & Chuvieco (2009) propose an adapted version, called GeoCBI (the Geometrically structured Composite Burn Index) (3), to include the fraction of plant cover (FCOV), and to improve correlations with spectral reflectance since it includes the spectral mixture recorded by remote sensing systems.

$$GeoCBI = \frac{\sum_{m_1}^{m_n}(CBI_m * FCOV_m)}{\sum_{m_1}^{m_n} FCOV_m} \tag{3}$$

m = vegetation stratum; n= number of strata.

4 2 Remote sensing assessment

Spatial information on fire severity is essential in planning ecosystem restoration.

The two most popular satellite-derived indices in the literature on fire severity measures are the normalized difference vegetation index (NDVI) and the normalized burn ratio (NBR). NDVI is computed by comparing the normalized ratio of near-infrared reflectance (NIR) with visible red reflectance (RED) values (4) (Keane *et al.* 2001), while NBR compares the normalized ratio of shortwave infrared reflectance (SWIR) with near infrared reflectance values (5) (Lopez-Garcia & Caselles 1991; Key and Benson 2005). The use of CBI and GeoCBI (Figure 2) for remote sensing products evaluations is quite generalized because of its semi-quantitative value due to its relation with the RED and NIR bands provided by several satellites (De Santis & Chuvieco 2007). Even the semi-qualitative methodology proposed by Ryan & Noste (1985) has been widely used and is linked to cartography to identify fire severity levels which have been defined by different authors; e.g. In Spain by Alloza *et al.* (2014) and Vega *et al.* (2013a).

FFI -- BURN SEVERITY -- COMPOSITE BURN INDEX

PD - Abridged	Examiners:			Fire Name:	
Administrative Unit		Project Unit		Macro Plot	
Field Date mmddyyyy	/ /	Fire Date mmyyyy	/		
Plot Aspect		Plot % Slope		UTM Zone	
Plot Diameter Overstory		UTM E plot center		GPS Datum	
Plot Diameter Understory		UTM N plot center		GPS Error (m)	
Number of Plot Photos		Plot Photo IDs			

BI – Long Form	% Burned 100 feet (30 m) diameter from center of plot =					Fuel Photo Series =			
STRATA RATING FACTORS	BURN SEVERITY SCALE							FACTOR SCORES	
	No Effect	Low		Moderate		High			
	0.0	0.5	1.0	1.5	2.0	2.5	3.0		
A. SUBSTRATES									
% Pre-Fire Cover: Litter = Duff = Soil/Rock = Pre-Fire Depth (inches): Litter = Duff = Fuel Bed =									∑ =
Litter/Light Fuel Consumed	Unchanged	--	50% litter	--	100% litter	>80% light fuel	98% Light Fuel		
Duff	Unchanged	--	Light char	--	50% loss deep char	--	Consumed		N =
Medium Fuel, 3-8 in.	Unchanged	--	20% consumed	--	40% consumed	--	>60% loss, deep ch		
Heavy Fuel, > 8 in.	Unchanged	--	10% loss	--	25% loss, deep char	--	>40% loss, deep ch		$\bar{X}$ =
Soil & Rock Cover/Color	Unchanged	--	10% change	--	40% change	--	>80% change		
CBI_1									
B. HERBS, LOW SHRUBS AND TREES LESS THAN 3 FEET (1 METER):									
%Pre-Fire Cover = % Enhanced Growth =									∑ =
% Foliage Altered (blk-brn)	Unchanged	--	30%	--	80%	95%	100% + branch loss		
Frequency % Living	100%	--	90%	--	50%	< 20%	None		N =
Colonizers	Unchanged	--	Low	--	Moderate	High-Low	Low to None		
Spp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High change		$\bar{X}$ =
CBI_1									
C. TALL SHRUBS AND TREES 3 to 16 FEET (1 TO 5 METERS):									
%Pre-Fire Cover = % Enhanced Growth =									∑ =
% Foliage Altered (blk-brn)	0%	--	20%	--	60-90%	> 95%	Significant branch loss		
Frequency % Living	100%	--	90%	--	30%	< 15%	< 1%		N =
% Change in Cover	Unchanged	--	15%	--	70%	90%	100%		
Spp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High Change		$\bar{X}$ =
CBI_1									
D. INTERMEDIATE TREES (SUBCANOPY, POLE-SIZED TREES)									
%Pre-Fire Cover = Pre-Fire Number Living = Pre-Fire Number Dead =									∑ =
% Green (Unaltered)	100%	--	80%	--	40%	< 10%	None		
% Black (Torch)	None	--	5-20%	--	60%	> 85%	100% + branch loss		N =
% Brown (Scorch/Girdle)	None	--	5-20%	--	40-80%	< 40 or > 80%	None due to torch		
% Canopy Mortality	None	--	15%	--	60%	80%	%100		$\bar{X}$ =
Char Height	None	--	1.5 m	--	2.8 m	--	> 5 m		
CBI_1									
Post Fire: %Girdled = %Felled = %Tree Mortality =									
E. BIG TREES (UPPER CANOPY, DOMINANT, CODOMINANT TREES)									
%Pre-Fire Cover = Pre-Fire Number Living = Pre-Fire Number Dead =									∑ =
% Green (Unaltered)	100%	--	95%	--	50%	< 10%	None		
% Black (Torch)	None	--	5-10%	--	50%	> 80%	100% + branch loss		N =
% Brown (Scorch/Girdle)	None	--	5-10%	--	30-70%	< 30 or > 70%	None due to torch		
% Canopy Mortality	None	--	10%	--	50%	70%	%100		$\bar{X}$ =
Char Height	None	--	1.8 m	--	4 m	--	> 7 m		
CBI_1									
Post Fire: %Girdled = %Felled = %Tree Mortality =									

Community Notes/Comments:	CBI = Sum of Scores / N Rated:	Sum of Scores	N Rated	CBI
	Understory (A+B+C)			
	Overstory (D+E)			
	Total Plot (A+B+C+D+E)			

STRATA	BURN SEVERITY SCALE							FACTOR SCORES
	No Effect	Low		Moderate		High		
	0	0.5	1.0	1.5	2.0	2.5	3.0	
A *SUBSTRATES*								
%DEAD LEAVES ON THE SOIL=					SOIL DEPTH (cm)=			
Litter/Light Fuel Consumed	Unchanged	--	50% litter	--	100% litter	>80% light fuel	98% light fuel	
Duff	Unchanged	--	light char	--	50% loss deep char	--	Consumed	
Medium /heavy Fuel	Unchanged	--	20% consumed	--	40% consumed	--	>60% loss, deep char	
Soil & Rock Cover/Color	Unchanged	--	10% change	--	40% change	--	>80% change	
			A. ∑ =		N=		$\bar{X}$ =	
B *HERBS, LOW SHRUBS AND TREES LESS THAN 1 METER*								
DOMINANT VEGETATION TYPE =					FCOV=			
%Foliage altered (blk- brn)	Unchanged	--	30%	--	80%	95%	100%+branch loss	
Frequency % Living	100%	--	90%	--	50%	<20%	0%	
New sprouts	Abundant	--	moderate-high	--	moderate	--	low-none	
			B. ∑ =		N=		$\bar{X}$ =	
C *TALL SHRUBS AND TREES 1 TO 5 METERS*								
DOMINANT VEGETATION TYPE =					FCOV=			
%Foliage altered (blk- brn)	0%	--	20%	--	60-90%	>95%	significant branch loss	
Frequency % Living	100%	--	90%	--	30%	<15%	<1%	
LAI change %	Unchanged	--	15%	--	70%	90%	100%	
			C. ∑ =		N=		$\bar{X}$ =	
D *INTERMEDIATE TREES 5 TO 20 METERS*								
DOMINANT VEGETATION TYPE =					FCOV=			
% Green (unalterad)	100%	--	80%	--	40%	<10%	none	
%Black/ Brown	0%	--	20%	--	60-90%	>95%	significant branch loss	
Frequency % Living	100%	--	90%	--	30%	<15%	<1%	
LAI change %	Unchanged	--	15%	--	70%	90%	100%	
Char Height	none	--	1,5 m	--	2,8 m	--	>5 m	
			D. ∑ =		N=		$\bar{X}$ =	
E *BIG TREES >20 METERS*								
DOMINANT VEGETATION TYPE =					FCOV=			
% Green (unalterad)	100%	--	95%	--	50%	<10%	none	
%Black/ Brown	0%	--	20%	--	60-90%	>95%	significant branch loss	
Frequency % Living	100%	--	90%	--	30%	<15%	<1%	
LAI change %	Unchanged	--	15%	--	70%	90%	100%	
Char Height	none	--	1,8 m	--	4 m	--	>7 m	
			E. ∑ =		N=		$\bar{X}$ =	

Figure 2. Field survey to collect information to calculate the Composite Burn Index (CBI, left image) according to Key & Benson (2003) and the modified version proposed by De Santis & Chuvieco (2009) (GeoCBI, right image) by highlighting new scores in gray.

In addition to the differenced NDVI (dNDVI) (6) and the normalized difference of NBR (dNBR) (7), a relative number of indices has been developed to generate fire severity maps. The dNBR index, initially proposed by Key and Benson (2005), is highly dependent on pre-fire vegetation characteristics as it represents an absolute value. Hence several authors have proposed new versions of burn severity metrics that derive from dNBR. Miller & Thode (2007) developed an index called the Relativized Normalized Burn Ratio (RdNBR) (8), which also relies on the difference between pre-fire and post-fire NBR values, and has been commonly used. This index emphasizes changes in the amount of pre-fire plant cover by including pre-fire NBR in the denominator to thus transform the dNBR into a relative scale to remove heteroscedasticity from the dNBR values distribution (Miller & Thode 2007). More recently, Parks *et al.* (2014) proposed a Relativized Burn Ratio (RBR) (9). RdNBR and RBR are relativized versions of dNBR, and both indices were designed to detect changes in fire severity, even where pre-fire vegetation cover is low.

All these indices have been used as independent variables to derive fire severity field indices at the pixel level, and a wide range of studies has demonstrated their sensitivity to changes in fire severity classes (Chu & Guo 2014). Both NDVI and NBR are widely used for severity assessments, but the best results are apparently obtained from NBR-based indices given the combination of two SWIR bands (Escuin *et al.* 2008). However, the results are discussed because the bitemporal image used to calculate spectral indices could be problematic due to image-to-image differences in illumination and phenology (Veraverveke *et al.* 2012). This may lead to poor performance and shows inconsistent fire severity quantification in adjacent areas. Veraverbeke *et al.* (2012) developed an alternative index based on short-wave infrared (SWIR) and mid-infrared (MIR) reflectance to improve performance compared to NBR-derived metrics. They demonstrated the potential of the SWIR-MIR band combination to detect fire effects (e.g. char fractional cover). Nevertheless, the spectral information required by this new metrics cannot be retrieved from current satellite imagery at an adequate spatial resolution.

$$NDVI = \frac{NIR -}{NIR +} \tag{4}$$

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{5}$$

.

$$dNDVI = NDVI_{prefire} - NDVI_{postfire} \tag{6}$$

.

$$dNBR = NBR_{prefire} - NBR_{postfire} \tag{7}$$

.

$$RdNBR = \frac{NBR_{prefire} - NBR_{postfire}}{\sqrt{\frac{NBR_{prefire}}{1000}}} \tag{8}$$

$$RBR = \left(\frac{dNBR}{(NBR_{prefire}+1.001)}\right) \tag{9}$$

However, some studies suggest that reliability of the described methods to identify spatial soil burn severity, compared to field vegetation damage results, is limited (Vega *et al.* 2013a). The influence of several factors, such as local conditions and soil characteristics, may condition calculations and hinder the generalized use of methods to calculate fire severity (Parks et al. 2014). Previous studies have demonstrated the difficulty of defining threshold values to classify fire severity into discrete severity classes (Cansler & McKenzie 2012; Parks *et al.* 2014). The characteristics and status of pre- and post-fire vegetation, and the time that has elapsed while assessing fire severity, strongly influence the results (Chu & Guo 2014). Moreover, accuracy depends on soil coverage and ecosystem characteristics, and on the availability of adequate satellite images to derive spectral indices (Hudak *et al.* 2007).

5 LABORATORY ASSESSMENTS

Some approaches are based on laboratory experiments, usually heating soil and/or humus samples in an oven or a muffle furnace with different exposure factors (time and temperature), and relate fire severity to changes in soil properties and infiltration processes. Wieting *et al.* (2017) simulated wildfire using a Wagner heat gun and suggested a collapse of the soil structure when the soil-surface temperature increased to 450–500 °C and>200 °C at the 1–2 cm depth. All organic materials were combusted, destroyed water repellency at the surface, and induced an increase in field-saturated hydraulic conductivity and more rapid initial volumetric water content. The fire severity impact can vary depending on soil characteristics. Araya *et al.* (2016) found that heating different soil types in muffle changed soil properties. The most critical temperatures are from 250 to 400ºC due to charring organic matter that reduced soil aggregate stability, cation exchange capacity (CEC), and carbon (C) and nitrogen (N) concentrations, plus the disappearance of kaolinite (Mataix-Solera *et al.* 2011).

Cancelo-González *et al.* (2012) and Lombao *et al.* (2015) included time of heating and fire recurrence in these studies. The latter authors conclude that physical and chemical properties can be used to detect the impact of high severity wildfires, but not the impact of prescribed fires or thermal shocks within a low temperatures range (50-254 ºC) under laboratory conditions. However, they used temperature-time curves to find that recurrence influenced the thermal response to a new heating event, and had direct effects on a wide range of soil biochemical and microbiological properties (Lombao *et al.* 2015). Therefore in laboratory experiments, variables are controlled and replicate ecosystems grow under the same conditions, which is not usual in wildfires or prescribed fire experiments. In addition, the advantage of laboratory experiment is the controlled measure of the selected parameters, which can enable predictive indicators of fire severity to be implemented, such as fire radiant energy (Smith *et al.* 2016). To extrapolate it to landscape-scale fires, uncertainty is tested in laboratory experiments, but medium-scale experiments are required as a bridge to validate this, i.e. Ecotron facilities or similar (Naeem *et al.* 1995). The research done in ecotron facilities should assess how different spatial scales are linked, from the laboratory to the landscape scale (Plaza-Alvarez *et al.* 2017, Moya *et al.* 2017). In addition, further studies are needed to validate fire severity effects depending on the differences in fire characteristics (energy release and duration), ecosystems (vulnerability and resilience), fuel model (live moisture, structure, flammability) (Finney *et al.* 2013; Michaletz & Johnson 2007) and the relationship of biological or physico-chemical response (Úbeda *et al.* 2009; Mataix-Solera *et al.* 2011; Zavala *et al.* 2014).

6 FIRE IMPACT AND MANAGEMENT

Proper post-fire management should be based on knowledge about the relationships that link ecosystem resilience, resistance and vulnerability and fire characteristics from both fire regime and fire behavior contexts, where fire (or burn) severity is one of the most important factors to assess fire damage (Alloza *et al.* 2014). Post-fire vegetation recovery increases relative humidity, reduces transpiration, intercepts rainfall and induces water infiltration, which reduces surface runoff and soil loss (Cerdà & Doerr 2005, 2008; Pérez-Cabello *et al.* 2012). In pine forests, needle coverage on the ash layer increases soil water retention capacity and acts as a protector agent against intense rainfalls by prolonging the time that the absorbent and protection effect by ash lasts (Cerdà & Doerr 2008). Fire damage can degrade biological soil properties, reduce soil seed banks and induce mortality in resprouters due to damage of meristematic tissues and fire severity (DeBano *et al.* 1998; Maia *et al.* 2012).

Fire severity can induce opposite effects on vegetation recovery depending on its functional types (Alloza *et al.* 2014). In chaparral, subshrub cover during the first growing season is inversely related to fire severity, whereas cover of suffrutescent plants (chamaephytes) is positively associated with fire severity (Keeley *et al.* 2008). Plant cover recovery in burned areas depends on the fire severity and spatial distribution of previous vegetation which influences the ecosystem response and defines changes in the plant-soil interphase, at least in the short and mid terms (Montorio *et al.* 2014). Other studies have observed good natural regeneration after high burn severity, fostered by high post-fire nutrient availability (Pausas *et al.* 2002), with positive effects on the dissemination of serotinous canopy seed banks (Moya *et al.* 2008; Vega *et al.* 2008a) or on the thermal scarification of seeds buried in soil (Martinez-Sanchez *et al.* 1999, Keeley 1991).

Burned soil undergoes biological, physical and chemical alterations that are not only related to fire severity directly, but are also indirectly due to ash incorporation (Jimenez-Pinilla *et al.* 2016), and to increasing pH that promotes plant regeneration (Bodí *et al.* 2014; Maia *et al.* 2012). However, Pereira *et al.* (2014) found that ashes dissolve after the first rainfall, which thus lowers pH and increases the amount of heavy metals in soil.

Soil structure is destroyed due to soil organic matter combustion (Mataix-Solera *et al.* 2004). With low fire burn severity, soil is usually covered by dead needles or coarse woody debris, which reduces surface runoff significantly compared to results on bare soil (Cerdà & Doerr 2008). High burn severity normally reduces aggregates, which promotes soil loss if the ash layer has been removed (Pereira *et al.* 2010). In some wildfires, the ash layer increases water retention capacity and reduces surface runoff (Cerdà & Doerr 2008), but it is not totally clear (Bodi *et al.* 2014). However, ash protection is effective only in the short term since ashes are usually dragged after intense rainfall (Pérez-Cabello *et al.* 2012) in the first or second month, depending on the climate (Pereira & Ubeda 2010).

7 MEASUREMENT AND IMPLICATIONS OF FIRE AND BURN SEVERITY

Burn severity is a key factor in post-fire management to quantify and map fire impacts, and to plan mitigation and rehabilitation treatments in fire-affected areas. However, burn severity assessments are costly in time and resources. In addition, they do not provide adequate coverage to generate spatially continuous information. Despite remote sensing technologies providing useful tools to assess the impacts of wildfire on ecosystems, debate continues about the most suitable metrics to identify the fire severity levels observed in the field (Escuin *et al.* 2008; Cansler & McKenzie 2012; Parks *et al.* 2014).

Using a common set of burn severity indicators and definitions for rapid post-fire assessments is crucial, such as pH or color, and biological indicators should be developed, such as microarthropod communities or microbial indices (Jain *et al.* 2008; Henig-Server *et al.* 2001; López-Poma & Bautista 2014; Moya *et al.* 2017; Vega *et al.* 2013b; Pourreza *et al.* 2014). The main feature is based on the dose and scalable response metrics, easily measured in the field, which promote the integration of fire dynamics into biophysical process models of several ecosystems, including spatial and temporal scales (Smith *et al.* 2017).

Guidelines should be developed to help users identify fire effects on soil and vegetation, such as the ForFireS Manual (EFFIS 2017), or those proposed by Parsons *et al.* (2010), Alloza *et al.* (2014) or Vega *et al.* (2013a). Consistent assessment methods encourage tools to be implemented for post-fire risk assessments of runoff and the erosion potential. This will increase the efficiency and speed of fire severity assessments, which will lead to more informed and financially prudent decision making about post-fire rehabilitation treatments. It will also allow researchers from different regions to obtain comparable results by promoting descriptions and local adjustments to develop soil burn severity classes or indices.

The demand and need for managers to provide cartographic information on fire severity as a tool to assess fire impact and ecosystem recovery should encourage researchers to find the most accurate method and reliable calculation, which should be validated by field sampling and include the generation of quick and updated protocols. By shifting in this direction, we propose moving toward a fire tolerance society, and eventually to co-existence, so that fire in all its severities and forms can continue to shape ecosystems (Moritz *et al.* 2014). Concerted efforts by Public Administrations and citizens are needed to embrace this challenge, as is a sophisticated and well-diffused message from researchers and scientists. Preventive efforts should not focus on preventing wildfires, but on reducing fire severity to similar levels to historic fire regimes by implementing fuel management; i.e. prescribed fires (Plaza-Alvarez *et al.* 2017; Sagra *et al.* 2017). Additional issues are also required: funds for stepped-up education; commitment from land management agencies; media committed to be a more ecologically literature; conservation groups to see the value in mixed-severity and not just low-severity fire; politicians to see the big picture that the post-fire landscape has an irreplaceable ecological value, and not just money from salvage logging for short-term profits (DellaSala *et al.* 2015).

8 CASE STUDIES: DOSE-RESPONSE EXPERIMENTS

8.1 CASE STUDY 1: A BENCH-SCALE FLAMMABILITY PROTOCOL TO SIMULATE THE EFFECT OF WATER CONTENT ON HEAT TRANSFER IN SOIL DURING PRESCRIBED BURNINGS

A bench-scale flammability protocol, based on the methodologies proposed by Rein *et al.* (2009) and Enninful & Torvi (2008), was developed to simulate soil heating during prescribed fires. A mass loss calorimeter (MLC) was used to run a series of tests (Figure 3) to check the possibilities of this device obtaining a dose-response effect of fire severity according to water content in soil. This methodology can help to validate thermal conductivity or heat transfer models, to improve prescriptions, and to reduce fire severity in soil during prescribed burnings. This protocol can be potentially used with different devices based on cone calorimeter assembly (e.g. cone calorimeter, fire propagation apparatus) or other devices capable of calibrating radiant heating with a high level of accuracy. The main strength of this methodology compared to oven-fan protocols is that radiant heat flux is constant and calibrated. The horizontal radiant heater orientation is a better approach and involves smoldering fire and heat transfer to soil under natural conditions (Enninful & Torvi 2008). This protocol allows a few monoliths to be extracted from the field to be burned with barely any handling, and is a reasonable surrogate of field conditions. The MLC has been tested to assess the flammability of dried forest fuels (Madrigal *et al*. 2009, 2011), live forest fuels (Madrigal *et al*. 2013) and barks of trees (Dehane *et al*. 2015). In this case study, we present an application of this device to describe litter and duff layer flammability, as well as the heat transfer in the first soil layer, which is the most vulnerable to fire severity.

8 1.1. Protocol description

Sampling monoliths

A pure forest area of *Pinus nigra* spp. *salzmannii* stands was selected, where climate is classified as humid Mediterranean (Allúe 1990), with a mean annual temperature of 11.9ºC (mean lowest temperatures of the coldest month of 0.5ºC; mean highest temperatures of the hottest month of 30.5ºC) and a mean annual precipitation of 595 mm (99 mm in summer). Calcareous soils dominate the study area, and the soil at the experimental site is classified as Leptosol (Lucas-Borja *et al.* 2016). This area was treated to reduce forest fuels using burnings with low intensity fire prescriptions to reduce fire severity in duff, soil and trunks (for more details, see Lucas-Borja *et al.* 2016). Thirty-six monoliths of 10x10x5 cm^3 were extracted at the different random sites of the plots before burning, including litter (L), fermentation layer (F), humus layer (H) and soil. They were transported to the laboratory and conditioned in a climatic chamber (temperature 20ºC, relative humidity 55%) to homogenize the moisture of all the samples.

Figure 3. The mass loss calorimeter (MLC FTT®) device used to run the flammability tests.

Treatments to simulate different water contents in soil

Three treatments with 12 replicates were used to carry out the experiment: (1) dried soil under climatic chamber conditions; (2) irrigation of 30 mL per monolith (3 mm of rain, as a surrogate of poor rainfall); (3) irrigation of 60 mL per monolith (6 mm of rain as a surrogate of moderate rainfall). The irrigation treatment was applied with a manual sprayer, and monoliths were tested after a 24-hour draining period in the climatic chamber. Under these conditions, the fuel moisture content of both the litter and fermentation layer was homogenized to 12% for all the treatments, and we assumed that verified moisture contents were reached in soil.

8.1.2. Flammability tests and temperature monitoring

A similar experimental protocol to that proposed by Enninful & Torvi (2008), but adapted to the MLC device (Madrigal et al. 2009), was followed. A constant heat flux of 25 kW/m^2 was selected to simulate a low-intensity fire. Experiments were piloted with a spark igniter. Six type K thermocouples (1 mm of diameter) were positioned in the center of the monolith (Figure 4) in the following positions: (1) over the monolith (air and flame temperature); (2) on the litter layer (L); (3) on the fermentation and humus layer (F+H); (4) 1 cm under the F+H layer; (5) 2 cm under the F+H layer; (6) 4 cm under the F+H layer. Temperatures were monitored at the 1-second frequency using a Datataker DT500 ® datalogger.

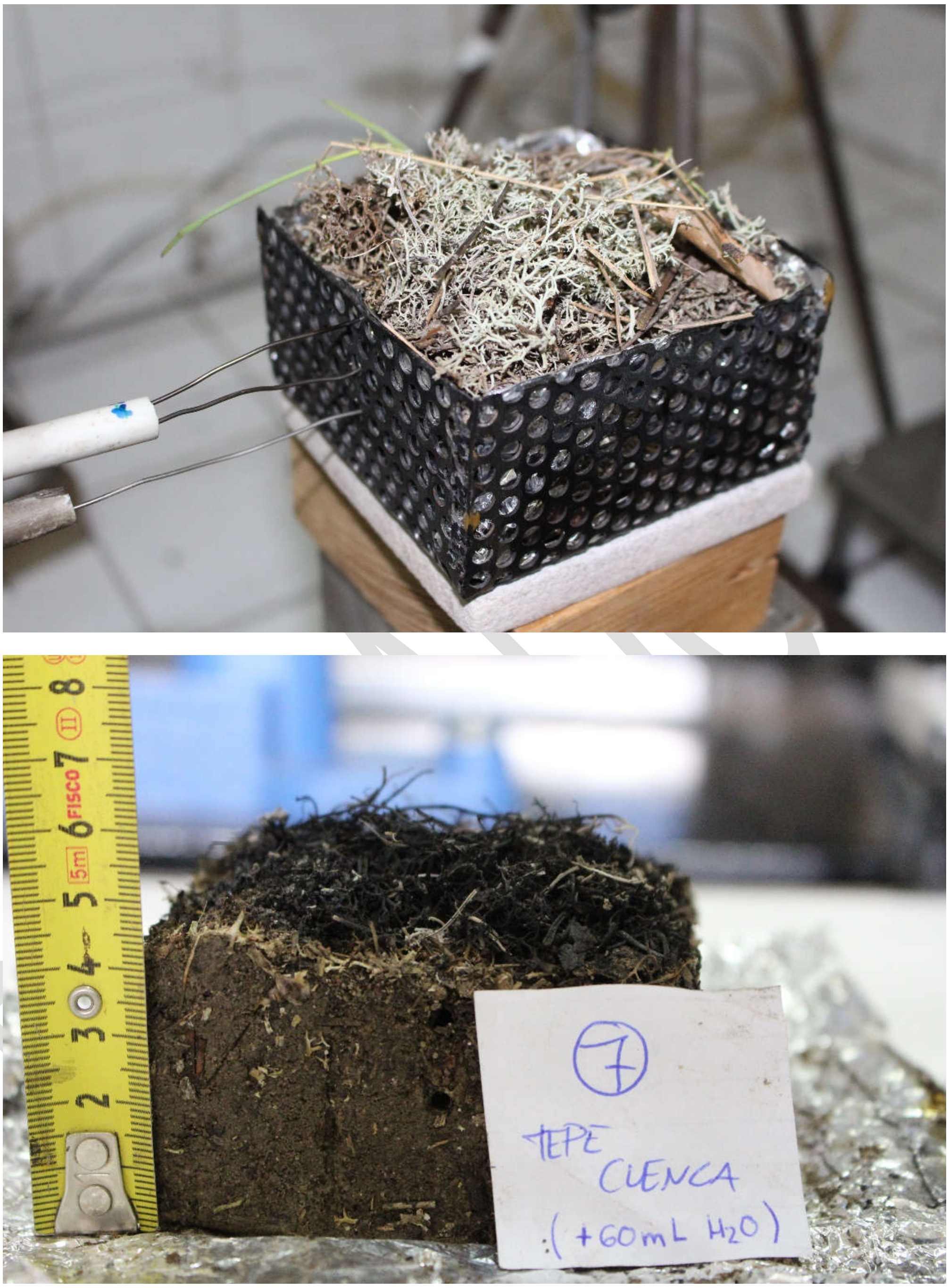

Figure 4. a) Position of thermocouples in soil (1, 2, and 4 cm under the Fermentation+Humus layer, before the MLC test and b) Monolith with Treatment 3 (60 mL of water irrigation) after test

The experimental procedure was as follows: (1) the monolith was exposed to the heat flux and the spark igniter was positioned immediately over the litter layer to allow litter to ignite; (2) in the heating phase, litter lost water and released flammable gases; (3) flammable gases generated the ignition of litter, and the MLC recorded the heat release rate (KW/m^2) in the flaming phase; (4) the fuel bed was consumed and the smoldering phase (combustion without flame) commenced; (5) when the smoldering phase of litter and the F+H layer finished, the monolith was removed from the heat source; (6) soil temperatures were monitored until thermocouples reached ambient temperature. The heat release rate curve shows the combustibility and sustainability of combustion in the different test phases (Figure 5a). The thermocouple signal allowed the temperatures of the different layers to be monitored during tests (Figure 5b).

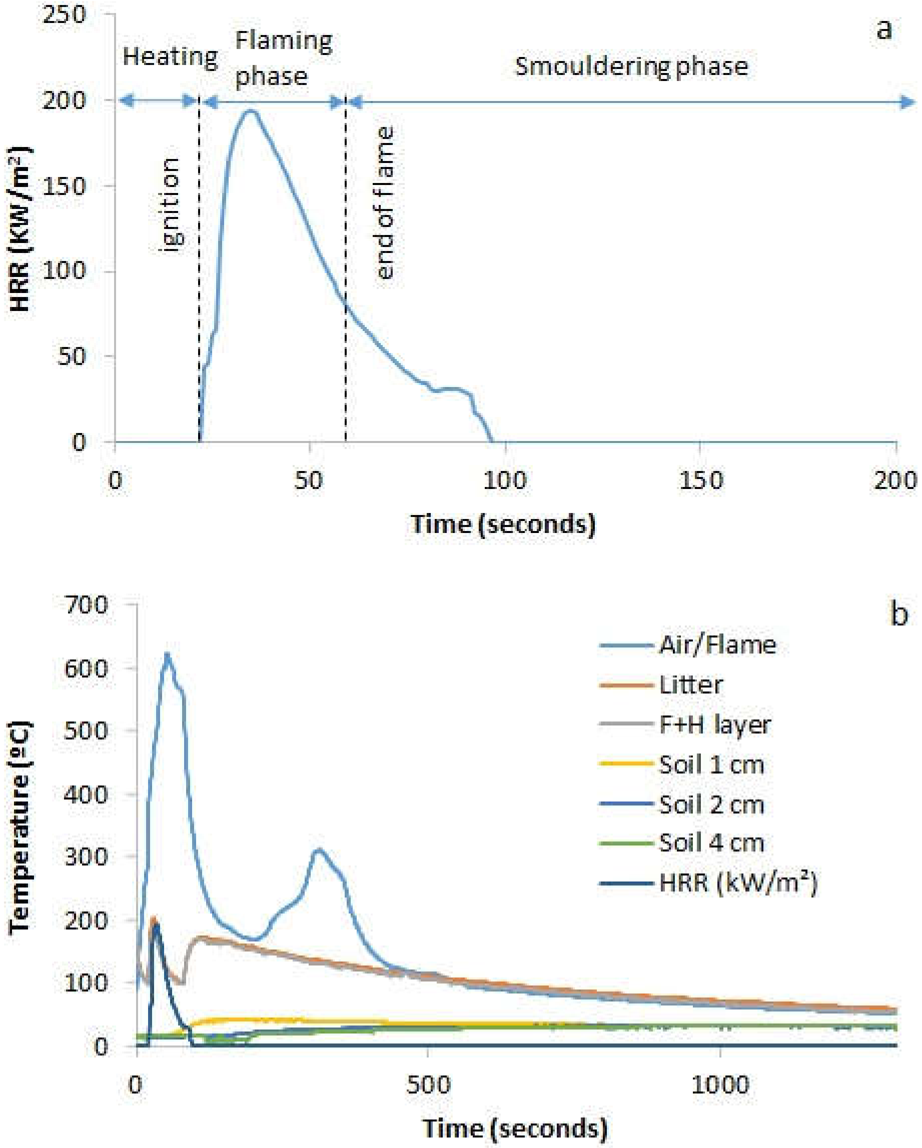

Figure 5. (a) The heat release rate (HRR) curve and (b) temperatures during a flammability test of a monolith, with the HRR curve overlapped. The X-axe scale differs for (a) and (b), time in seconds (s).

8.1.3. Results

Flammability

The heat release rate (HRR) curves showed wide variability among samples because of the large differences in the fuel bed (land F+H layers) among the monoliths being detected. Nevertheless, average curves (Figure 6) showed few differences in the peak heat releases (PHR) among treatments when considering that the limit of repeatability for the PHR of forest fuels gave a difference of 15% (Madrigal *et al.* 2009). Therefore, the irrigation dose had a minor effect on fuel bed flammability.

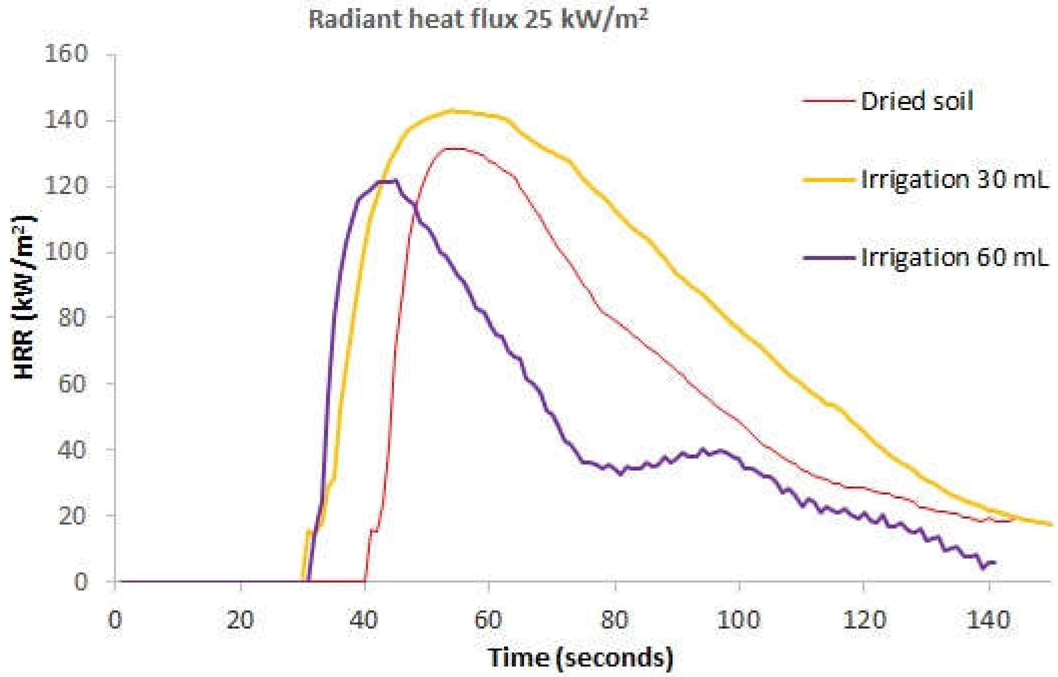

Figure 6. Average heat release rate of litter for the analyzed treatment (dried fuels, Irrigation 30 mL, irrigation 60mL). Heat flux selected: 25 kW/m^2. Piloted ignition (spark igniter) was selected. The fuel moisture content of litter was 12% for all the treatments.

Effect of water irrigation (dose) on soil temperature (response)

For similar heatings (Figure 6), irrigation of monoliths generated large differences in the thermal regime during the experiments (Figure 7). A wide variability of maximum temperatures and times over 60ºC (TT60) for the dried monoliths was detected compared to the irrigated ones (Figure 8). We observed a trend to reach the lower maximum temperature according to higher irrigation. The time over 60ºC (TT60) was a better soil fire severity index because it could condition the survival of soil microbial populations. In this case, TT60 was similar for both irrigation treatments, and showed that presence of water in soil could strongly reduce soil fire severity during the prescribed burnings. On the contrary, executing prescribed burnings with low soil water content levels could cause severe damage, as seen in the dried soil treatment.

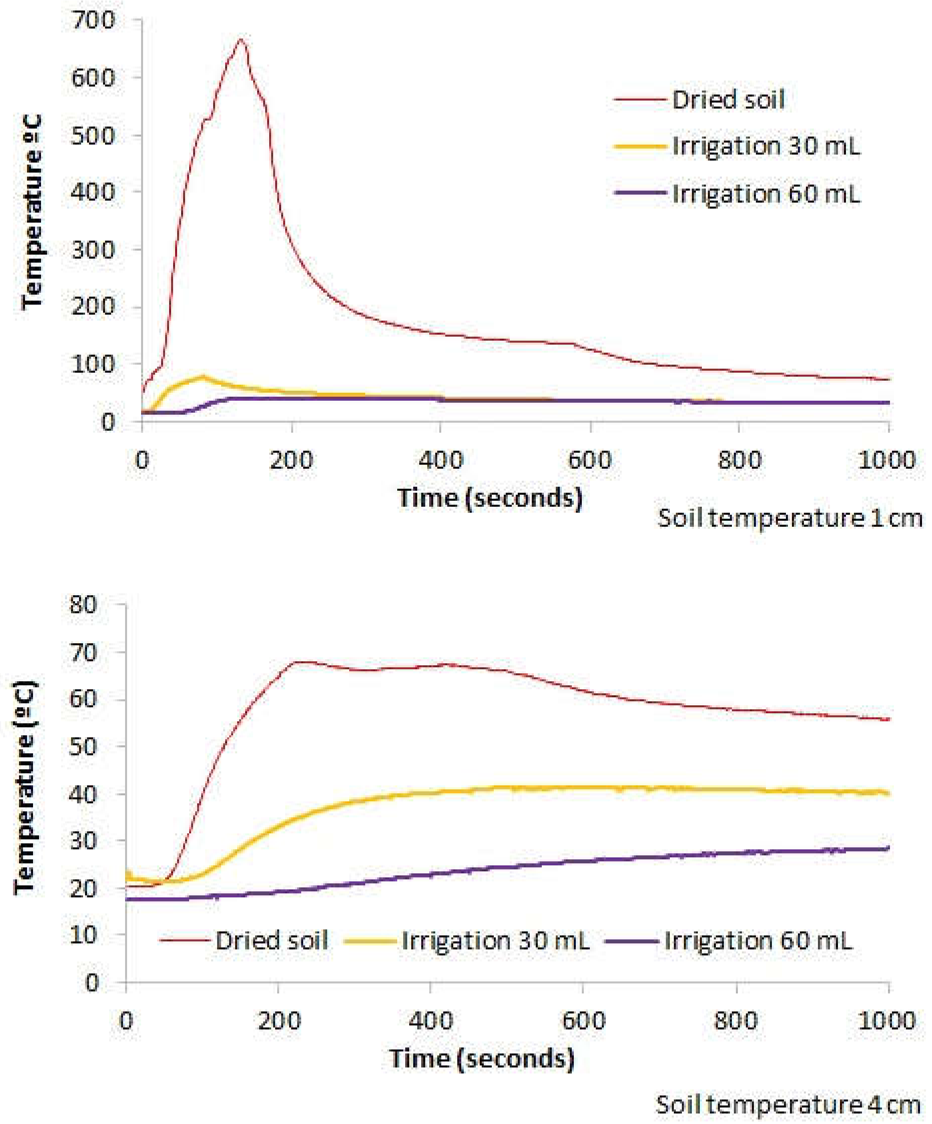

Figure 7. Soil temperature (response) during tests for the analyzed treatments (dose): (a) soil temperature 1 cm under the F+H layer; (b) soil temperature 4 cm under the F+H layer.

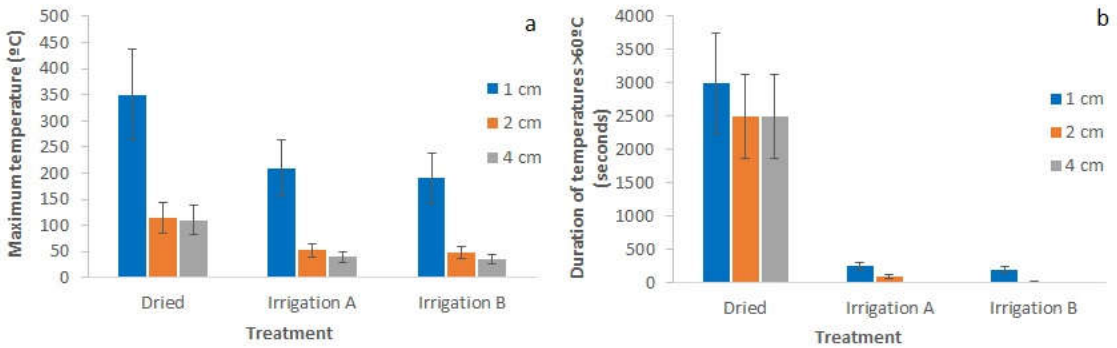

Figure 8. Mean plots (Standard error in bars) for (a) maximum temperature (TMAX in ºC) and (b) time over 60ºC (TT60 in seconds) in soil at 1 cm, 2 cm and 4 cm under the F+H layer. Treatments are Dried soil, Irrigation A=30 mL, irrigation B=60 mL.

8.1.4. Conclusions and potential applications

The draining and conditioning that took place in a climatic chamber 24 h after treatment correctly homogenized the FMC of fuel beds. Indeed the methodology allowed similar soil heating for all the treatments as a surrogate of the real conditions during a prescribed fire after different rain episodes (without rain, 3 mm and 6 mm).

These results were strikingly similar to those recorded in the field experiments during the prescribed burnings (Lucas-Borja *et al.* 2016). Therefore, we consider that this methodology can reasonably reproduce field conditions. These experiments can also complete information from field experiments to improve prescription during burnings in different kinds of soils and ecosystems. The possibility of increasing the radiant heat flux in the MLC device would allow soil temperature regimes to be compared for different heating values, to simulate distinct fire intensities, to highlight differences in prescribed burnings as regards forest fires, and the vulnerability/resilience of distinct ecosystems to this fuel treatment.

8.2. CASE STUDY 2: EXPERIMENTAL FIRES OF SOIL MONOLITHS UNDER SEMI-NATURAL CONDITIONS IN A BURNING BENCH

8.2.1. Introduction

As explained in the preceding sections, fire severity is recognized as a decisive factor in ecologically-based fire management given its influence in the alteration of crucial soil properties (Mataix-Solera *et al.* 2011; Vega *et al.* 2013b) and enhancing post-fire runoff and erosion (Benavides-Solorio & MacDonald 2005; Vega et al. 2005; Cawson *et al.* 2013; Vieira *et al.* 2015; Fernández & Vega 2016). Post-fire soil conditions may interact with other post-fire environmental influences in the field, such as rainfall, runoff, wind, erosion, bioturbation, etc., and an accurate comparison with unburned soils is not always possible. The experimental approach described herein could be very useful to better understand soil heating profiles and the changes in some soil physical properties associated with soil burn severity.

Some methodologies are based on the use of unaltered soil cores or soil monoliths that are burned under semi-natural conditions to simulate field conditions and to obtain different soil burn severities. These approaches use burning benches in the experiments carried out in an outdoor combustion tunnel to burn soil monoliths (Madrigal *et al.* 2010; Fontúrbel *et al.* 2011; Aznar *et al.* 2016; García-Oliva *et al.* 2018). In these experiments, natural fuels are utilized as the energy source.

These experiments seem to adequately reproduce the temperature courses observed in mineral soil during experimental fires carried out in field (Klopatek *et al.* 1990; DeBano *et al.* 1998). In most forest fires, combustion starts by flaming fine forest floor fuels (litter and downed and dead twigs) which cause humus ignition. Then humus combustion transfers energy to mineral soil by conduction, which is considered the main mechanism of heat transfer to soil in forest fires (Frandsen & Ryan 1986; Neary *et al.* 2005). Consequently, the role played by forest floor fuels in soil heating processes is relevant, irrespectively of their contribution to the changes in nutrients, carbon and other soil parameters.

In this section we summarize a protocol to burn intact monoliths of soil and forest floor to study the effects of soil burn severity on the thermal regime and on soil physical properties.

8.2.2. Protocol description

Sampling soil monoliths

In each representative forest stand selected for soil monolith sampling, several randomly oriented transects were established. Samples were collected from systematically selected points in transects separated by 20 m. Each sample consisted of a soil monolith, 40 x 40 x 10 cm deep, carefully extracted to maintain the original soil structure. Each monolith included organic horizons: litter (Oi), fermentation (Oe) and humus (Oa) layers, and 10 cm of surface mineral soil. Soil monoliths were collected in pairs. Metal frames (40 x 40 cm) were used to remove the monolith by inserting them into the ground up to a depth of 25 cm. Each monolith was segregated from the subjacent soil by horizontally introducing a metal plate at the bottom of the monolith. Monoliths were carefully transported to the laboratory in containers and were then air-dried to obtain distinct levels of moisture, monitored by TDR probes in a subset of them.

Burning experiments

Soil monoliths were placed on a burning bench (300 cm long x 200 cm wide x 50 cm deep), positioned at a wind tunnel outlet (Figure 9). Monoliths were placed on the bench in groups of six on a soil layer, with a similar space left between them and the borders of the bench (Figure 10). Packed soil was used to fill all the gaps to obtain a common mineral soil level. Then, maritime pine intact forest floor blocks, collected from each study site, were placed above the packed soil to obtain a common horizontal litter surface across the bench. Finally, a variable load of fuel, made of maritime pine litter and woody fuel, was homogeneously spread above the litter layer top to cover the entire burning bench to make up a continuous fuel bed. A continuous fuel layer (200 cm long) was also placed on a supplementary burning table, between the tunnel outlet and the burning bench to enable a complete 500-cm fire run. A fireline was lighted with a torch and fire was allowed to run freely, helped by a light air flow (0.6 m/s).

Figure 9. View of the burning bench during an experimental fire.

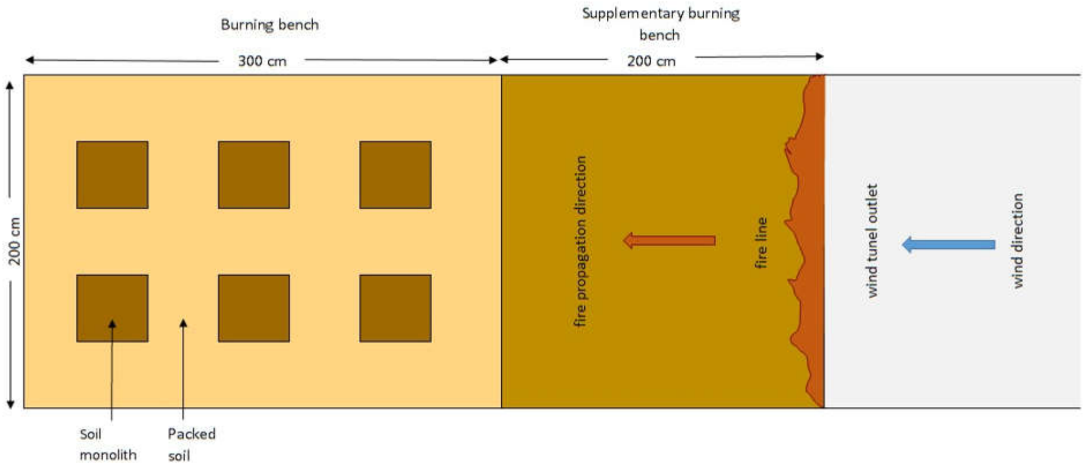

Figure 10. Scheme of the placement of soil monoliths on the burning bench.

Before burning, the pre-fire duff (Oe+Oa) level was labeled with four small metal nails embedded in each soil monolith with the head at the same level as the Oe layer top. Temperatures during burning were recorded with twelve 1-mm diameter grounded-junction inconel sheathed K type thermocouples, connected to data-loggers. Thermocouples were laterally inserted into the monoliths at three positions and at four different depths (humus layer surface, mineral soil surface and –2 cm and – 5 cm below the mineral soil surface).

The moisture contents of the organic horizons were obtained by collecting small samples immediately before burning and subsequently once oven-dried. The samples of the mineral soil portion of monoliths were collected at depths of 0-2 cm and 2-5 cm to obtain their respective moisture content.

Fuel consumption was obtained by the difference between the dry weight of the added fuel and the combustion residues, by assuming that the Oi layer was almost completely consumed during fire. Combustion remains were carefully picked up to the nail head level.

First series of experiments

In this set of experiments, intact soil monoliths were collected from two pine forests with contrasting soils: an acid, coarse-textured soil, with high organic matter content (site 1, in the province of Pontevedra; NW Spain), and a neutral heavy-textured soil with low organic matter content (site 2, in the province of Cuenca, central Spain) to compare two soil burn severity levels in these different soils burned under similar conditions. It is not possible to achieve this objective under field conditions. Soil monoliths were collected at both study sites as explained above. The monoliths used for light burning were uniformly irrigated by microsprinkling to field capacity and were then allowed to air-dry in a greenhouse for 3 days before burning. The monoliths destined for severe burning were not watered. The duff moisture content in the monoliths assigned to light burns varied between 88% and 196% in the Pontevedra and Cuenca soils, and was less than 12% at both sites for those assigned to severe burns. Soil moisture content varied between 30% and 43% in the monoliths for light burns and was less than 6% for the severe burns.

A non parametric Mann–Whitney U test (25 monoliths per treatment) was used to analyze the effect of treatment (severe and light burning) within each soil type on the thermal regime parameters during burning, duff depth and soil C content. In the first case, comparisons between soil types in the same treatment were also made. Regression techniques were used to examine any possible relationships between thermal regime parameters and duff depth reduction and soil C consumption immediately before burning, and for each site separately.

Results

The maximum temperatures reached at all the positions in the severely burned samples were significantly higher than in the slightly burned samples in both the Pontevedra and Cuenca soils (Figure 11). The maximum temperatures reached in the severely burned Pontevedra soil were significantly higher than in the corresponding Cuenca soil, and at both the soil surface and the 2-cm depth. However in the slightly burned soils, values were similar in both soil types. In turn, differences in the duration of high temperatures (Figure 12) were small between the soil burn severity levels in the Cuenca soil. In contrast, the differences for the Pontevedra soils were clear. As a whole, the severely burned Pontevedra soil underwent a higher and more prolonged heat pulse, which penetrated more deeply into soil than in the Cuenca soils. As a result, the degree of soil burn severity in the Cuenca soil was probably not high enough to alter the soil structure, as suggested by the lower temperatures reached during burning.

The relative reduction in duff depth was very high in the severely burned soils of Pontevedra (88.5±3.9%) and Cuenca (87.8±3.6%), but was significantly lower in the slightly burned soils at these two sites (44.6%±5.3% and 67.5±6.4%, respectively). Only in the severely burned soils of Pontevedra was the consumption of soil organic matter appreciable, with frequent signs of structure alteration, as reflected by greater absolute reductions in the soil C concentration (4.9±0.6%) than in the soils of Cuenca (0.8±0.2%). The maximum temperatures and duration of temperatures over 200ºC, measured on the soil surface and at a 2 cm soil depth, were positively related to the burn depth of the Pontevedra soils (r^2 ranged from 0.48 to 0.53; $p<0.01$; $n=50$) and soil C consumption (r^2 ranged from 0.46 to 0.58; $p<0.01$; $n=50$), whereas these relationships were not found for the Cuenca soils.

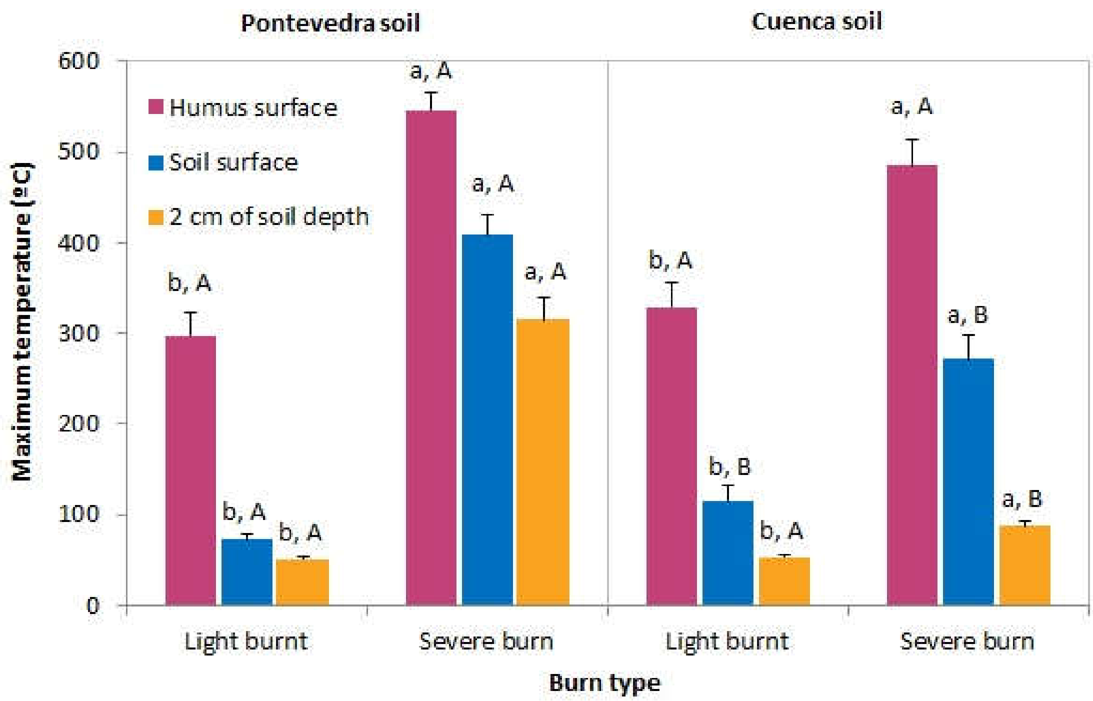

Figure 11. Mean values of maximum temperatures reached at three depths during experimental burning of 100 soil monoliths from soils collected in two *P. pinaster* sites, Pontevedra (n=50) and Cuenca (n=50). Bars are standard errors. Within each measurement position, different lower case letters indicate statistically significant differences between soil burn severities in each site, and different capital letters, between sites in each soil burn severity (Mann-Whitney test, p<0.05).

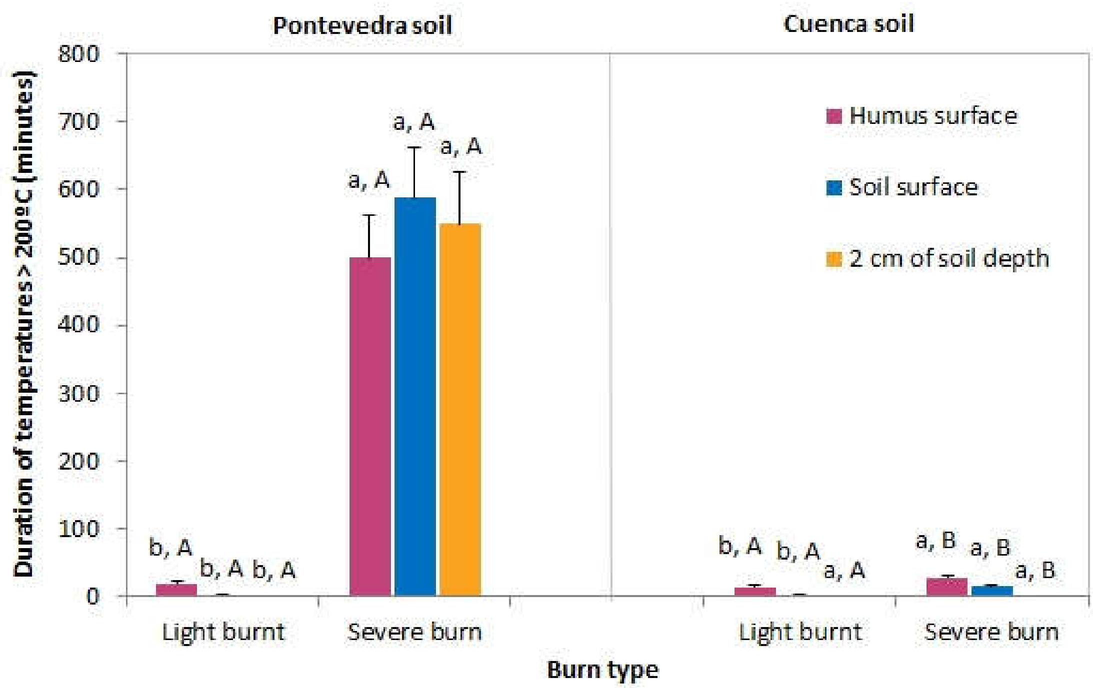

Figure 12. Mean values of duration of temperatures > 200º C, reached at three depths during burning of 100 soil monoliths from soils collected in two *P. pinaster* sites, Pontevedra (n=50) and Cuenca (n=50). Bars are standard errors. Within each measurement position, different lower case letters indicate statistically significant differences between soil burn severities in each site, and different capital letters, between sites in each soil burn severity (Mann-Whitney test, p<0.05).

Second series of experiments

A second series of burnings was carried out with to analyze the effect of the verified soil burn severity levels on the soil physical properties associated with soil erodibility. The corresponding pairs of soil monoliths remained unburned to allow comparisons. Immediately after burning, each burned monolith was assigned to a soil burn severity level according to the visual indicators described in Vega *et al.* (2013b), and explained in Section 4.1 of this chapter. For the soil physical properties, levels 0 (unburned), 2 and 5 of soil burn severity were considered.

In each monolith, soil water repellency was determined on the duff layer (if present), soil surface, and 2 cam and 5 cm below the mineral soil surface using the ethanol percentage test (King 1981). This test consists in the application of different ethanol dilutions (0, 3, 5, 8.5, 13, 18 and 36%). The obtained values allowed us to group monoliths into seven categories following Doerr et al. (2002). Soil aggregate stability was determined following the method described by Kemper & Rosenau (1986). Aggregate size fractions of 5-2 mm, 2-1 mm, 1-0.25 mm, 0.25-0.05 and <0.05 mm were considered, and the percentage by weight of aggregates in each fraction was used to calculate the dry mean weight diameter index. Total soil C was determined by dry combustion in a LECO CNS-2000 (Leco Corporation, St. Joseph, MI). The furnace temperature was set at 1350°C for the 0.25 g soil samples. All the soil samples were air-dried and then passed through a 2-mm sieve before being analyzed. The same determinations were made in the unburned soils.

The non parametric Mann–Whitney U test was used to analyze the differences between soil burn severities (levels 2 and 5) between the thermal regime parameters and soil properties (levels 0, 2 and 5) at each measurement position.

Results

The temperature during the experimental fires (Figure 13) was higher in soil burn severity 5 in all the strata (note that the entire humus layer was consumed at the fire severity 5 level). The maximum temperature rapidly dropped with depth, but this drop at level 5 was less pronounced. The mean durations of temperatures > 200ºC were long at fire severity level 5. They ranged from 3 to 6 minutes at soil burn severity level 2, to between 600 and 980 minutes at soil burn severity level 5.

Two typical temperature-time profiles on the humus surface, soil surface and at the 2 cm soil depth of the soils burned with soil burn severity 2 and 5 are shown in Figures 14 and 15. Peaks of high temperatures were reached in soil with soil burn severity level 2, whereas temperatures over 300°C persisted for more than 20 h at the soil surface and at the 2 cm soil depth of soils with soil burn severity level 5. Temperature peaks showed short delays among the different depths.

The temperature profiles observed at soil burn severity level 5 indicate that significant drops in soil organic matter, the deterioration of both structure and porosity, and the degradation of other soil properties may have occurred as substantial organic matter consumption begins within the 200–250ºC range to be completed at around 460ºC (Giovannini *et al.* 1988).

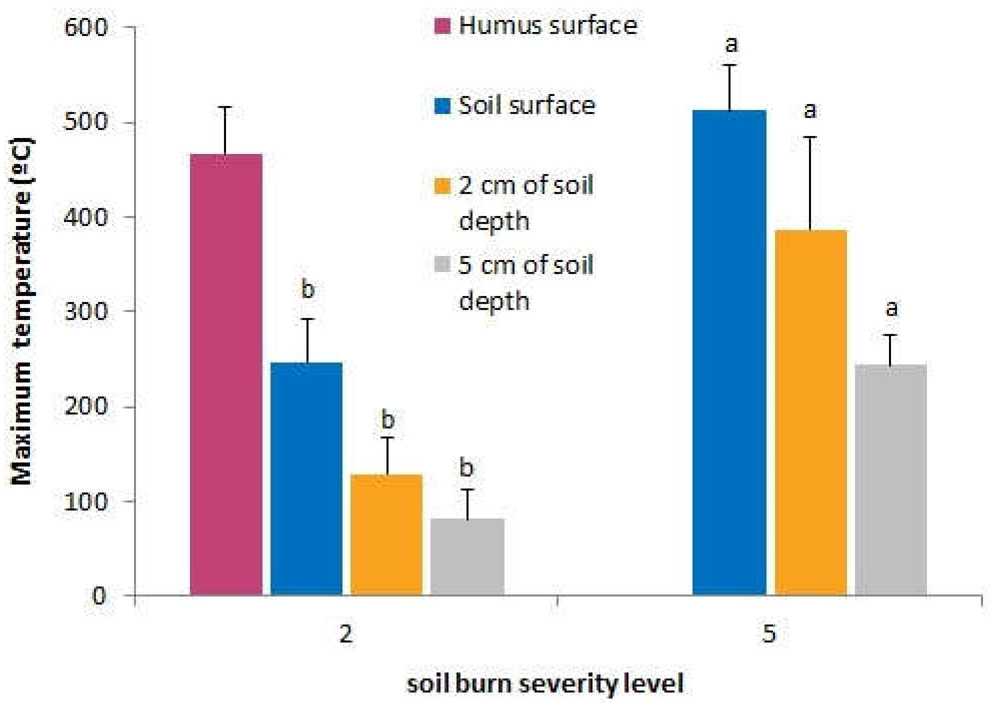

Figure 13. Mean values of maximum temperatures reached at four soil depths during experimental burning of 24 soil monoliths collected in *P. pinaster* stands in NW Spain. Bars are standard errors. Within each measurement position, different letters indicate statistically significant differences between soil burn severities (Mann-Whitney test, p<0.05).

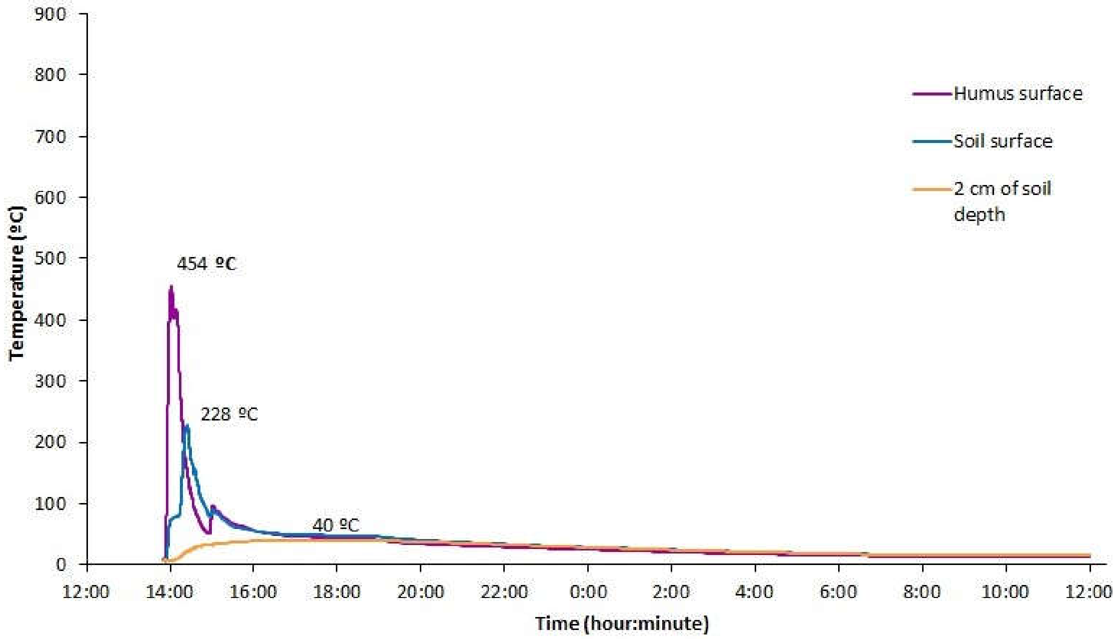

Figure 14. Temperature profile during an experimental fire of a monolith with level 2 of soil burn severity, at the humus surface, mineral soil surface and at 2 cm of soil depth.

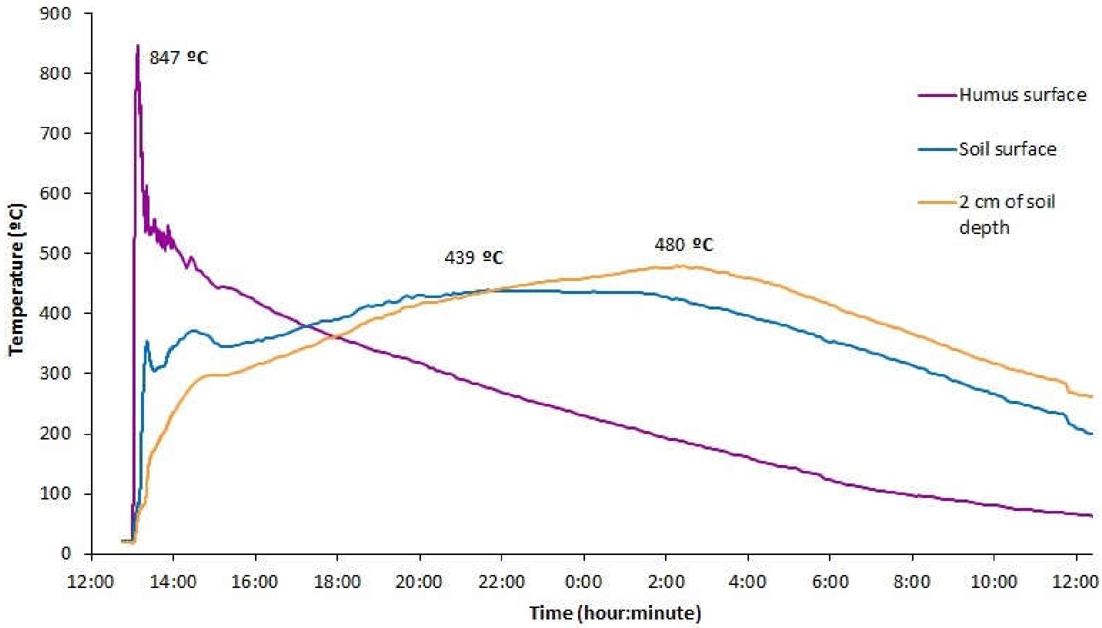

Figure 15. Temperature profile during an experimental fire of a monolith with level 5 of soil burn severity, at the humus surface, mineral soil surface and at 2 cm of soil depth.

Soil properties

The unburned soils (control) showed extreme soil water repellency on the soil organic cover surface, and on the mineral soil surface, 2 cm and 5 cm below (Figure 16). This confirms previous results in pine stands recorded in coarse-textured soils with high soil organic matter content, which is usual in NW Spain (Varela *et al.* 2005; Rodríguez-Alleres *et al.* 2007, 2012). In the burned soils, the soil water repellency degree lowered as the soil burn severity level increased. In fact soil water repellency almost disappeared at the highest soil burn severity level. This agrees with previous results when the same soil burn severity classification was used after wildfires in Galicia, NW Spain (Fernández *et al.* 2016), where soil water repellency was measured in the field by a mini-disc infiltrometer. The results obtained herein showed the clear relationship between persistence of soil water repellency and the soil thermal regime. In soil heating experiments using a muffle, Doerr *et al.* (2004), García-Corona *et al.*. (2004) and Varela *et al.* (2005) found that temperatures under 175ºC had very little effect on soil water repellency, which is completed eliminated when temperatures range between 260 and 340ºC.

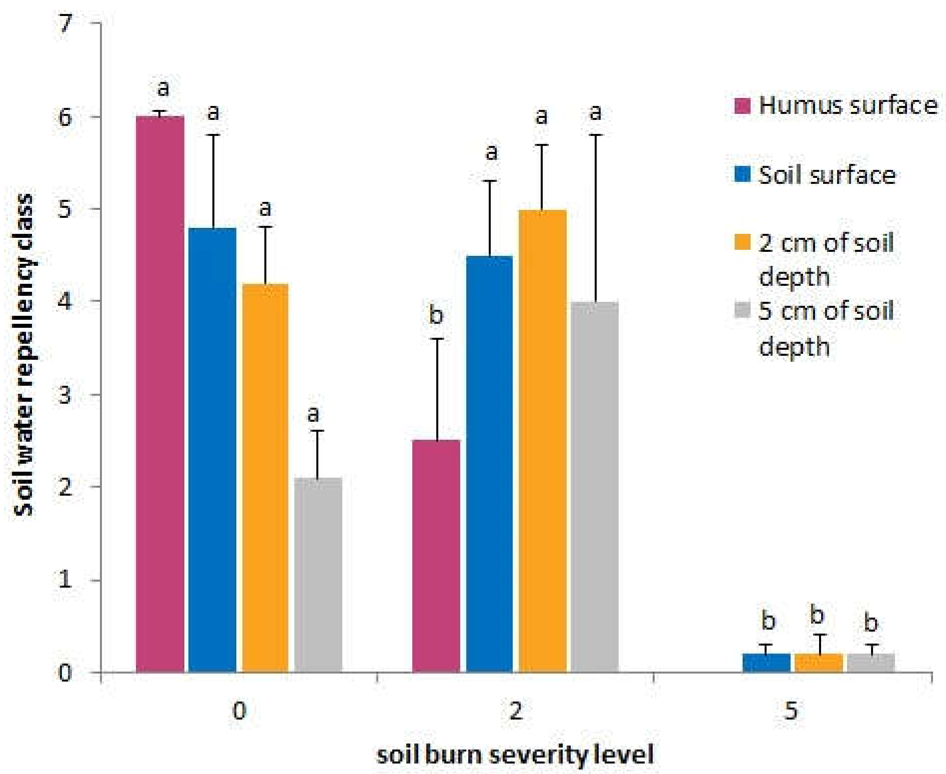

Figure 16. Soil water repellency class for different soil burn severity levels (0, 2 and 5), at the humus surface, mineral soil surface and 2 and 5 cm of soil depth. Bars are standard errors. Within each measurement position, different letters indicate statistically significant differences between soil burn severities (Mann-Whitney test, $p<0.05$).

Soil organic C (Figure 17) significantly decreased when the soil burn severity level increased. Very high soil burn severity soils showed reduced soil organic content in relation to unburned soils of 97%. These results agree with the observations made by Vega et al. (2013b) after a wildfire in NW Spain. The overall mean value of the mean weight diameter (Figure 18) showed a slightly lower soil burn severity level compared with the unburned control. A significant decrease was measured in the soils burned at a very high soil burn severity. These results indicate that small size fractions increased when soil burn severity rose, similarly to the results reported by Mataix-Solera & Doerr (2004) and Varela *et al.* (2010).

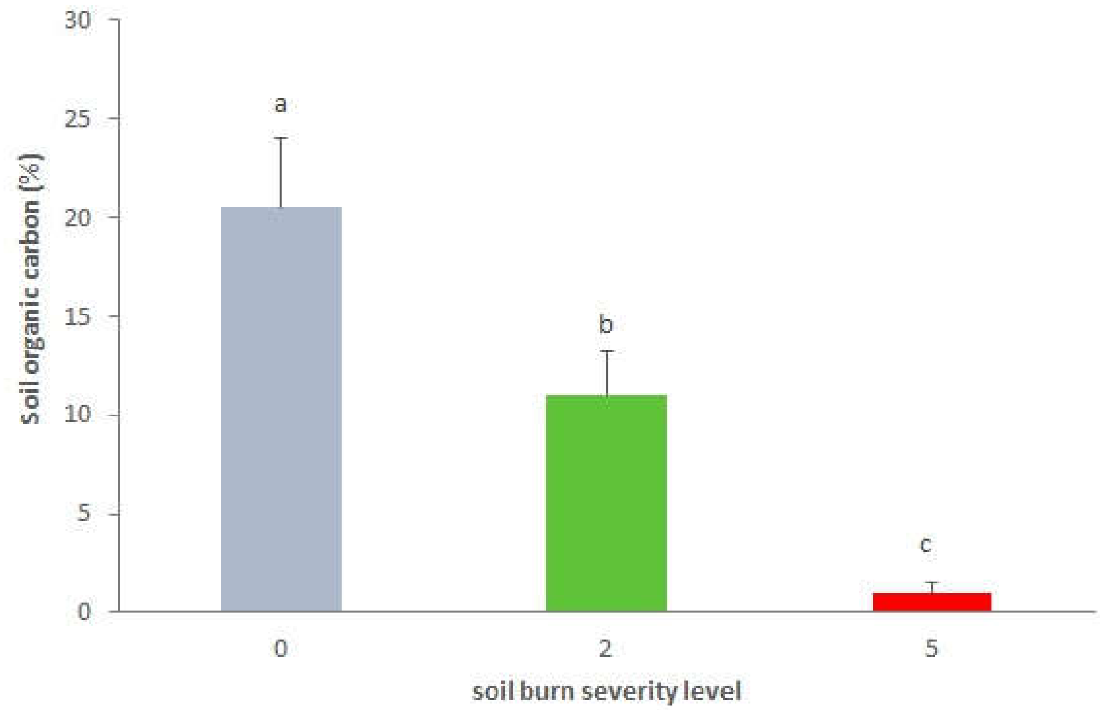

Figure 17. Soil organic Carbon (%) of soil samples (0-2 cm) classified by level of soil burn severity (0, 2 and 5). Bars are standard errors. Different letters indicate statistically significant differences between soil burn severities (Mann-Whitney test, p<0.05).

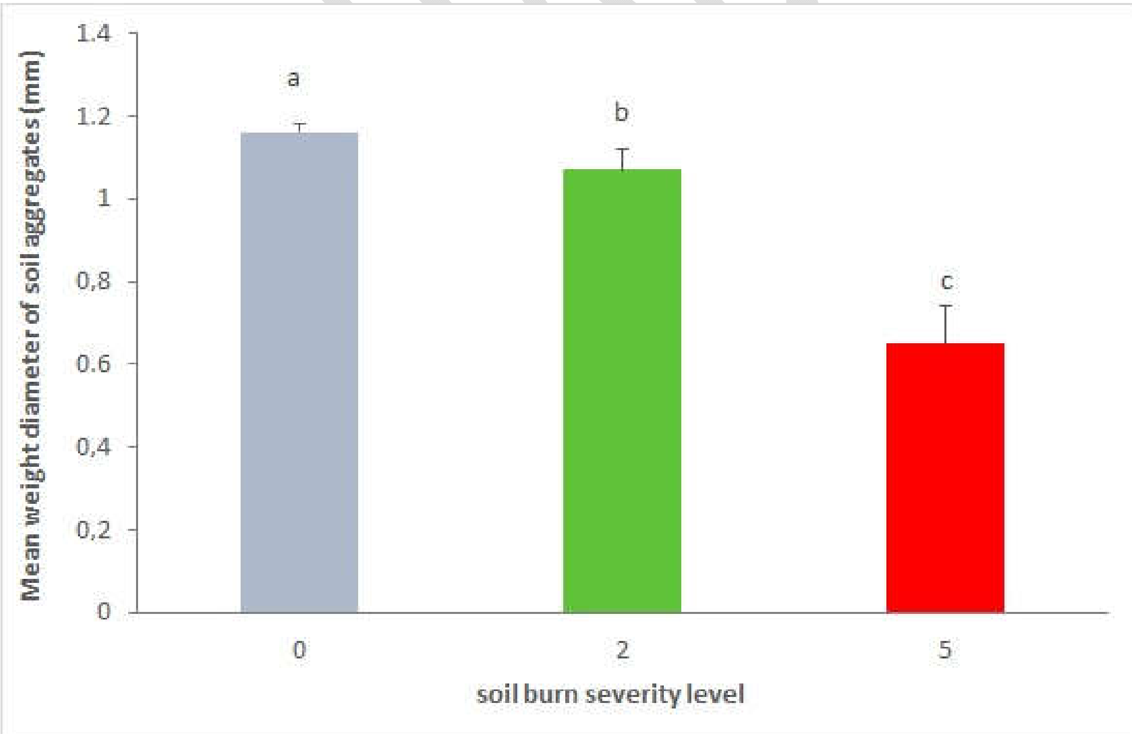

Figure 18. Mean weight diameter of soil aggregates (mm) of soil samples (0-2 cm) classified by level of soil burn severity (0, 2 and 5). Bars are standard errors. Different letters indicate statistically significant differences between soil burn severities (Mann-Whitney test, p<0.05).

8.2.3. Conclusions

The first series of experiments on the burning bench exhibited the capital role played by the moisture content of the forest floor and the upper mineral soil layer to explain the maximum temperatures reached during burning in mineral soil and in elevated temperature duration. These results also underline the relevance of pre-fire duff depth and initial soil C content to explain soil C consumption under dry soil and duff conditions. In contrast, when the moisture content in forest floors and topsoil was high, this reduction was limited at both sites. Our results also suggest that in Mediterranean forest soils with low duff depth and soil C content, high soil C consumptions should not be expected, not even under drought conditions. In contrast in Atlantic forest soils, high duff depth and high soil C content values enhance prolonged high temperature durations, which lead to major reductions in soil C.

The second burning experiments reflected the good agreement between the thermal regime during burning and the visual signs of two verified soil burn severity levels. These different levels were also associated clearly with distinct changes in soil C content, soil water repellency and the mean diameter of aggregates, which suggests the utility of the employed soil burn severity classification system. Interestingly, water repellency was totally destroyed at the highest severity level, which indicates great soil heating penetration. This, along with the dramatic soil C consumption and the significant drop in the mean diameter of soil aggregates, clearly suggests strong susceptibility to soil erosion at that burn severity level. Future actions should focus on the mid- and long-term effects of the alterations observed, along with the influence on rain infiltration capacity in burned soils and runoff generation.

ACKNOWLEDGMENTS

The authors thank Helen Warburton for editing the English. This work was funded by the Spanish Institute for Agricultural and Food Research and Technology (INIA) through the awarded National Research Project GEPRIF (RTA2014-00011-C06), and was also co-financed by FEDER funds.

REFERENCES

Agee JK (1996) The influence of forest structure on fire behavior. In *Proceedings of the 17th Annual forest vegetation management conference.* 16-18 January, Redding, California, USA. Pp 52-68,

Alloza JA, García S, Gimeno T, Baeza MJ, Vallejo VR (2014) *Guía técnica para la gestión de montes quemados*. Ministerio de Agricultura, Alimentación y Medio Ambiente, Madrid.

Allué JL (1990) *Atlas fitoclimático de España*.Taxonomías. INIA-MAPA.Madrid.

Araya SN, Meding M, Berhe AA (2016) Thermal alteration of soil physico-chemical properties: a systematic study to infer response of Sierra Nevada climosequence soils to forest fires. *Soil* **2**,351-366.

Arcenegui V, Mataix-Solera J, Zornoza R, Pérez-Bejarano A, Mataix-Beneyto J, Gómez I (2010) Estimation of the maximum temperature reached in burned soils using near-infrared spectroscopy: Effects of soil sample pre-treatments. *Geoderma* **158** (1), 85-92.

Aznar JM, González-Pérez JA, Badía D, Martí C (2016) At what depth are the properties of a gypseous forest topsoil affected by burning? *Land Degradation and Development* **27**, 1344-1353.

Benavides-Solorio J, MacDonald LH (2005) Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* **14**, 457-474.

Bodí M, Martin D, Balfour V, Santín C, Doerr S, Pereira P, Cerdà A, Mataix-Solera J (2014) Wildland fire ash: Production, composition and eco-hydro-geomorphic effects. *Earth-Science Reviews* **130**, 103-127

Brotons L, Aquilué N, de Cáceres M, Fortin MJ, Fall A (2013) How Fire History, Fire Suppression Practices and Climate Change Affect Wildfire Regimes in Mediterranean Landscapes. *Plos One* **8 (5)**, e62392.

Cancelo-González J, Rial-Rivas ME, Barros N, Díaz-Fierros F (2012) Assessment of the impact of soil heating on soil cations using the degree-hours method. *Spanish Journal Soil Science* **2(3)**, 32-44

Cawson JG, Sheridan GJ, Smith HG, Lane PNJ (2013) Effects of fire severity and burn patchiness on hillslope-scale surface runoff, erosion and hydrologic connectivity in a prescribed burn. *Forest Ecology and Management* **310**, 219-233.

Cansler CA, McKenzie D (2012) How robust are burn severity indices when applied in a new region? Evaluation of alternate field-based and remote-sensing methods. *Remote Sensing* **4**, 456-483.

Cerdà A, Doerr SH (2005) The influence of vegetation recovery on soil hydrology and erodibility following fire: an eleven-year investigation. *International Journal of Wildland Fire* **14**, 423-437.

Cerdà A, Doerr SH (2008) The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *Catena* **74 (3),** 256-263.

Cerdà A, Robichaud PR (2009) Fire Effects on Soil Infiltration.In *Fire Effects on Soils and Restoration Strategies* (Eds A Cerdà, PR Robichaud). Pp 81-104. Science Publishers, Enfield.

Chafer CJ, Noonan M, Macnaught E (2004) The post-fire measurement of fire severity and intensity in the Christmas 2001 Sydney wildfires. *International Journal of Wildland Fire* **13**, 227–240

Chafer CJ (2008) A comparison of fire severity measures: An Australian example and implications for predicting major areas of soil erosion. *Catena* **74**, 235–245.

Chu T, Guo X (2014) Remote Sensing Techniques in Monitoring Post-Fire Effects and Patterns of Forest Recovery in Boreal Forest Regions: A Review. *Remote Sensing* **6(1)**, 470-520.

Chuvieco E, Riano D, Danson FM, Martin P (2006). Use of a radiative transfer model to simulate the postfire spectral response to burn severity. *Journal of Geophysical Research-Biogeosciences* **111**, G04S09.

DeBano LF, Neary DG, Ffolliott PF (1998) *Fire's effects on ecosystems*. John Wiley and Sons, Inc. New York.

DeBano LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **231–232**, 195–206.

Dehane B, Madrigal J, Hernando C, Bouhraoua R, Guijarro M (2015) New bench-scale protocols for characterizing bark flammability and fire resistance in trees: Application to Algerian cork. *Journal Fire Science* **33(3)**, 202-217.

DellaSala DA, Hanson CT, Baker WL, Hutto RL, Halsey RW, Odion DC, Berry LE, Abrams RW, Heneberg P, Sitters H (2015) Flight of the Phoenix: Coexisting with Mixed-Severity Fires. In *The Ecological Importance of Mixed-Severity Fires* (Eds DA DellaSala, CT Hanson) pp 372-396. Elsevier.

De Santis A, Chuvieco E (2007) Burn severity estimation from remotely sensed data: Performance of simulation versus empirical models. *Remote Sensing of Environment* **108(4)**,422-435.

De Santis A, Chuvieco E (2009) GeoCBI: A modified version of the Composite Burn Index for the initial assessment of the short-term burn severity from remotely sensed data. *Remote Sensing Environment* **113**, 554–562.

Doblas-Miranda E, Martínez-Vilalta J, Lloret F, Álvarez A, Ávila A, Bonet FJ, Brotons L, Castro J, Curiel Yuste J, Díaz M, Ferrandis P, García-Hurtado E, Iriondo JM, Keenan TF, Latron J, Llusià J, Loepfe L, Mayol M, Moré G, Moya D, Peñuelas J, Pons X, Poyatos R, Sardans J, Sus O, Vallejo VR, Vayreda J, Retana J (2015) Reassessing global change research priorities in mediterranean terrestrial ecosystems: how far have we come and where do we go from here? *Global Ecology and Biogeography* **24 (1)**, 25-43.

Doblas-Miranda E, Alonso R, Arnan X, Bermejo V, Brotons L, de las Heras J, Estiarte M, Hódar JA, Llorens P, Lloret F, López-Serrano FR, Martínez-Vilalta J, Moya D, Peñuelas J, Pino J, Rodrigo A, Roura-Pascual N, Valladares F, Vilà M, Zamora R, Retana J (2017) A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: Beyond drought effects. *Global and Planetary Change* **148**, 42-54.

Doerr SH, Blake WH, Shakesby RA, Stagnitti F, Vuurens SH, Humphreys GS, Wallbrink P (2004) Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. *International Journal of Wildland Fire* **13**, 157-163.

Doerr SH, Dekker LW, Ritsema CJ, Shakesby RA, Bryant R (2002) Water repellency of soils: The influence of ambient relative humidity. *Soil Science Society American Journal* **66**, 401-405.

Enninful E, Torvi D (2008) A variable property heat transfer model for predicting soil temperature profiles during simulated wildland fire conditions. *International Journal of Wildland Fire* **17 (2)**, 205.

Enright NJ, Fontaine JB, Lamont BB, Miller BP, Westcott VC (2014) Resistance and resilience to changing climate and fire regime depend on plant functional traits. *Journal Ecology* **102**, 1572–1581.

Escuin S, Navarro R, Fernández P (2008) Fire severity assessment by using NBR (normalized burn ratio) and NDVI (normalized difference vegetation index) derived from LANDSAT TM/ETM images. *International Journal Remote Sensing* **29**, 1053–1073.

Fernández C, Vega JA (2016) Modelling the effect of soil burn severity on soil erosion at hillslope scale in the first year following wildfire in NW Spain. *Earth Surface Processes and Landforms* **41**, 928-935.

Flannigan MD, Stocks BJ, Wotton BM (2000) Climate change and forest fires. *Science of the Total Environment* **262 (3)**, 221-229.

Fonturbel MT, Vega JA, Pérez-Gorostiaga P, Fernández C, Alonso M, Cuiñas P, Jiménez E (2011) Effects of soil burn severity on germination and initial establishment of maritime pine seedlings in two contrasting experimentally burned soils. *International Journal Wildland Fire* **20**, 209-222.

Fonturbel T, Fernandez C, Vega JA (2016) Prescribed burning versus mechanical treatments as shrubland management options in NW Spain: Mid-term soil microbial response. *Applied Soil Ecology* **107**, 334-346.

Frandsen WH, Ryan KC (1986) Soil moisture reduces belowground heat flux and soil temperature under a burning fuel pile. *Canadian Journal of Forest Research* **16**, 244–248.

García-Corona R, Benito E, de Blas E, Varela ME (2004) Effects of heating on some soil physical properties related to its hydrological behaviour in two north-western Spanish soils. *International Journal Wildland Fire* **13**, 195-199.

García-Oliva F, Merino A, Fonturbel MT, Omil B, Fernández C, Vega JA (2018) Severe wildfire hinders renewal of soil P pools by thermal mineralization of organic P in forest soil: analysis by sequential extraction and 31P NMR spectroscopy. *Geoderma* **309**, 32-40.

Gonzalez-De Vega S, de las Heras J, Moya D (2016) Resilience of Mediterranean terrestrial ecosystems and fire severity in semiarid areas: Responses of Aleppo pine forests in the short, mid and long term. *Science of the Total Environment* **573**, 1171-1177.

González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter—a review. *Environment International* **30 (6)**, 855-870.

Grau-André R, Davies GM, Waldron S, Scott EM, Gray A (2017) Leaving moss and litter layers undisturbed reduces the short-term environmental consequences of heathland managed burns. *Journal of Environmental Management* **204**, 102-110.

Hudak AT, Morgan P, Bobbitt MJ, Smith AMS, Lewis SA, Lentile LB, Robichaud PR, Clark JT, McKinley RA (2007) The Relationship of Satellite Imagery to Fire Effects. *Fire Ecology* **3 (1)**, 64-90.

Jain TB, Gould WA, Graham RT, Pilliod DS, Lentile LB, Gonzalez G (2008) A soil burn severity index for understanding soil-fire relations in tropical forests. *AMBIO: A Journal of the Human Environment* **37(7-8)**, 563-568.

Jiménez-Pinilla P, Lozano E, Mataix-Solera J, Arcenegui V, Jordán A, Zavala LM (2016) Temporal changes in soil water repellency after a forest fire in a Mediterranean calcareous soil: Influence of ash and different vegetation type. *Science of The Total Environment* **572**, 1252-1260.

Keane RE, Burgan R, van Wagtendonk J (2001) Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. *International Journal WildlandFire* **10 (4)**, 301-319.

Keeley JE (1991) Seed Germination and Life History Syndromes in the California Chaparral. *Botanical Review* **57 (2)**, 81-116.

Keeley JE (2009) Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of WildlandFire* **18(1)**,116-126

Keeley JE, Brennan TJ, Pfaff AH (2008) Fire Severity and ecosystem responses from crown fires in California shrublands. *Ecology Applied* **18 (6)**, 1530–1546

Keeley JE, Bond WJ, Bradstock RA, Pausas JG, Rundel PW (2012) *Fire in Mediterranean Ecosystems: Ecology, Evolution and Management*. Cambridge University Press.

Kemper WD, Rosenau RC (1986) Aggregate stability and size distribution. In *Methods of soil analysis* (Ed A Klute) *Agronomic Monographies* **9,** 425–442. ASA, Madison, WI.

Key CH, Benson NC (2003) *The composite burn index (CBI): field rating of burn severity*. US Geological Survey Northern Rocky Mountain Science Center. US Department of the Interior, Geological Survey, Northern Rocky Mountain Science Center.

Key CH, Benson NC (2005) Landscape assessment: ground measure of severity, the Composite Burn Index. In *FIREMON: Fire effects monitoring and inventory system. General Technical Report, RMRS-GTR-164-CD: LA1-LA51* (Ed DC Lutes) Ogden, UT: USDA Forest Service, Rocky Mountain Research Station.

King PM (1981) Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Australian Journal Soil Research* **19**, 275-285.

Klopatek CC, DeBano LF, Klopatek JM (1990) Impact of fire on the microbial processes in pinyon±juniper woodlands: management implications. In *Effects of Fire Management of Southwestern Natural Resources. USDA For. Serv. Gen. Tech. Rep. RM-191*. pp 197-205.

Legg CJ, Maltby E, Proctor MCF (1992) The ecology of severe moorland fire on the North York Moors: seed distribution and seedling establishment of *Calluna vulgaris*. *Journal Ecology* **80**, 737-752.

Lombao A, Barreiro A, Cancelo-González J (2015) Impact of thermal shock on forest soils affected by fires of different severity and recurrence. *Spanish Journal Soil Science* **5 (2)**, 165-179.

Lopez Garcia MJ, Caselles V (1991) Mapping burns and natural reforestation using Thematic Mapper data. *Geocarto International* **6**, 31-37.

López-Poma R, Bautista S (2014) Plant regeneration functional groups modulate the response to fire of soil enzyme activities in a Mediterranean shrubland. *Soil Biology and Biochemistry* **79**, 5–13.

Lucas-Borja ME, Madrigal J, Candel-Pérez D, Jiménez E, Moya D, de las Heras J, Guijarro M, Vega JA, Fernández C, Hernando C (2016) Effects of prescribed burning, vegetation treatment and seed predation on natural regeneration of Spanish Black pine (*Pinus nigra* Arn, ssp.salzmannii) in pure and mixed forest stands. *Forest Ecology Management* **378**, 24-30

Maia P, Pausas JG, Arcenegui V, Guerrero C, Pérez-Bejarano A, Mataix-Solera J, Varela MET, Fernandes I, Pedrosa ET, Keizer JJ (2012) Wildfire effects on the soil seed bank of a maritime pine stand-The importance of fire severity. *Geoderma* **191**, 80-88

Madrigal J, Hernando C, Guijarro M, De Castro A, Díez C, Marino E (2009) Evaluation of forest fuel flammability and combustion properties with an adapted Mass Loss Calorimeter device. *Journal Fire Science* **27(4)**, 323-342.

Madrigal J, Hernando C, Guijarro M, Vega JA, Fonturbel T, Perez-Gorostiaga P (2010) Smouldering fire-induced changes in a Mediterranean soil (SE Spain): effects on germination, survival and morphological traits of 3-year-old *Pinus pinaster* Ait. *Plant Ecology* **208**, 279–292.

Madrigal J, Guijarro M, Hernando C, Díez C, Marino E (2011) Effective heat of combustion for flaming combustion of Mediterranean forest fuels. *Fire Technology* **47(2)**, 461-474

Madrigal J, Hernando C, Guijarro M (2012) A new bench-scale methodology for evaluating flammability of live forest fuels. *Journal Fire Science* **31(2)**, 131-142.

Martinez-Sanchez JJ, Ferrandis P, De las Heras J, Herranz JM (1999) Effect of burnt wood removal on the natural regeneration of *Pinus halepensis* after fire in a pine forest in Tus valley (SE Spain). *Forest Ecology and Management* **123**, 1–10.

Mataix-Solera J, Doerr SH (2004) Hydrophobicity and aggregate stability in calcareous topsoil from fire affected pine forests in southeastern Spain. *Geoderma* **118**, 77-88.

Mataix-Solera J, Cerdà A, Arcenegui V, Jordán A, Zavala LM (2011) Fire effects on soil aggregation: a review. *Earth-Science Reviews* **109 (1)**, 44-60.

Mavsar R, Varela E, Corona P, Barbati A, Marsh G (2012) Economic, legal and social aspects of post-fire management. In *Post-Fire Management and Restoration of Southern European Forests* (Eds F Moreira, M Arianoustsou, P Corona, J de las Heras) *Managing Forest Ecosystems* **24**, 45-78.

Montorio Llovería R, Pérez-Cabello F, García-Martín A, Vlassova L, de la Riva Fernández J (2014) La severidad del fuego: revisión de conceptos, métodos y efectos ambientales. In *Geoecología, cambio ambiental y paisaje: homenaje al profesor José María García-Ruiz* (Eds J Arnáez, P González-Sampériz, T Lasanta, BL Valero) pp 427-440. IPE-CSIC y Universidad de La Rioja, Arnedo.

Moreno JM, Oechel WC (1989) A simple method for estimating fire intensity after a burn in California chaparral. *Acta Oecologica* **10**, 57–68.

Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, Leonard J, McCaffrey S, Odion DC, Schoennagel T, Syphard AD (2014) Learning to coexist with wildfire. *Nature* **515(7525)**, 58-66.

Moya D, Plaza-Álvarez PA, Sagra J, Lozano E, Alfaro-Sánchez R, Lucas-Borja ME, Arcenegui V, Morugán-Coronado A, Ferrandis P, García-Orenes F, Mataix-Solera J, de las Heras J (2017) Quemas controladas en planta piloto ecotron forestal Mediterráneo: variacion de actividad enzimatica y glomalina por severidad. In *Proceedings of 7º Congreso Forestal Español*, Avila (Spain).

Moya D, De las Heras J, Lopez-Serrano FR, Leone V (2008) Optimal intensity and age of management in young Aleppo pine stands for post-fire resilience. *Forest Ecology and Management* **255**, 3270–3280.

Naeem S, Lawton JH, Thompson LJ, Lawler SP, Woodfin RW (1995) Biotic diversity and ecosystem processes: using the Ecotron to study a complex relationship. *Endeavour* **19 (2)**, 58-63.

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology Management* **122**, 51-71.

Neary DG, Ryan KC, DeBano LF (2005) Wildland fire in ecosystems: effects of fire on soils and water. In *Gen.Tech.Rep. RMRS-GTR-42 (4)*. Ogden, UT: U S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.250 p.

NWCG (2006) Glossary of wildland fire terminology. National Wildfire Coordinating Group, Incident Operations Standards Working Team, <http://www.nwcg.gov/pms/pubs/glossary/index.htm>.

Parsons A, Robichaud PR, Lewis SA, Napper C, Clark JT (2010) Field guide for mapping post-fire soil burn severity. In *Gen. Tech. Rep. RMRS-GTR-243*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.49 p

Parks SA, Dillon GK, Miller C (2014) A new metric for quantifying burn severity: The Relativized Burn Ratio. *Remote Sensing* **6**, 1827-1844.

Pereira P, Úbeda X (2010) Spatial distribution of heavy metals released from ashes after a wildfire. *Journal of Environmental Engineering and Landscape Management* **18 (1)**, 13-22.

Pereira P, Ubeda X, Martin D, Mataix-Solera J, Cerdà A, Burguet M (2014) Wildfire effects on extractable elements in ash from a Pinus pinaster forest in Portugal. *Hydrological Processes* **28 (11)**, 1099-1085.

Pérez B, Moreno JM (1998) Methods for Quantifying Fire Severity in Shrubland-Fires. *Plant Ecology* **139 (1)**, 91-101

Pérez-Cabello F, Cerdà A, de la Riva J, Echeverría MT, García-Martín A, Ibarra P, Lasanta T, Montorio R, Palacios V (2012) Micro-scale post-fire surface cover changes monitored using high spatial resolution photography in a semiarid environment: A useful tool in the study of post-fire soil erosion processes. *Journal of Arid Environments* **76**, 88-96.

Plaza-Álvarez P, Sagra J, Moya D, Lucas-Borja ME, Alfaro-Sánchez R, de las Heras J (2017) Effects of low intensity prescribed burnings on soil infiltration and water repellency in a Mediterranean pine forest. *Forests* **8 (7)**, 248.

Pourreza M, Mohsen Hosseini S, Sinegani AAS, Matinizadeh M, Dick WA (2014) Soil microbial activity in response to fire severity in Zagros oak (Lindl.) forests, Iran, after one year. *Geoderma* **213**, 95-102.

Regueira N, Benito E, Fontúrbel MT, Fernandez C, Jiménez E, Vega JA (2015) Efectos de quemas experimentales de diferente severidad en el carbono orgánico y en las propiedades físicas del suelo. *Flamma* **6(3)**, 129-133.

Rein G, Cleaver N, Ashton C, Pironi P, Torero JL (2009) The severity of smouldering peat fires and damage to the forest soil. *Catena* **78**, 304-306.

Robichaud PR, Lewis SA, Ashmun LE (2008) New procedure for sampling infiltration to assess post-fire soil water repellency. *Research Note RMRS-RN-33*. Fort Collins, CO: U S.Department of Agriculture, Forest Service, Rocky Mountain Research Station. 14 p.

Rodríguez-Alleres M, Benito E, de Blas E (2007) Extent and persistence of water repellency in north-western Spanish soils. *Hydrological Processes* **21**, 2291-2299.

Rodríguez-Alleres M, Varela ME, Benito E (2012) Natural severity of water repellency in pine forest soils from NW Spain and influence of wildfire severity on its persistence. *Geoderma* **191**, 125-131.

Rollins MG (2009) LANDFIRE: a nationally consistent vegetation, wildland fire and fuel assessment. *International Journal of WildlandFire* **18**, 235–249.

Ryan KC, Noste NV (1985) *Evaluating prescribed fires.In 'Proceedings, Symposium and Workshop on Wilderness Fire*. 15–18 November 1983, Missoula, MT (Eds JE Lotan, BM Kilgore, WC Fischer, RW Mutch) pp 230–238. USDA Forest Service, Intermountain Forest and Range Experiment Station, *General Technical Report INT-182*, Missoula, MT.

Ryan KC, Jones AT, Koerner CL, Lee KM (2012) Wildland fire in ecosystems: effects of fire on cultural resources and archaeology. *Gen. Tech. Rep. RMRS-GTR-42-3*. Fort Collins, CO: U S.Department of Agriculture, Forest Service, Rocky Mountain Research Station.224 p.

Sagra J, Plaza-Álvarez PA, Moya D, Lucas-Borja ME, Alfaro-Sánchez R, de las Heras J, Ferrandis P (2017) Predation influence on seedling recruitment in Mediterranean forests after prescribed burning. *Forests* **8(7)**, 243.

Schepers L, Haest B, Veraverbeke S, Spanhove T, Vanden Borre J, Goossens R (2014) Burned Area Detection and Burn Severity Assessment of a Heathland Fire in Belgium Using Airborne Imaging Spectroscopy (APEX). *Remote Sensing* **6**, 1803-1826.

Smith AMS, Sparks AM, Kolden CA, Abatzoglou JT, Talhelm AF, Johnson DM, Boschetti L, Lutz JA, Apostol KA, Yedinak KM, Tinkham WT, Kremens RL (2016) Towards a new paradigm in fire severity research using dose-response experiments. *International Journal of WildlandFire* **25(2)**, 158-166.

Sommers WT, Stanley GC, Conard SG (2011) *Fire History and Climate Change*. Joint Fire Science Program, Project 09-2-01-09.pp 190.

Úbeda X, Pereira P, Outeiro L, Martin DA (2009) Effects of fire temperature on the physical and chemical characteristics of the ash from two plots of cork oak (*Quercus suber*). *Land Degradation Development* **20,** 589–608.

Vallejo VR, Arianoutsou M, Moreira F (2012) Fire Ecology and Post-Fire Restoration Approaches. In Southern European Forest Types. In *Post-Fire Management and Restoration of Southern European Forests* (Eds F Moreira, M Arianoustsou, P Corona, J de las Heras) *Managing Forest Ecosystems* **24**, 93-119.

Varela ME, Benito E, De Blas E (2005) Impact of wildfires on surface water repellency in soils of northwest Spain. *Hydrological Processes* **19**, 3649-3657.

Varela ME, Benito E, Keizer JJ (2010) Effects of wildfire and laboratory heating on soil aggregate stability of pine forests in Galicia: The role of lithology, soil organic matter content and water repellency. *Catena* **83**, 127-134.

Vega JA, Fernández C, Fonturbel T (2005) Throughfall, runoff and soil erosion after prescribed burning in gorse shrubland in Galicia (NW Spain). *Land Degradation Development* **15**, 1-15.

Vega JA, Fontúrbel T, Fernández C, Díaz-Raviña M, Carballas T, Martín A, González-Prieto S, Merino A, Benito E (2013a) *Acciones urgentes contra la erosión en áreas forestales quemadas. Guía para su planificación en Galicia*. Centro de Investigación Forestal de Lourizán (Consellería do Medio Rural e do Mar, Xunta de Galícia), Instituto de Investigaciones Agrobiológicas de Galicia del CSIC (IIAG-CSIC), Universidad de Santiago de Compostela, Universidad de Vigo.FUEGORED. Santiago de Compostela. 139 pp

Vega JA, Fontúrbel T, Merino A, Fernández C, Ferreiro A, Jimenez E (2013b) Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical and microbial properties in pine forests and shrubland. *Plant and Soil* **369 (1)**, 73-91.

Veraverbeke S, Hook S, Hulley G (2012) An alternative spectral index for rapid fire severity assessments. *Remote Sensing of Environment* **123**, 72-80.

Vieira DCS, Fernández C, Vega JA, Keizer JJ (2015) Does soil burn severity affect the post-fire runoff and interrill erosion response? A review based on meta-analysis of field rainfall simulation data. *Journal of Hydrology* **523**, 452-464.

Wieting C, Ebel BA, Singha K (2017) Quantifying the effects of wildfire on changes in soil properties by surface burning of soils from the Boulder Creek Critical Zone Observatory. *Journal of Hydrology: Regional Studies* **13**, 43-57.

Zavala LM, de Celis R, Jordán A (2014) How wildfires affect soil properties. A brief review. *Cuadernos de Investigación Geográfica* **40 (2)**, 311-331.