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Small variations in soil properties control fire-induced water repellency

La repelencia al agua inducida por el fuego está controlada por pequeñas variaciones en las propiedades del suelo
Controlo por pequenas alterações nas propriedades do solo da repelência de água induzida através do fogo

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ABSTRACT

Fire induced soil water repellency (WR) is controlled by many different factors (temperature reached, amount and type of fuel, etc.). Soil properties may determine the occurrence and intensity of this property in burned soils. The objectives of this paper are to make advances in the study of soil properties as key factors controlling the behaviour of fire-induced WR, and to study the impact of pre-fire SOM content and SOM quality in fire-induced soil WR. In this research, experimental laboratory burnings were carried out using soil samples from different sites with different lithologies, soil types and plant species. Soil samples from the same site differ only in quantity and quality of soil organic matter, as they were collected from under different plant species. All soil samples were heated in a muffle furnace at 200, 250, 300 and 350 ºC without the addition of any fuel load. WR was measured using the water drop penetration time test (WDPT). The results showed significant differences between soil types and plant species, indicating that small differences in soil properties may act as key factors controlling the development and persistence of WR reached, with burned soil samples ranging from wettable to extremely water repellent. The main soil property controlling the response was texture, specifically sand content. The quality of organic matter was also observed to have an effect, since soil samples from the same site with similar organic matter contents, but collected from beneath different plant species, showed different WR values after burning.

RESUMEN

La repelencia al agua (WR) inducida por el fuego es una propiedad controlada por muchos factores diferentes (temperaturas alcanzadas, cantidad y tipo de combustible, etc.). Algunas propiedades del suelo pueden determinar la presencia y la intensidad de esta propiedad en los suelos quemados. Los objetivos principales son: avanzar en el estudio de la influencia de algunas propiedades clave en el control del comportamiento de la WR en suelos quemados, así como estudiar la influencia de la cantidad y la calidad de la materia orgánica del suelo en su desarrollo cuando es afectada por el calentamiento. En éste estudio, hemos realizado quemas controladas en laboratorio utilizando muestras de suelo de diferentes sitios con litologías y tipos de suelos diferentes y recogidas bajo distintas especies vegetales. Las muestras recogidas en diferentes sitios difieren en algunas propiedades del suelo, mientras que las muestras de suelo tomadas del mismo sitio sólo se diferencian en la cantidad y la calidad de la materia orgánica del suelo, ya que se recogieron bajo distintas especies de plantas. Todas las muestras de suelo se calentaron en horno de mufla a 200, 250, 300 y 350 ºC. La repelencia al agua se midió mediante el test del tiempo de penetración de la gota de agua (WDPT). Los resultados mostraron diferencias significativas entre los tipos de suelos y especies vegetales, y se comprobó que pequeñas diferencias en algunas propiedades del suelo pueden actuar como factores clave controlando el desarrollo y persistencia de la repelencia al agua, con muestras de suelo quemadas que variaban entre hidrofílicas a extremadamente repelentes al agua. La propiedad que principalmente controló el comportamiento de la repelencia al calentamiento fue la textura y más concretamente el contenido de arena. Por otro lado se observó que la calidad de la materia orgánica también afecta, ya que muestras de suelo de mismo sitio y con contenido de materia orgánica similar, pero tomadas bajo diferentes especies vegetales mostraron valores muy diferentes de repelencia al agua tras la quema.

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RESUMO

A repelência à água (WR) induzida no solo pelo fogo é uma propriedade controlada por diversos fatores (temperatura atingida, quantidade e tipo de combustível, etc.). Algumas propriedades podem determinar a presença e intensidade da WR nos solos afetados pelo fogo. O objetivo deste artigo é demonstrar os últimos avanços no estudo das propriedades do solo, como factores chave, que controlam o comportamento da hidrofobicidade induzida pelo fogo, o impacto do conteúdo de matéria orgânica pré-fogo e a qualidade da matéria orgânica em solos afetados por repelência pós-incêndio. Neste estudo, foram realizadas queimadas controladas em laboratório, utilizando amostras de solo de locais com diferentes substratos litológicos e com diferentes tipos de solo, colonizados por diferentes espécies vegetais. As amostras recolhidas em diferentes locais diferem nalgumas propriedades do solo, enquanto as amostras de solo recolhidas no mesmo local apenas diferem na quantidade e qualidade da matéria orgânica, dado que foram recolhidas em áreas colonizadas por diferentes espécies de plantas. Todas as amostras foram submetidas às temperaturas de 200, 250, 300 e 350 °C num forno. A WR foi medida através do teste da gota de água (WDPT). Os resultados mostraram diferenças significativas entre os tipos de solos e plantas estudadas. Observaram-se pequenas diferenças em algumas propriedades do solo, que podem atuar como fatores-chave que controlam o desenvolvimento e persistência da WR nos solos queimados, que variam entre o hidrofílico e o extremamente repelente à água. A propriedade que mais influencia o comportamento da WR é a textura, especialmente o teor em areia. Por outro lado, observou-se que a qualidade da matéria orgânica também afetou a WR, dado que em amostras de solo recolhidas no mesmo local e com conteúdo em matéria orgânica semelhante, mas recolhidas em solos colonizados por diferentes espécies de plantas, mostraram valores muito diferentes de repelência à água após a queimada.

KEY WORDS
Forest fire, soil heating, hydrology, hydrophobicity, organic matter quality

PALABRAS CLAVE
Incendio forestal, calentamiento del suelo, hidrofobicidad, hidrología, calidad de la materia orgánica

PALAVRAS-CHAVE
Incêndio Florestal, aquecimento do solo, hidrofobia, hidrologia, qualidade da matéria orgânica

1. Introduction

Water repellency (WR) is a property of soils that can occur under natural conditions (Mataix-Solera et al. 2007; Lozano et al. 2013; Jordán et al. 2013) but it is one that is usually induced or enhanced as a result of forest fires in Mediterranean environments (Mataix-Solera and Doerr 2004; Arcenegui et al. 2008; Zavala et al. 2009a). In fire-affected soils, the presence and degree of WR is controlled by many different factors, such as the temperatures reached in the soil (DeBano and Krammes 1966; Doerr et al. 2004; García-Corona et al. 2004; Dlapa et al. 2008; Jordán et al. 2011), the amount and type of fuel (Arcenegui et al. 2007; Granged et al. 2011), the vegetation type (Jordán et al. 2009; Mataix-Solera et al. 2007; Zavala et al. 2009a, 2009b) or the type of ash and degree of combustion (Bodí et al. 2011). Recently it has been proved that some soil properties may also determine the occurrence and intensity of this property in burned soils. For example, Mataix-Solera et al. (2008) confirmed under laboratory burning conditions that terra rossa soils showed very low susceptibility to develop WR by burning. They concluded that this process is controlled by different soil properties, such as organic matter and clay content and, even more importantly, clay mineralogy, as it was found that kaolinite content was the key factor controlling the occurrence of fire-induced WR in terra rossa soils. Recent studies in areas affected by wildfires in Spain and Israel have confirmed this behaviour (Mataix-Solera et al. 2013).

An unanswered question is whether the quality of pre-existing organic matter can influence the development and degree of WR after burning. This research aims to shed light on this issue. Our initial hypothesis is that plant species must have an influence, as WR occurs in unburned soils (Mataix-Solera et al. 2007), not only because of the soil organic matter (SOM) content, but also depending on its quality (Lozano et al. 2013). Soil heating affects not only SOM content (Mataix-Solera et al. 2002; Mataix-Solera et al. 2011) but also its quality (Almendros and González-Vila 2012). These changes may vary depending on the initial SOM quality and condition, the occurrence and degree of post-burn soil WR and soil properties.

In this research, experimental laboratory burnings were carried out using soil samples collected from different sites under different Mediterranean plant species. Samples collected from different sites differ in some soil properties, while soil samples from the same site were collected under different plant species, with varying content and quality of SOM. Our hypothesis is that the same heating treatment will produce different responses of WR depending on soil type and plant species. The objectives of this paper are [i] to make advances in the study of soil properties as key factors controlling the behaviour of fire-induced WR, as some gaps exist in current knowledge, [ii] to study the impact of pre-fire SOM content and [iii] SOM quality in fire-induced soil WR.

2. Materials and Methods

2.1. Soil sampling

Three sites were selected for this study (1 in Cádiz, S Spain, and 2 in Alicante, E Spain) comprising 4 different lithologies (**Table 1**). Twelve soil samples (0-2.5 cm depth) were collected under different plant species (*Pinus halepensis, Pinus pinaster, Quercus coccifera, Quercus suber, Rosmarinus officinalis, Juniperus oxycedrus, Erica australis, Pistacia lentiscus* and *Olea europaea*); **Table 1**.

In each area we made a soil sampling to collect a representative sample per site by collecting different subsamples from different points (n=20). Samples HF1 to HF5 were collected from different soil types (Lithic Xerorthents, Typic Haploxerolls and Typic Haploxeralfs) developed from Miocene sandstone and clay substrates (Didon 1960-1962) in "Los Alcornocales" Natural Park (Cádiz, S Spain), between 294 and 598 m.a.s.l. with a mean annual rainfall of 1440 mm. Dominant vegetation species are cork oak (*Q. suber*), heath (*E. australis*), mastic (*P. lentiscus*), maritime pine (*P. pinaster*) and olive

Table 1. General description and location of study sites

Location	Coordinates	Elevation (m.a.s.l.)	Slope (%)	Mean annual rainfall (mm)	Lithology	Soil type (Soil Survey Staff 2006)	Dominant plant species	Sample Code
"Los Alcornocales" Natural Park, Cádiz	36°29'44''N 5°38'53''W	483	6.5	1440	Miocene sandstone	Lithic Xerorthent	*Erica australis*	HF1
	36°27'27''N 5°37'49''W	294	13.7	1440			*Pinus pinaster*	HF2
	36°30'53''N 5°38'29''W	538	14.4	1440		Typic Haploxeroll	*Quercus suber*	HF3
	36°28'23''N 5°37'13''W	397	5.6	1440	Miocene clay and sandstone	Typic Haploxeralf	*Pistacia lentiscus*	HF4
	36°28'23''N 5°37'13''W	398	8.5	1440			*Olea europaea*	HF5
"Sierra de la Taja", Pinoso, Alicante	38°22'59''N 0°58'52''W	803	3.5	260	Jurassic limestone	Lithic Xerorthent	*Pinus halepensis*	HF6
							Quercus coccifera	HF7
							Juniperus oxycedrus	HF8
							Rosmarinus officinalis	HF9
"Sierra de la Grana", La Torre de les Maçanes, Alicante	38°35'54''N 0°23'33''W	951	2.2	405	Tertiary limestone	Typic Xerorthent	*Quercus coccifera*	HF10
							Juniperus oxycedrus	HF11
							Pinus halepensis	HF12

tree (*O. europaea*). Samples HF6 to HF9 were collected from Lithic Xerorthents developed from Jurassic limestones in Sierra de la Taja (Alicante, E Spain), under Aleppo pine (*P. halepensis*), Kermes oak (*Q. coccifera*), prickly juniper (*J. oxycedrus*) and rosemary (*R. officinalis*). Finally, samples HF10 to HF12 were collected from Typic Xerorthents developed from Tertiary limestones in Sierra de la Grana (Alicante, E Spain) under Aleppo pine (*P. halepensis*), Kermes oak (*Q. coccifera*) and prickly juniper (*J. oxycedrus*).

2.2. Soil characterization

Soil characterization was carried out on air-dried and sieved (2 mm) samples and included pH (1:2.5 w/v, distilled water); electrical conductivity (EC; 1:5 w/v, distilled water); texture (Bouyoucos method; Gee and Bauder 1986); SOM content, determined by potassium dichromate oxidation (Nelson and Sommers 1982); and calcium carbonate content, determined by the Bernard calcimeter method (Hulseman 1966).

2.3. Heating treatments

Soil samples (approximately 60 g) were placed in porcelain containers (8.5 cm diameter, 3.5 cm depth) and heated in a pre-heated muffle furnace (Nabertherm, P320, Bremen, Germany) at 200, 250, 300 and 350 ºC for 20 minutes. The rate of heating of soils measured with thermocouples was between 10-15 ºC/min depending on the temperature used. These temperatures were selected based on previous experiments which showed that WR by burning appears or is enhanced in this temperature range (Arcenegui et al. 2007; Mataix-Solera et al. 2008; Zavala et al. 2010). In contrast, in dry soils, WR is destroyed at temperatures above 350 ºC (Robichaud and Hungerford 2000; Zavala et al. 2010).

2.4. Soil water repellency (WR) measurements

Prior to WR assessment, approximately 15 g of each soil sample was placed on separate 50-mm diameter plastic dishes and exposed to a controlled laboratory atmosphere (20 ºC, ~50% relative humidity) for one week in order to eliminate the potential effects of any variations in the preceding atmospheric humidity on soil WR and in accordance with Doerr et al. (2005). The water drop penetration time (WDPT) test (Wessel 1988) was used to measure the persistence of WR. This involved placing three drops of distilled water (~0.05 ml) on the sample surface and recording the time required for their complete penetration. The average WDPT for triplicate drops was assigned to each sample. Unburned soil samples were used as control. Soil WR was classified according to **Table 2**.

Table 2. Soil water repellency classes and WDPT intervals used in this study. After Bisdom et al. (1993) and Doerr (1998)

Soil water repellency classification	WDPT interval (s)	WDPT Class
Wettable	≤ 5	≤ 5
Slightly water repellent	6-10	10
	11-30	30
	31-60	60
Strongly water repellent	61-180	180
	181-300	300
	301-600	600
Severely water repellent	601-900	900
	901-3600	3600
Extremely water repellent	> 3600	> 3600

2.5. Statistical procedures

Assumptions of normality and homogeneity of variances were tested using the Shapiro-Wilk and Brown-Forsyth tests, respectively. Spearman correlation analyses were made for soil properties and WR from control samples, heated at 200 ºC and 250 ºC in order to support the results and observations made after heating treatments. All computations were made using STATISTICA version 6 (StatSoft 2001).

3. Results and Discussion

3.1. Soil properties

Table 3 shows the main soil characteristics. The main differences in soil properties between samples used are the following: regarding textures, samples HF1, HF2 and HF3 have the highest sand content, ranging from 72 to 80% (loamy sand – sandy loam texture), while samples HF4 and HF5 have the highest clay content (46 and 44% respectively; clayey texture). The carbonate content is very low in all samples from “Los Alcornocales Natural Park” (HF1 to HF5) ranging from 0.2 to 3.2%. In contrast, the 3 samples from “Sierra de la Grana” (HF10 to HF12) have the highest carbonate content (60.8 to 69.5%). The carbonate content of soil samples from “Sierra de la Taja” (HF6 to HF9) ranges from 21.3 to 33.8%. Soil acidity is higher in soil samples from “Los Alcornocales” Natural Park, especially in the sandy loamy/loamy sandy samples (HF1, HF2 and HF3), with a pH between 6.2 and 6.8, compared with samples from Alicante (HF6 to HF12), where the mean annual rainfall is substantially lower (**Table 1**), and the pH ranges from 7.8 to 8.2 (**Table 3**). SOM content is high in HF4 and HF5 samples (Cádiz), 15.5 and 14.5% respectively in the first 5 cm depth. In the rest of the samples, SOM contents ranges from 9.5% (HF1) to 13.1% (HF8) (**Table 3**).

3.2. Soil water repellency before and after heating treatments

Results of WR assessment before and after the heating treatments are shown in **Table 4**.

Table 3. Characterization of soil samples used in the experiment (0-5 cm depth). Soil texture classification as in Soil Survey Staff (1993)

Soil sample	Sand (%)	Silt (%)	Clay (%)	Soil texture	CO_3^{2-} (%)	SOM (%)	pH	EC (µS cm^{-1})
HF1	80	14	6	Loamy Sand	2.8	9.5	6.8	127
HF2	62	18	20	Sandy Loam	3.2	10.4	6.3	54
HF3	72	18	10	Sandy Loam	0.4	11.1	6.2	76
HF4	32	22	46	Clay	0.2	15.5	7.2	267
HF5	34	22	44	Clay	0.4	14.5	7.0	268
HF6	22	70	8	Silt Loam	21.9	13.0	7.8	394
HF7	42	44	14	Loam	33.8	12.8	8.0	323
HF8	36	56	8	Silt Loam	21.3	13.7	8.0	306
HF9	36	46	18	Loam	31.0	10.9	8.1	274
HF10	54	32	14	Sandy Loam	60.8	11.8	8.2	380
HF11	46	40	14	Loam	69.5	10.4	8.1	357
HF12	58	34	8	Sandy Loam	68.1	10.0	8.1	402

Most control samples were wettable, and only HF2 and HF3 showed slight WR (10 and 30 s WDPT Class respectively). Depending on the soil sample, WR showed different responses after heating. Extreme WR was observed after heating at 200 ºC (HF1, HF2 and HF3), 250 ºC (HF1 and HF12) and severe after heating at 250 ºC (HF3 and HF10) and 300 ºC (HF12). On the contrary, some samples did not show heat-induced WR development at any temperature (HF7, HF8 and HF9; **Table 4**).

Table 4. Water repellency (WDPT, s in classes) for each soil sample in control (unheated) and heated at different temperatures

Soil sample	WDPT class (s)				
	Control	200 ºC	250 ºC	300 ºC	350 ºC
HF1	< 5	> 3600	> 3600	< 5	< 5
HF2	10	> 3600	< 5	< 5	< 5
HF3	30	> 3600	3600	< 5	< 5
HF4	< 5	10	600	< 5	< 5
HF5	< 5	30	< 5	< 5	< 5
HF6	< 5	10	< 5	< 5	< 5
HF7	< 5	< 5	< 5	< 5	< 5
HF8	< 5	< 5	< 5	< 5	< 5
HF9	< 5	< 5	< 5	< 5	< 5
HF10	< 5	< 5	3600	< 5	< 5
HF11	< 5	< 5	10	< 5	< 5
HF12	< 5	10	> 3600	3600	< 5

The contrasted WR behaviour can be explained by the analysis of the soil properties of samples used in this study (**Table 3**). The results showed that both highly and slightly calcareous soil samples can develop extreme WR. This is in agreement with previous studies reporting less frequency and persistence of WR in calcareous than in acidic soils by Mataix-Solera and Doerr (2004) and Arcenegui et al. (2008). But these studies have also demonstrated that extreme WR can be found in calcareous soils with neutral to alkaline pH.

According to Doerr et al. (2000), texture is a key soil property affecting the response of WR after heating. In this research, severe WR was observed only in HF3 (72% sand content), HF10 (54%) samples after heating at 250 ºC and in HF12 (58%) at 300 ºC. Also, extreme WR was only observed in HF1 (80% sand content), HF2 (62%) and HF3 (73%) samples after heating at 200 ºC and in HF1 (80%) and HF12 (58%) at 250 ºC. Soil samples with sand content ≤ 46% ranged between wettable and slightly water-repellent except HF4 (32% sand content), which showed strong WR at 250 ºC (**Figure 1** and **Table 4**).

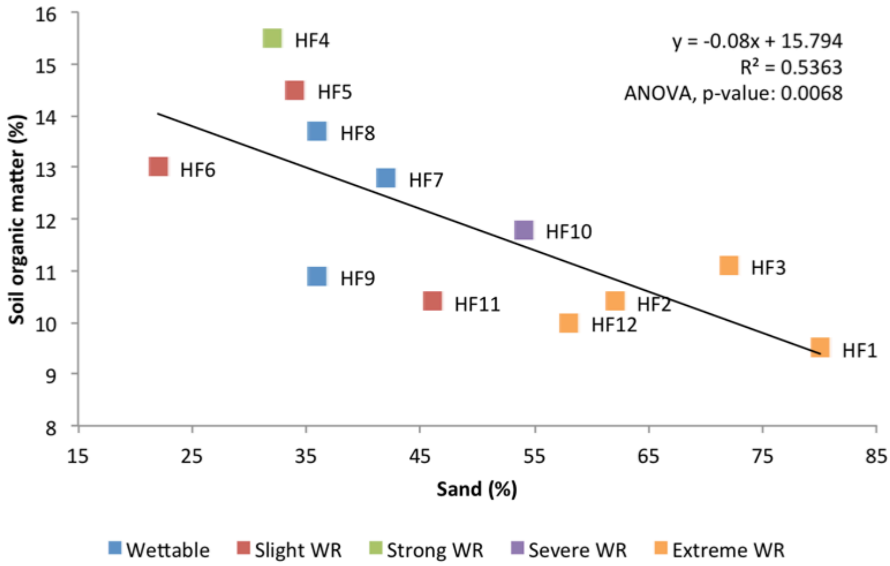

Figure 1. Linear relationship between soil organic matter and sand content (%) of soil samples used in the experiment. Colors represent the maximum WDPT class reached after heating according to Table 2.

Table 5 shows the correlation coefficients between soil properties and WR after heating. The sand content showed a moderate correlation with WR after heating at 250 ºC, but no significant correlations were observed at other temperatures or in control samples.

Although samples with low SOM/sand ratio developed extreme values of WR (Figure 1), initial SOM content was not significantly correlated with WR (Table 5). Factors such as organic matter and texture have been described as factors controlling fire-induced WR (DeBano 1981; Arcenegui et al. 2007; Mataix-Solera et al. 2008). Organic compounds from SOM redistribute and concentrate during burning (DeBano 1991; DeBano and Krammes 1966). Consequently, if conditions for the development of WR occur, a higher degree of WR should be expected in burned soils when the SOM content prior to burning is high. In contrast, our results show that extreme WR was induced only in HF1 (9.5% SOM), HF2 (10.4%) and HF3 (11.1%) after heating at 200 ºC and HF1 and HF12 (10%) at 250 ºC. Strong WR was observed after heating at different temperatures, but only at

Table 5. Spearman correlation coefficient for soil properties and WR from control samples (WR-Control), samples heated at 200 ºC (WR-200) and 250 ºC (WR-250). P-values are shown between parentheses. Non-significant coefficients are not shown

	Sand	Silt	CO_3^{2-}	pH	EC	WR-Control
Silt	-0.650 (0.031)					
pH		0.623 (0.039)	0.827 (0.006)			
EC		0.709 (0.019)	0.774 (0.010)	0.808 (0.007)		
SOM	-0.8 (0.008)					
WR-Control				-0.656 (0.030)	-0.640 (0.034)	
WR-200		-0.768 (0.011)	-0.664 (0.028)	-0.869 (0.004)	-0.641 (0.034)	0.6113 (0.043)
WR-250	0.612 (0.042)					

SOM contents ≥ 11.8%. In contrast, samples with SOM content ≥ 12.8% were wettable or slightly WR after heating, except one (HF showed strong WR at 250 ºC). It can be suggested that the soil texture controlled the occurrence of fire-induced WR more effectively than the SOM. Sandy soils are more prone to develop WR because of the lower specific surface area to be covered by hydrophobic substances (Doerr et al. 2000; González-Peñaloza et al. 2013).

We can also observe that samples from the same place, and therefore with similar soil properties, show different responses in function of the dominant species, thus affecting the quality of their SOM. It is important for example in the case of HF4 and HF5 where the only difference is that HF4 was collected beneath *Pistacia lentiscus* and HF5 beneath *Olea europaea*.

In a similar way, although samples HF10, HF11 and HF12, collected in Sierra de la Grana, show homogeneous properties (loam to sandy loam texture, 60.8-69.5% carbonates, 10.0-11.8% SOM, pH 8.1-8.2 and EC 357-402 µS cm^{-1}; **Table 3**), different responses of WR to heating can be observed (**Table 4**), and then mainly attributed to the plant species through the induced quality of their SOM. It is suggested that SOM under *P. halepensis* is more prone to develop WR when heated at 250-300 ºC than SOM from soils under other species. In the case of soil samples collected in Sierra de la Taja (HF6-HF9), only slight WR was observed in HF6 (collected under *P. halepensis*) after heating to 200 ºC, and this despite the sample showing the highest SOM/sand ratio (**Figure 2**). WR was induced by heating in all samples from soils under pines (HF1, HF6 and HF12), although severity of WR varied as a result of the influence of other properties. Many studies point out that soils under pines are more prone to develop WR, both in unburned (Buczko et al. 2002; Doerr et al. 2000; Lichner et al. 2012; Lozano et al. 2013; Mataix-Solera et al. 2007) and burned soils (Arcenegui et al. 2008; Huffmann et al. 2001; Mataix-Solera and Doerr 2004; Varela et al. 2005; Zavala et al. 2009a). Pine residues contain large amounts of resin, wax, and aromatic oils, which are compounds responsible for WR (see the review by Doerr et al. 2000).

4. Conclusions

Small differences in some soil properties can control the occurrence and persistence of soil WR developed by burning. Previous studies pointed out that texture is one of the main factors, with sandy soils being more prone to WR due to their lower specific surface area. Recent investigations also show that the mineralogy of clay fraction can greatly control the WR in burned soils. The results of this study confirm the results of previous research and suggest that the properties of pre-burn SOM (which depends on the plant species) is a key factor affecting this property when soil is affected by burning.

The high spatial variability of soil WR in burned areas has been mainly attributed to the expected differences in temperature reached in burned soils as a consequence of fuel distribution and fire behaviour. Understanding how small differences in some soil properties affect the changes in WR after a fire can help to explain the high spatial variability with regard to this property found under field conditions in burned areas.

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