Temporal evolution of water repellency and preferential flow in the post-fire

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Intro

Forest fires usually intensify erosive process due to the reduction of vegetation cover and degradation of aggregation in the topsoil. Another common effect of wildifres is the development of soil water repellency, which in turn favors the formation of runoff, inhibiting or delaying infiltration. Under these conditions, infiltration occurs only when ponded water or runoff flow finds macropores and cracks in the soil surface, producing preferential flow pathways. When water infiltrates through these paths, a significant portion of the soil remains dry, limiting the supply of nutrients to the roots, favoring the rapid leaching of nutrients and agrochemicals, and other impacts on flora and hydrological processes at hillslope- or basin-scale.

The existence of irregular wetting fronts has been observed frequently in burned or unburned water repellent soils. Although some authors have suggested that preferential flow paths may be more or less permanent in the case of unburned soils, the temporal evolution of preferential flow has been rarely studied in burned soils during the post-fire, after water repellency decreases or disappears.

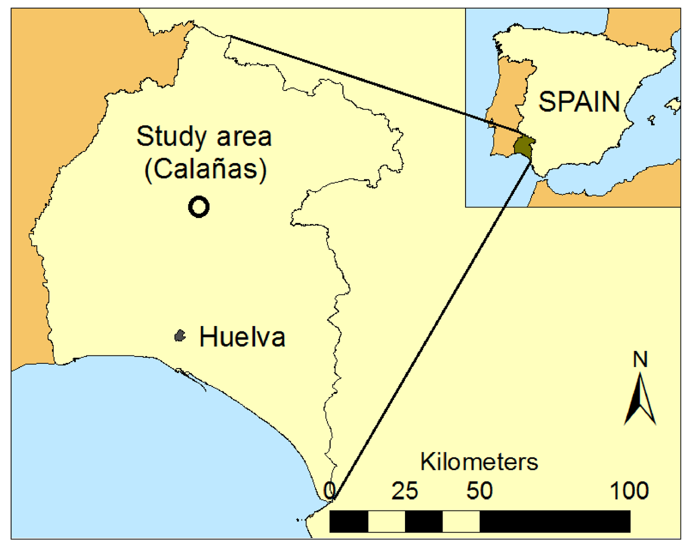

Figure 1. Study area in SW Spain.

Objectives

This research focuses on the temporal evolution of water repellency and preferential flows in an area affected by fire. We have studied [i] the evolution of wetting fronts, [ii] the evolution of the intensity of soil water repellency and [iii] the evolution of water infiltration rates during a 4-years period after burning.

Materials and methods

Study area

In July 6th 2011, a wildfire caused by negligence affected a forested area (*Pinus pinea* and *Eucalyptus globulus*) near Calañas (province of Huelva, southwestern Spain; **Figure 1**). About 9,000 m^2 were burned, affecting shrubland and woodlands, approximately at coordinates 37º 39' N/ 6º 51' W (285 m a.s.l.). The climate is Mediterranean, with cool, humid winters and warm, dry summers. According to the nearby weather station "Alosno Tharsis-Minas" (Alosno, located at coordinates 37º 35' N/ 7º 7' W; 286 m a.s.l.), the average annual precipitation is 616.4 mm, with a maximum monthly value of 104.8 mm (December) and a minimum of 2.6 mm (August). The mean annual temperature is mild, 6.9 °C, with a maximum monthly mean temperature of 25.4 °C (August) and a minimum monthly mean of 9.9 °C (January).

Experimental design and soil analysis

A study plot was selected in a moderately burned area. In order to determine original soil characteristics, a soil profile was described in an adjacent area (2 m from the study plot). For this, triplicate soil samples were collected every 5 cm between 0 and 60 cm depth. Soil samples were transported in plastic bags to the laboratory, dried at laboratory room temperature (25 ºC) until a constant weight, sieved to eliminate coarse soil particles (> 2 mm). Soil acidity (pH in soil extract 1:2.5 soil:water), soil organic C content (Walkley-Black method) and soil texture (pretreatment with H_2O_2, 6%, to remove organic matter) by the Bouyoucos method were determined.

A TDR transect was installed 72 h after fire and used until January 2014 to monitor moisture content and observe the wetting front dynamics. 252 TDR probes were inserted horizontally (every 5 cm between 0 and 100 cm horizontal distance and every 5 cm between 5 and 60 cm depth) in the excavated profile and fixed using a wire mesh and nails. Measurements were recorded in July (summer) and December/January (winter) between July 2011 and January 2015. In summer campaings, rainfall simulation was used to measure the wetting front.

Table 1. Classification of intensity of soil water repellency by the EPT method.

EPT class	Ethanol (%)	Soil water repellency class
1	0	Very wettable
2	3	Wettable
3	5	Slightly water repellent
4	8.5	Moderately water repellent
5	13	Strongly water repellent
6	24	Very strongly water repellent
7	36	Extremely water repellent

In the same dates, intensity of soil water repellency and infiltration rates were determined on the soil surface in the vertical projection of TDR probes, carefully removing litter, small branches, residues and coarse mineral particles. Intensity of soil water repellency was determined using the ethanol percentage test (EPT). Drops (0.5 µL) of decreasing ethanol concentrations were applied onto the soil surface using a micro-pipet until one of the drops balled out in the first 5 seconds after application. This allows the classification of the soil surface into a surface tension category between two consecutive ethanol concentrations. Ethanol concentrations and corresponding intensities of soil water repellency are shown in **Table 1**.

Infiltration rates were determined using a Mini-disc Infiltrometer device (MDI; Decagon Devices, Inc. Pullman, WA). When the measuring area was irregular, a thin layer of fine silica was applied to the soil surface. In order to avoid the effect of soil water repellency, a solution of ethanol (36%) was used instead of water. The infiltrated volume was recorded at regular time intervals (30 s) and hydraulic conductivity was calculated after infiltration of at least 30 mL.

Results and discussion

Soil properties

Soil characteristics are shown in **Table 2**. Soil was acidic, with pH decreasing from 6.5 (0-5 cm) to 5.5 (55-60 cm). Organic C content varied between 4.4 and 4.5 between 0 and 20 cm, and decreased progressively with depth until 1.8 (55-60 cm). Soil texture varied between clay loam at the surface and sandy loam in depth. The soil material was wettable between 0 and 10 cm and very wettable in the rest of the soil profile.

Table 2. Characteristics of unburned soil. Variables did not fit the normal distribution (Shapiro-Wilk p-value ≤ 0.05). The last row shows median values and range between parentheses.

Depth (cm)	pH	Organic C content (%)	Sand (%)	Clay (%)	Water content (%)	EPT
0-5	6.5	4.5	36.1	28.8	0.06	2
5-10	6.3	4.4	36.1	27.8	0.75	2
10-15	6.1	4.4	36.9	26.3	0.87	1
15-20	6.1	4.4	39.0	26.0	0.92	1
20-25	6.1	2.1	60.4	19.1	1.2	1
25-30	5.9	2.0	56.8	18.4	1.92	1
30-35	5.8	2.0	57.4	18.2	0.8	1
35-40	5.7	2.0	55.1	17.7	1.94	1
40-45	5.7	1.9	61.3	12.8	1.09	1
45-50	5.6	1.9	65.2	11.9	0.98	1
50-55	5.5	1.9	68.9	12.6	0.69	1
55-60	5.5	1.8	71.9	11.7	0.44	1
Median (range)	5.9 (5.5, 6.5)	2 (1.8, 4.5)	57.1 (36.1, 71.9)	18.3 (11.7, 28.8)	0.9 (0.1, 1.9)	1 (1, 2)

Evolution of the intensity of soil water repellency

Figure 2 shows the weekly rainfall during the four weeks previous to each sampling campaign. **Figure 3** shows the evolution of ETP with time on the soil surface.

Significant differences were found among median values of EPT for the different sampling campaigns (Mood's median test p-value: 0.0000). Median EPT varied between 6 (summer 2011) and 3 (summer and winter 2015). In general, it decreased progressively during the 4 years following fire. Although EPT decreased one or two classes between summer and winter during the first 2 years of the experiment, differences decreased with time, and the same EPT value was observed in both seasons during 2014.

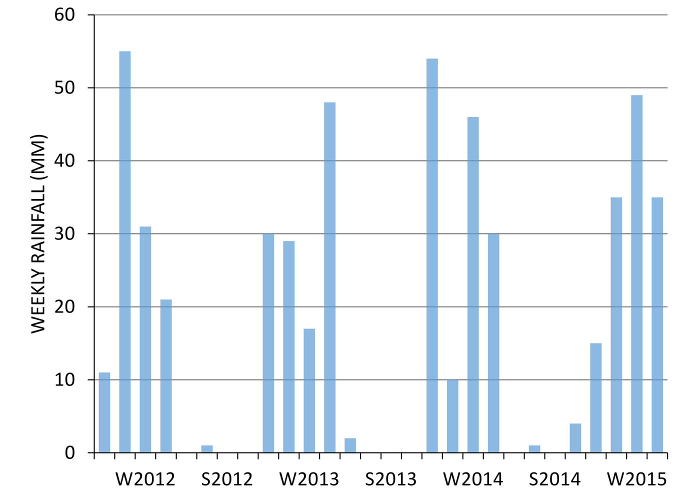

Figure 2. Weekly rainfall during the four weeks previous to each sampling campaign.

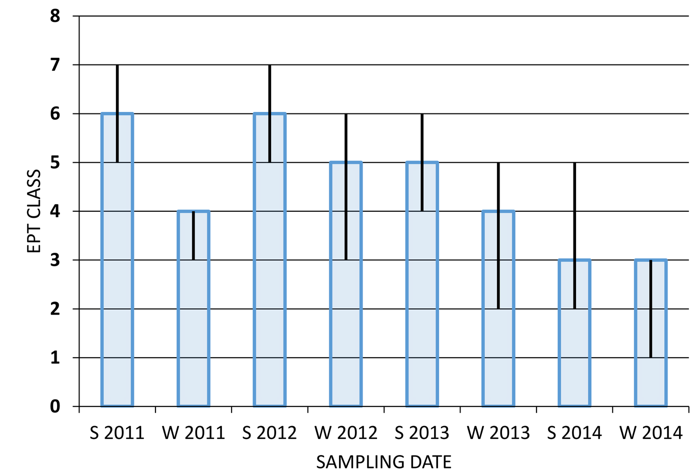

Figure 3. Variation of the intensity of soil water repellency (median EPT class) with time. Black lines show the range of variation for each case. N = 20 for each sampling date.

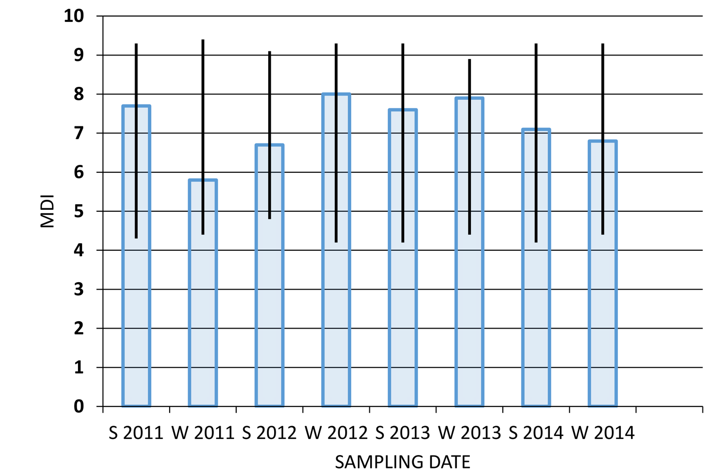

Figure 4. Variation of the mini-disc infiltrometer data (MDI, ml min^{-1}) with time. Black lines show the range of variation for each case. N = 20 for each sampling date.

Evolution of infiltration rates

Figure 4 shows the evolution of infiltration rates on the soil surface (MDI data). Median MDI data varied between 5.8 and 7.9 ml min^{-1}, and no significant differences were found among different sampling campaigns (Mood's median test p-value: 0.3077). As infiltration rates were determined using ethanol (36%), not water, further variations of the wetting front are assumed to be due only to water repellency changes.

Evolution of the wetting front

Figure 5 shows the evolution of the wetting front between summer 2011 and winter 2015. In the summer of 2011, just after burning, fire-induced soil water repellency clearly inhibited infiltration. Ponding and water retention in the first few centimeters causes the pressure of the water column to "break" hydrophobicity in certain points. In addition, natural pores and cracks are used by the water flow. This is evident, since the effect of water subhorizontal pathways between 30 and 50 cm depth was observed. Water repellency contributes to an heterogeneous wetting front and the appearing of preferential flow paths and dry soil pockets. Over time, the intensity of hydrophobicity at the soil surface is progressively reduced (**Figure 3**), allowing the soil to become more wettable. Thus, the irregularity of the wetting front is also progressively reduced until it becomes homogeneous at the end of the experiment.

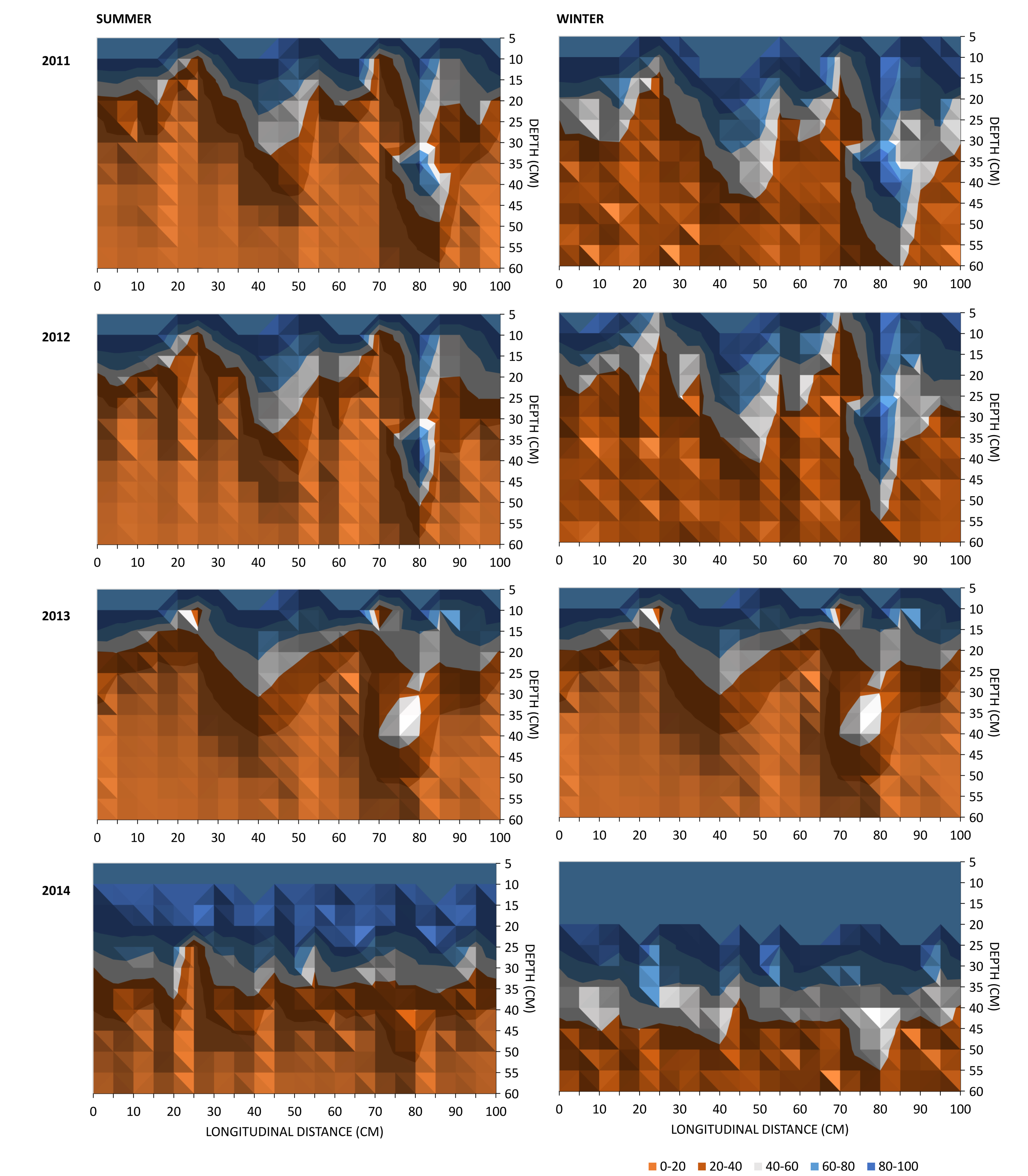

Figure 5. Variation of the water content (vol. %) with time in the soil profile for each sampling campaign.

Conclusions

This work has helped to understand the dynamics of water infiltration into soil during the post-fire. The presence of irregular wetting fronts and preferential flow paths has important consequences for vegetation and soil functioning to be considered and included in plans for restoration of burned areas.
Hydrophobicity caused by fire in a previously wettable soil resulted in the appearance of irregular wetting fronts.
High intensities of water repellency persisted during the first two years after fire. But after this period, it was progressively reduced until soil became slightly water repellent or wettable.
The decrease in intensity of water repellency also produced a gradual disappearance of the wetting front irregularity, recovering the initial conditions 4 years after the fire.

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