Stones induce patchy distribution of soilwater repellency in burned soils

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Introduction

Especially in recent years, much attention has been paid to the study of soil water repellency (SWR) and, in particular, to fire-induced SWR. Burning induced SWR appears during combustion, when a significant amount of soil organic matter is volatilized and lost, but a small quantity is moved downward following the temperature gradient in the first centimeters of soil condensing on the surface of soil aggregates and particles as hydrophobic coatings. The strength of fire-induced SWR depends mostly on temperatures reached during burning, the amount and type of litter consumed and pre-fire soil moisture level, the period of time these temperatures occur in the soil and soil properties. It is commonly accepted that SWR is induced or considerably enhanced when temperatures between 175 and 200 ^oC are reached during burning. In contrast, when temperatures above 280 ^oC are reached, SWR is destroyed. Water repellent soils can be difficult to model because of their extreme spatial and temporal variability. One factor not usually considered when studying the spatial distribution of SWR is the presence of stones resting on the soil surface or partly embedded. Stones at the soil surface or in the top layer of soil directly affect the physical soil properties and hydrological response. However, no attention has been paid to the effect of stones resting on the soil surface in the development of water repellency.

stones on the soil surface may affect the distribution of heat during burning, and, consequently, may change the expected spatial distribution of SWR. During burning, temperature peaks at the soil surface under stones reaches are delayed respect to uncovered. In contrast, temperature peaks may be longer, increasing the time of residence of high temperatures. In consequence, stones may change the expected spatial distribution of SWR. Up to date, very scarce research concerns the effect of stones at the soil surface on the fire-induced pattern of soil water repellency.

The aim of this research is to study the effect of stones and stone cover on the spatial distribution of SWR under different fire severities.

Methods

Experiment A: controlled burn

Experiments were carried out in the Blanco White experimental farm (Sevilla). Soil at the experimental area is clay-sandy loam (sand 64.1%, silt 15.3% and clay 19.6%), pH is 7.5 and CO_3Ca content is 18.3%. Soil plots (1.0 × 1.5 m^2) were marked with vertical metal bars and stones (8-10 cm in diameter) were regularly arranged at each plot in order to get 0, 15, 30, 45 and 60% stone cover, as shown in **Figure 1-a**. Stones were kept on the soil surface during three months before experimental burning. Every 60 s, soil temperature was recorded 1 cm below the soil surface under stones and bare soil.

Fuel (6.5-7.5 kg m^{-2}) was added to soil plots in order to simulate natural shrubs (**Figure 1-b**). Fuel density was. Fuel structure was 50% fine branches (<5 mm) and 50% thick branches (>15 mm). Burning lasted until spontaneous extinction (**Figure 1-c**) after 15 minutes. Soil samples (0-10 cm) were collected 2 days after burning and monthly during a 7-month period later. Soil samples for laboratory analyses were collected using a cylindrical core (4.8 cm in diameter) inserted 10 cm in soil and were transported to laboratory, air dried and homogenized. SWR was assessed under field conditions using the water drop penetration time method (WDTP) at 0, 10 and 20 mm depth in areas under stones (US) and covered by stones (CS).

Figure 1. Some details of the experimental work: (a) soil plots with 0, 15, 30, 45 and 60% stone cover; (b) soil plot after addition of fuel; (c) soil plot during burning.

Experiment B: wildfire

In July 6th 2011, a wildfire affected a forested area (*Pinus pinea* and *Eucalyptus globulus*) near Calañas (Huelva, SW Spain). Soil from unburned adjacent areas was characterized (pH, organic C content and texture).

The burned area was divided in different zones according to fire severity: unburned (control areas not affected by fire), low, moderate and high fire severity. Areas with homogeneous fire severity were divided in subareas with low (<20%) and high stone cover (>60%), as shown in **Figure 2**. **Figure 3** shows a scheme of the experimental design. The minimum size of the selected subareas was 10 m^2 and the minimum distance between adjacent areas was 4 m. SWR was assessed using the water drop penetration time (WDPT) in randomly selected points under (US) and between stones (with maximum spacing between stones 20 cm; BS) during the first 7 days immediately following burning. Soil was classified as wettable (WDPT < 30 s), slightly water repellent (31-60 s), moderately water repellent (61-180 s) and strongly water repellent (181-360 s). Previously to these assessments, ashes and litter were gently brushed away when present.

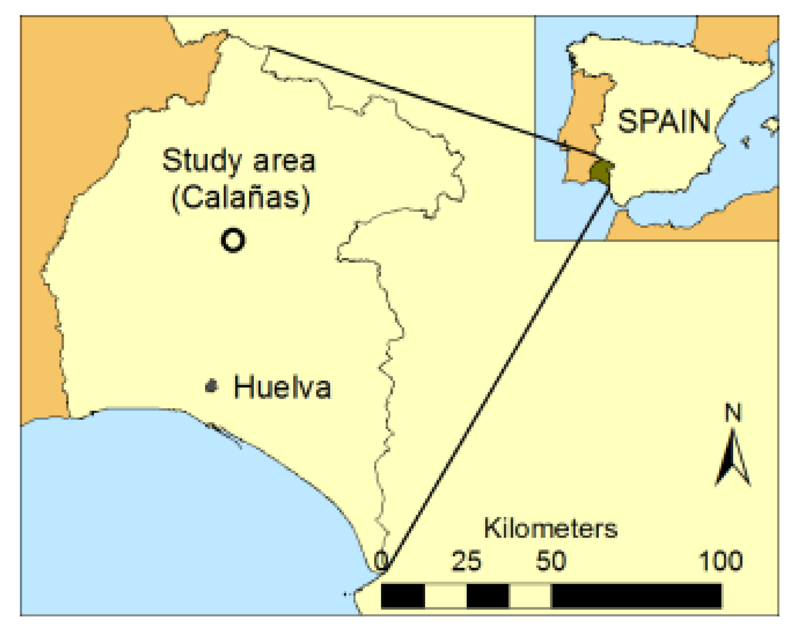

Figure 2. Location of the wildfire-affected area.

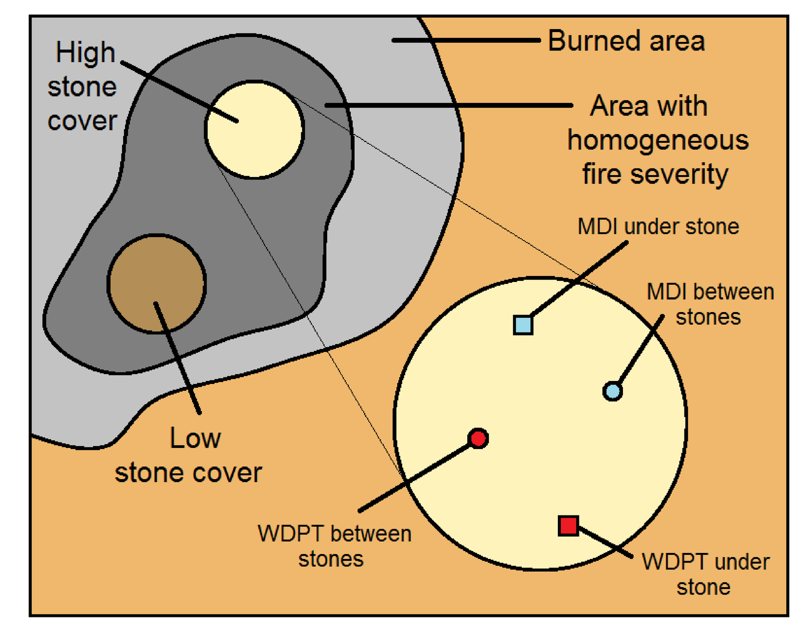

Figure 3. Field sampling scheme. The number of determinations varied with the size of each sampling area, minimum distance between determinations was 1 m. In burned areas, minimum distance to unburned soil was 5 m.

Results

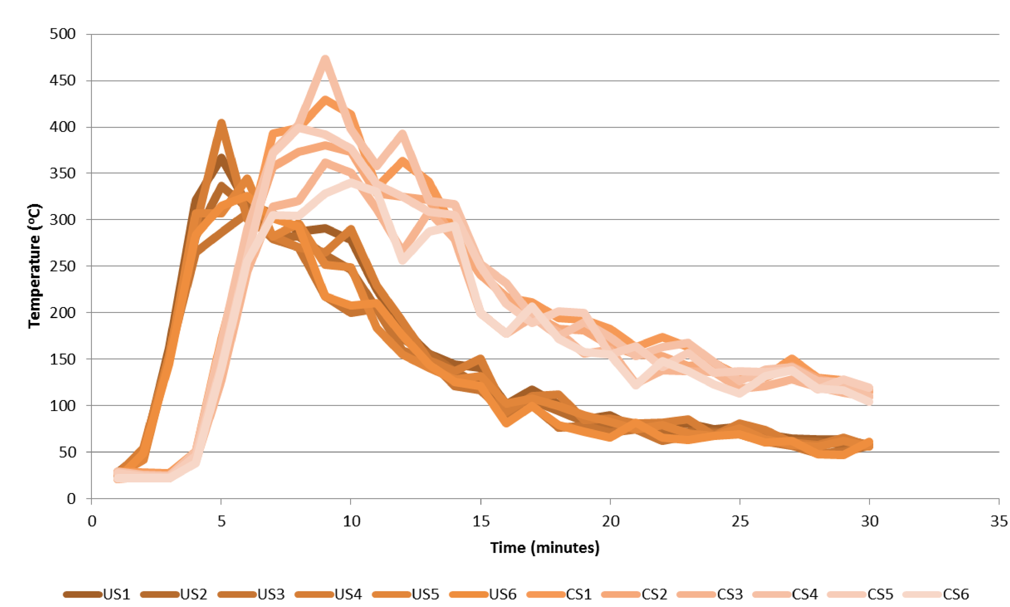

Figure 4. Temperature records during the controlled burn (experiment A). US: soil under stones; CS: soil covered by stones.

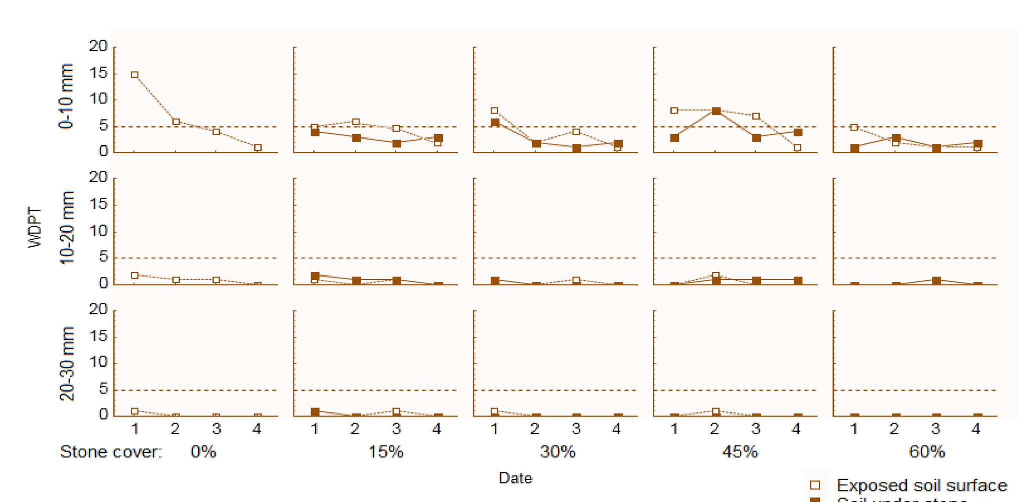

Figure 5. Soil water repellency (WDPT, s) for different stone cover classes, soil depth and dates (months after burning).

Experiment A

Temperature recorded at 1 cm under the soil surface is shown in **Figure 4**. Temperature reached in uncovered soil areas reached 300-350 ^oC, with short-time peaks. In contrast, temperature at stone-covered soil areas reached 350-400 ^oC peaks. In addition, peaks were delayed approximately 5 minutes and were longer in time, with temperatures above 300 ^oC over 14 minutes.

The monthly evolution of SWR in the 0-10, 10-20 and 20-30 mm soil layers is shown in **Figure 5**. Wettable character was stable below 10 mm, with SWR remaining unaffected by burning. In contrast, soil areas under stones and no stones showed different behaviors. SWR was triggered at 0-10 mm depth in plots under 0% stone cover immediately after burning, and decreased progressively until soil material became wettable two monts after burning. Slight SWR (average WDTP between 5 and 10 s) was observed by sampling dates 1 and 3 at exposed inter-stone areas from soil plots under 15, 30 and 45% stone cover. Stone-covered areas remained wettable or slightly water repellent (average WDPT ranging between 1 and 6 s) character. SWR was not observed at 60% stone cover soil plots.

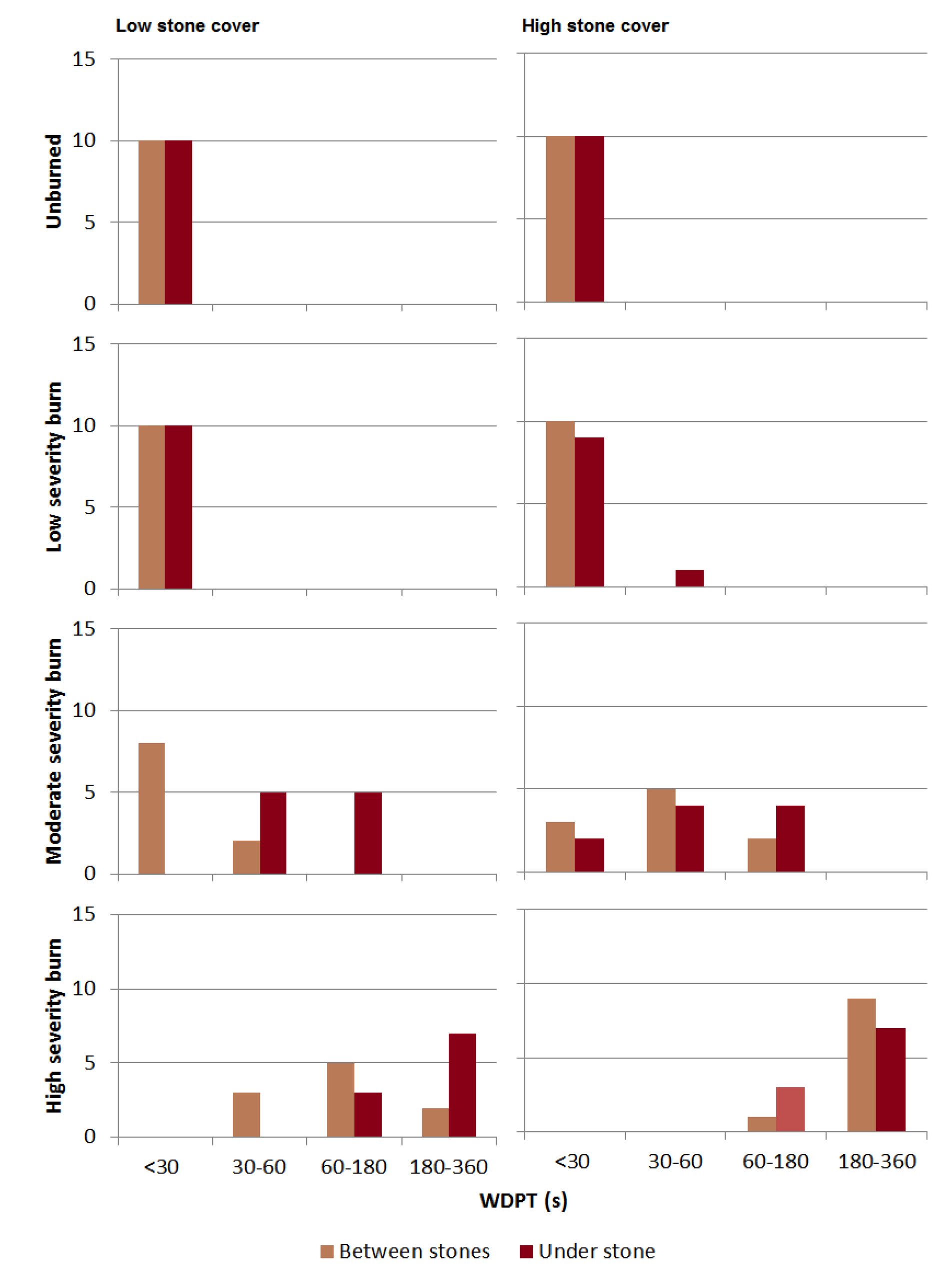

Figure 6. Number of WDPT data for different classes (<30, 30-60, 60-180 and 180-360 s), fire severity and stone cover class (low, <20%; high, >60%).

Table 1. . Results of the Wilcoxon rank test for WDPT values (mean ± standard deviation, s) from areas with different fire severity, stone cover class and type of determination (between stones and under stone).

Fire severity	Stone cover	BS	US	W, p
Unburned	<20%	2±1	2±1	> 0.5
	>60%	2±1	2±1	> 0.5
	W, p	> 0.05	> 0.05	
Low	<20%	3±2	13±7	0.0010
	>60%	3±2	17±10	0.0003
	W, p	> 0.05	> 0.05	
Moderate	<20%	23±11	58±18	0.0007
	>60%	45±17	53±28	>0.05
	W, p	0.0100	> 0.05	
High	<20%	101±54	239±102	0.0010
	>60%	263±71	322±173	> 0.05
	W, p	0.0006	>0.05	

Experiment B

WDPT from unburned and burned soils under different fire severities and stone cover is shown in **Figure 6**. Unburned soils are wettable, while WDPT increased to 9±9 s in low-severely burned areas. No significant differences were found between WDPTs from unburned and low-severity burned sites. In contrast, moderate- and high-severely burned areas showed slight and strong SWR, respectively.

Most soil points were considered wettable in unburned and low-severely burned points (89 of 90 points). Moderate to severely burned soils were classified as wettable (32.5%), slightly (40.0%) and moderately water repellent (27.5%). In high-severely burned areas, all points showed WDPTs above 30 s, with slight (7.5%), moderate (30.0%) and strong SWR (62.5%).

When considering stone cover, different results were observed according to fire severity (**Table 1**). In US areas, no significant differences were observed for WDPT between high and low stone cover areas under different fire severities. In BS points, no significant differences were observed between low (<20%) and high stone cover (>60%) in unburned soils and soils affected by low-severity burning. Significant differences were found between mean WDPT from BS points under different stone cover classes in moderate- and high-severity burned areas. In moderate-severity burned areas, WDPT increased significantly from 23±11 s (wettable) in low-stone-cover areas to 45±17 s (slight SWR) in high-stone- cover areas. In high-severity burned areas, WDPT increased significantly from 101±54 s (moderate SWR) in low stone cover areas to 263±71 s (strongly water repellent) in high stone cover areas (p=0.0006).

In control unburned areas, no significant differences were observed between WDPT values from BS and US points under low or high stone cover classes. In contrast, in burned areas, SWR increased significantly from BS to US points. In areas affected by high severity burning and high stone cover (>60%), no significant differences were found for SWR from BS and US areas, although mean WDPTs were 263±71 and 321±173 s, respectively.

Conclusions

In both cases, soil WR was induced in the soil surface contacting rock fragments after burning. Severity of WR ranged between subcritical or slight (low severity burning) and strong (high severity burning). Soil WR was also found to increase with rock fragment cover, especially after moderate or high severity burning, both under and between rock fragments. It is suggested that high density of rock fragments on the soil surface create a continuous surface of high residence of temperature peaks (in agreement with García-Moreno et al., 2013). Combustion of plant residues in oxygen depletion conditions between adjacent nearby rock fragments contributes to heat transfer to the soil surface and consequent enhanced soil WR.