

Post-fire evolution of soil properties in a Mediterranean heathland after experimental burning

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Introduction

Fire is an important agent which can induce important changes in the chemical and physical characteristics of soils. Burning severity can modulate the recovery of plant communities and the quantity and intensity of changes in fire-affected soil system. While low severity burning does not affect soils in an important manner, severe burning can affect a wide range of soil properties (e.g., nutrient availability, pH, organic matter content, texture, structure, etc). Fire-induced changes on soil properties can have an impact on soil productivity of burnt areas, in some cases in an irreversible way. Wildfires can decrease or completely destroy plant cover, altering the rainfall interception and evapotranspiration rates, influencing the hydrological surface processes and cycles, generally increasing erosion rates. Depending on the environmental conditions, the recovery of the vegetation canopy after wildfires in the Mediterranean area can be quite rapid due to the adaptation of plant communities to the disturbances caused by scorching. During wildfires, only a small part of the heat generated is transmitted to the first centimetres of the soil profile. The intensity of the changes produced in the physical and chemical characteristics of the soil depends on the temperatures reached at different soil depths, the time of residence of temperature peaks, and the stability of the different soil components. The scientific literature shows that the organic matter is strongly related to the stability of the structure and bulk density (BD), and it is a well-known aggregate stabilizing agent in soils. Positive relationships between organic matter content and aggregate stability (AS) have been reported by several authors. Decreased AS has been observed after fires, but laboratory and field experiments have shown that positive relationships between soil organic matter content and AS may not be as common as suspected in the case of burned soils, where high AS and low organic matter contents can be found. Long-term studies are necessary in order to assess the relationship between the behaviour of soil structure in time and other post-fire processes.



Another physical property of soils which is strongly affected by fire is soil water repellency. Depending on temperature, time of heating, type of soil and fuel, fire can induce, enhance or destroy soil water repellency.

The objectives of this study are to study the changes and post-fire evolution of some physical and chemical parameters (soil organic matter content, texture, pH, electrical conductivity, soil water repellency, BD and AS) of a Mediterranean soil under heathland during a period of 3 years following an experimental burning.

Methods

An experimental fire was conducted on May 2007 in a 0.12 ha area (30 m × 40 m) in a south-facing hillslope in Algeciras Range (Cádiz, SW Spain), with slopes ranging between 8 and 12% (Fig. 1). A thermocouple system was applied to measure soil temperatures during the burning, linked by buried electrical cables to a data-logger, according to Fig. 2. Data from each sensor were recorded every 60 seconds between burning initiation and 1 hour after natural fire extinction.

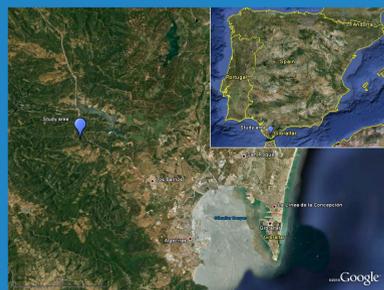


Figure 1. Study area.

Ten experimental plots (1 × 1 m²) were randomly selected in the experimental area and marked. Undisturbed soil samples (0–20 mm) for laboratory analyses were collected and transported in plastic bags under pre-fire conditions, immediately after the fire, and after a 1-year, 2-year, and 3-year period. Water repellency determinations were performed on-site (under field-moist conditions) and at the laboratory (Fig. 4). In the laboratory, soil samples were divided in subsamples for the different analyses. All sample collections and on-site determinations were carried out during 1–15 May 2007, 2008, 2009 and 2010.

Triplicate soil subsamples for chemical and texture analyses were used and average values were considered as representative. Subsamples were air-dried, sieved (0–2 mm) and homogenized for chemical analysis. Laboratory determinations included organic carbon, texture, pH, electric conductivity (EC), bulk density, aggregate stability (CND test) and water repellency (WDPT test).

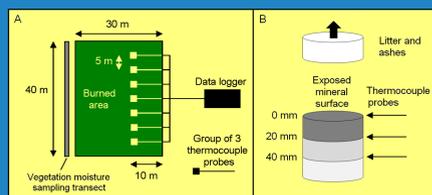


Figure 2. (A) Design of the thermocouple system in the experimental plot and the transect for vegetation moisture sampling. (B) Detail of the insertion of thermocouple probes at different depths before experimental burning.

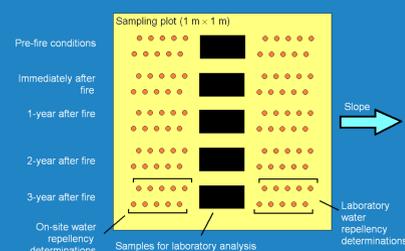


Figure 3. Sampling scheme at each plot.

Results

Table 1. Pre-fire fuel and environmental conditions and properties of fire behavior.

Fuel moisture and environmental conditions		Fire characteristics	
Air moisture	29.4%	Burning technique	Strip headfire
Soil moisture	4.3%	Maximum flame height	
Wind speed	< s ⁻¹	Average rate of spread (r)	s ⁻¹
Air temperature	32 °C	Average temperature peaks at soil surface	420 °C
Dry <i>Erica australis</i> moisture	3.1%	below soil surface	257 °C
Fresh <i>Erica australis</i> moisture	105.9%	Fireline intensity (H×W×r)	720,0 kW m ⁻¹ s ⁻¹
Litter moisture	9.2%		
Average fuel load (w)	2.7 ± 0.5 kg m ⁻²		
Heat yield (H)	2051.3 kW kg ⁻¹		

Pre-fire fuel and environmental conditions and properties of fire behavior are shown in Table 1. Data from thermocouples provided information of the combustion rate and residence time of peak temperatures. Fig. 4 shows temperature versus time since ignition recorded at 0, 20 and 40 mm depth by the nearest and the farthest thermocouple to the ignition point. Temperatures over 300 °C persisted for 30–50 minutes, and temperatures higher than 450 °C were reached for some minutes in several points at the soil surface (0 mm depth). An approximate delay of temperature peaks of 40 minutes between both points exists (Fig. 4). Temperature peaks show short delays between different depths. The delay of peak temperatures at 0, 20 and 40 mm did not reach 60 seconds as recorded by the nearest thermocouple to the ignition point. In contrast, peak temperatures at the farthest point from ignition were delayed at 40 mm depth (318 °C, 55 minutes) respect to the surface, 0 mm (435 °C, 50 minutes). These differences can be attributed to spatial heterogeneity of soil properties and fire intensity.

Vegetation cover was near 100% over the study site before the burning. The average fuel loading in the area was 2.7 ± 0.5 kg m⁻². Small variations were observed in the severity of fire across the burnt area. After burning, the biomass was almost completely consumed and the soil surface was covered with ashes and charred litter. This layer was homogeneously distributed through the experimental area, except at a few points where the fuel load was higher. This layer remained partially on the soil surface until autumn 2007, when it was removed by heavy storms and sporadic strong eastern winds. Plants were similarly consumed and herbaceous plant bases were deeply burnt.

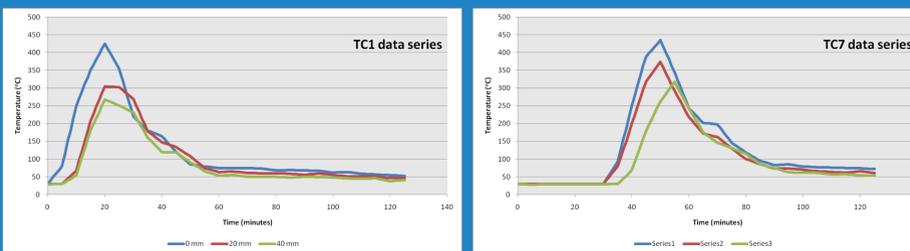


Figure 5. Temperature-time profiles at 0, 20 and 40 mm depth registered by the nearest (A) and the farthest (B) thermocouple to the ignition point.

Changes in organic matter content occurred due to the fact that the average temperatures reached between 257 °C (2 cm below soil surface) and 420 °C (soil surface) during the experimental fire. Despite small significant differences, relatively stable organic matter contents (1.1–1.5%) can be explained by the selection of highly stable organic compounds (humic acids and humins).

Significant changes were observed between the period immediately after fire and the 3-year determinations, although no significant differences were observed for the 1–3-year period. Nevertheless, this progressive increase of the coarser fraction observed during the study period cannot be attributed to burning. Post-fire soil erosion processes can induce selective removal of finer fractions by splash (eg, clay and silt fractions) and lead to an increase of the coarser fraction. The stable proportion of sand fraction during the 1–3-year period can be an outcome of exhaustion of the fine particles susceptible to detachment during the first two years after burning, when the higher decreases in clay fraction were observed, in contrast to the 2-year and 3-year measurements, when the proportion of clay did not vary considerably.

Table 2. Mean values ± standard deviation for organic matter content (OM, %), sand, silt and clay content pH, electrical conductivity (EC, dS m⁻¹), bulk density (BD, g cm⁻³) and aggregate stability (AS, CND) under pre-fire conditions, immediately after fire, 1 year, 2 years, and 3 years after fire, and results of the Kruskal-Wallis test (p). Within a column means followed by the same letter did not show significant differences.

	OM	Sand	Silt	Clay	pH	EC	BD	AS
Pre-fire conditions	3.1 ± 0.2 c	41.9 ± 3.7 a	38.6 ± 5.6	19.5 ± 3.2 c	6.2 ± 0.2 a	0.2 ± 0.0 a	1.4 ± 0.0 a	101.5 ± 3.9 d
Immediately after fire	1.1 ± 0.1 a	52.7 ± 5.7 b	36.6 ± 6	10.8 ± 1.6 d	7.5 ± 0.2 c	1.4 ± 0.2 b	1.5 ± 0.1 b	66.6 ± 1.6 a
One year after fire	1.3 ± 0.1 a	58.8 ± 5.4 bc	35.7 ± 5.6	5.6 ± 1.0 a	7.1 ± 0.2 d	0.2 ± 0.0 a	1.5 ± 0.1 b	69.8 ± 1.3 b
Two years after fire	1.5 ± 0.2 b	59.7 ± 7.8 bc	34.6 ± 7.6	5.8 ± 0.3 a	6.7 ± 0.2 b	0.2 ± 0.0 a	1.5 ± 0.1 b	74.0 ± 2.6 c
Three years after fire	1.5 ± 0.1 b	61.7 ± 9.1 c	32.7 ± 9.1	5.7 ± 0.3 a	6.3 ± 0.2 a	0.2 ± 0.0 a	1.6 ± 0.1 b	73.8 ± 2.0 c
Kruskal-Wallis p	0.0000	0.0000	0.1618	0.0000	0.0000	0.0000	0.0001	0.0000

The pH increase observed immediately after the burning can be explained by the complete oxidation of the organic matter during the exposure of the soil surface to high temperatures and the release of cations by ashes, which can enter the exchange complex and expulse protons to the soil solution. During the postfire, soil acidity decreased progressively until it reached pre-fire levels 3 years after fire.

Mean EC increased 70 times immediately after the fire according to pre-fire conditions as a consequence of the soluble inorganic ions that are released during the combustion of soil organic matter. After a 1-year period, EC returned to the prefire values and remained stable for the rest of the experiment. EC values were expected to decrease or increase with pH. In contrast, average EC shows a large increase immediately after fire. Our results confirm that a narrow correlation of pH and EC does not always exist. Differences may be due to spatial heterogeneity, but decomposition of charred residues, dynamics of ashes, hydrological processes and other factors may be involved. Further research is necessary to study the relationship between pH and EC in the postfire.

BD increased progressively between the pre-fire and post-fire conditions years, although no significant changes were observed immediately after fire, 1-year, 2-year and 3-year determinations (1.5 ± 0.1 g cm⁻³, on average). BD shows a moderate correlation with OM (R Spearman 0.659, p = 0.000000). AS, measured as the CND value, decreased immediately after fire.

As expected in soils with moderate-poor clay content, the strong decrease in AS could be caused by the combustion of organic matter content at temperatures around 400 °C, causing a collapse of the aggregates. 1–2 years after fire, the CND value increased significantly, what can be induced by the small increase in organic matter content observed during this period. Also, the slight increase in AS may be due to increased water repellency, which can reduce the entry of water into the soil matrix. Therefore, after destruction of the water repellency by intense burning in the soil surface, the slight increase in AS observed 2 and 3 years after the fire can be caused by erosion of the wettable and unstable aggregates in the soil surface, with water repellent and more stable aggregates become exposed.



Figure 5. Detail of the WDPT test in the laboratory.

The proportion of field-moisture water repellent soil samples decreased immediately after the fire to 44%, and then increased progressively, approaching the initial value during the following three years (Figure 5). Destruction of water repellency in the 0–20 mm layer may be induced by the high temperatures observed, which were, on average, between 257 °C (20 mm deep) and 420 °C (surface). Observed average temperatures in the soil surface are enough to completely destroy soil water repellency, but it can be induced or enhanced 2 cm below the soil surface, where average temperatures reached 257 °C.

Soil water repellency increased progressively during the study period. The proportion of field-moisture water repellent samples increased to 74% (1-year after fire), 81% (2-year) and 88% (3-year). (Fig. 6)

After the removal of the vegetation and increased post-fire erosion risk, detachment and loss of wettable soil material after 3 years can lead to exposition of subsurface aggregates not affected by burning temperatures, where natural hydrophobicity persists. Average temperatures observed 20 mm below the soil surface could not be enough to destroy water repellency if the occurrence time of high temperatures was short.

Progressive re-establishment of water repellency during the three years following the fire can also be associated to the observed increase in organic matter content. This result confirms that water repellency observed in soils under the heathland at the study area is not necessarily a consequence of wildfires, but a natural attribute of these soils, as previously suggested by the authors. Nevertheless, the organic matter content observed at the end of the experimental work did not reach pre-fire values (just half of the initial content, approximately), and other factors may be involved. The next stage in future research should include the study of hydrophobic organic substances in the ecosystem and the characterization of microbial activity.

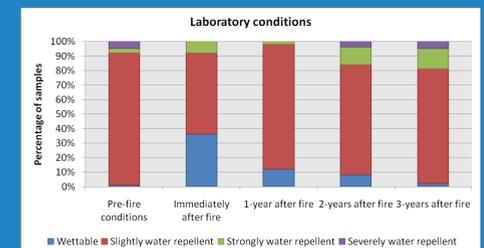
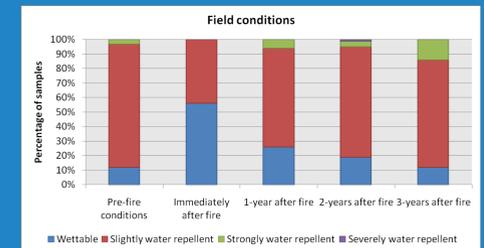


Figure 6. Proportion of water repellency classes under pre-fire conditions, immediately after the fire, 1 year, 2 years, and 3 years after fire, under field and laboratory conditions.