Impact of ash wettability on splash erosion and runoff rates in the postfire. A case study after a prescribed fire

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1. INTRODUCTION

Although an ash layer is usually ephemeral, it has important consequences for hydrological and erosive processes in the postfire. Some authors have reported increased water surface flow due to sealing of the soil surface and pore clogging by ash. On the other hand, delayed or reduced runoff rates due to the water storage capacity of a wettable ash layer have been also observed. In absence of vegetation cover, an ash layer may also protect soil against the direct impact of raindrops, so reducing the intensity of particle detachment and sediment yield. But either from different fire sites or within the same burned area, ash properties and its hydrological and geomorphic response may vary largely in space and time. After fire, ash may cover the soil surface forming a continuous or discontinuous layer, which may condition the spatial distribution of runoff/infiltration areas and the connectivity of water and sediments through the slope. Even when the ash cover is near 100%, spatial and time heterogeneity and different physical properties may exist due to several factors.

Ash properties depend largely on the burned species, vegetation type and environmental properties. It is known that the mineralogical composition of ash and charred litter is conditioned by the dominant fuel source, burned plant material can condition also ash water repellency and, indirectly, hydrological and geomorphic soil processes.

Complete combustion of organic residues lead to the formation of wettable white ash, while partial combustion leads to hydrophobic gray or black ash, where organic substances still exist. Consequently, a patchy pattern of ash color and wettability is observed after fire depending on the combustion completeness.

Different authors have reported heterogeneous depth of the ash layer, considering that the thickness of the ash layer is key for understanding the evolution of burned soils. In addition, redistribution processes (by wind or water) act not only causing large changes in the amount and depth of ash in the short term but also modifying the properties o the exposed surface as a result of mixing different types of ash produced. In burned soils, it has been observed that depth of the ash layer is progressively reduced and redistributed at different rates as a result of runoff flow, wind, topography, dissolution, compaction, and incorporation into the soil profile.

To present, scientific literature shows that a very high number of papers has focused on the study of the hydrological and erosive response of soils affected by fires. However, most of these studies have focused on properties such as the influence of the presence of ash in the formation and the effects of runoff, while few have studied particle detatchment after the direct impact of the raindrops on an ash layer. Similarly, there are very few studies comparing the impact of splash erosion in relation with local variations of ash water repellency. This work aims to address this gap by studying the intensity of splash erosion and comparing it to the soil response to simulated rainfall in a soil covered by wettable and water-repellent ash after a prescribed burn in a Mediterranean shrubland.

2. MATERIAL AND METHODS

Figure 1. Study area.

2.1 PRESCRIBED FIRE

In 20 November 2012, a prescribed fire was carried out in "Las Navas", a natural area near Almaden de la Plata (Sevilla, SW Spain; Figures 1 and 2). Soils are shallow, developed from acidic metamorphic rocks (schists, slates and pyrophyllites). Woody vegetation is dominated by shrub legumes (*Calicotome villosa* and several species of *Ulex* and *Genista*).

The experimental area (60 m × 30 m) marked using metal bars and a 15-m wide band all around was plowed to eliminate the risk of fire spreading during the experiment. At the moment of ignition, air temperature was around 20 ºC and the wind speed was 0.0 km. The experimental area was allowed to burn during 2.5 h. After burning, the soil surface was covered by a pattern of white and black ash, indicating varying degrees of combustion completeness. For security, water was sprayed to ensure fire extinguishment.

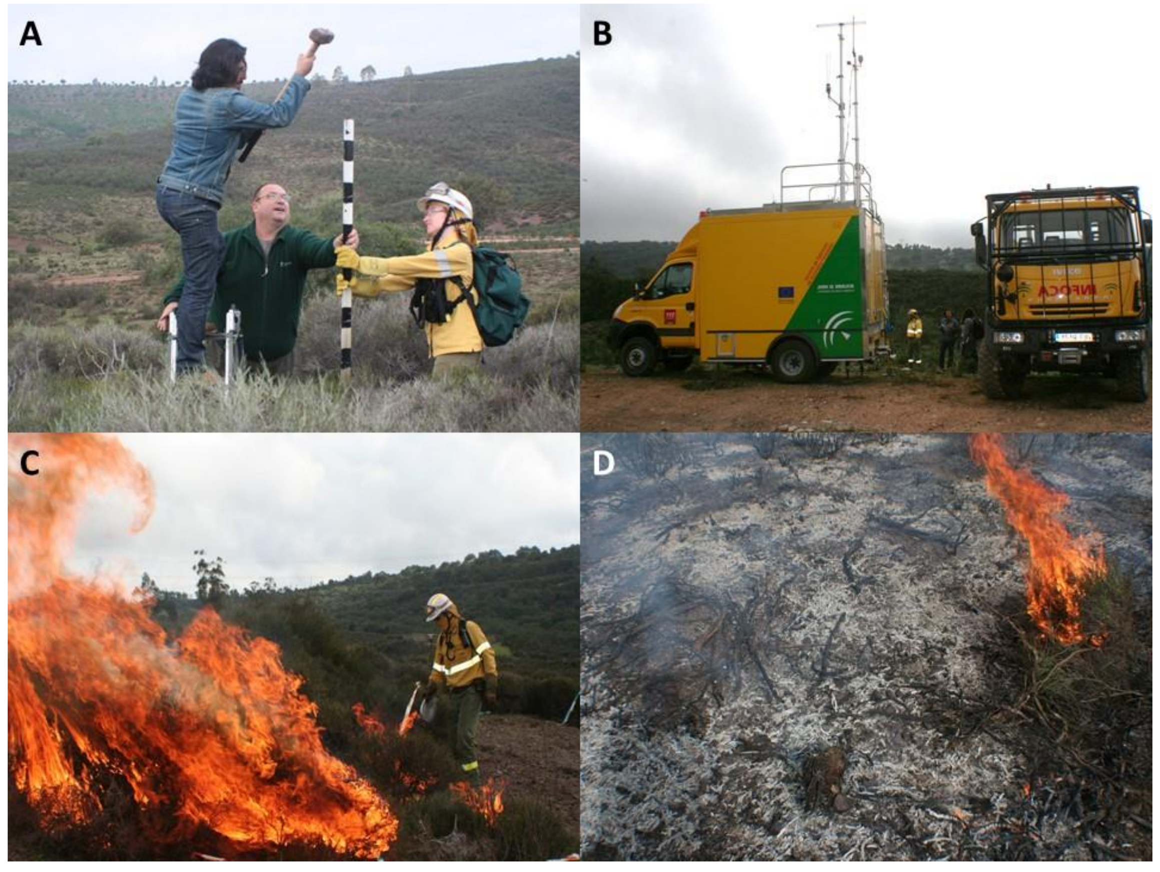

Figure 2. A: installation of levelling rods. B: mobile weather station. C: detail of ignition. D: detail of the burned area at the end of the prescribed fire, showing black and white ash layers.

Previously to burn, ten soil samples (0-5 cm depth) were collected inside the experimental area at 10 points selected by randomly generated coordinates (with 5-m minimum distance to the border) for soil characterization (Figure 3-A). Soil samples were transported in plastic bags to the laboratory, spread in paper trays and left drying during 7 days under standard laboratory conditions. When dry, soil samples were sieved (2 mm) and coarse materials were removed.

2.4 SPLASH EROSION

To determine the intensity of splash erosion, 15 plots (100 cm radious) were selected on wettable ash (SW) and other 15 plots on water-repellent ash (SR). Ash water repellency was assessed with the EPT test. At each plot, a splash-sediment collection system was installed in the center of the circular area (Figure 3-B). This system consists of two funnels arranged one inside the other, with a filter paper between them to collect sediment displaced by the impact of raindrops (Figure 4). Each pair of funnels was inserted into the ground protruding about 10 mm to prevent the capture of sediments from runoff. Filter papers were oven-dired (48 h, 110 ºC) and weighted before installing. Filter papers with sediments captured at each point were collected and substituted monthly and the amount of sediment was determined gravimetrically after oven drying (48 h, 110 ºC) between November 2012 and May 2013.

Temporal changes in ash depth in splash erosion plots were measured using knitting needles at seven points (one per sampling date; Figure 3-B). In order to compare the evolution of splash erosion with water repellency of the neighbouring exposed surface, water repellency was assessed in five points at each plot at the time of collection of filters. In order to avoid influence of one point on others, points were selected on one radial line orthogonal to the direction of slope (Figure 3-B).

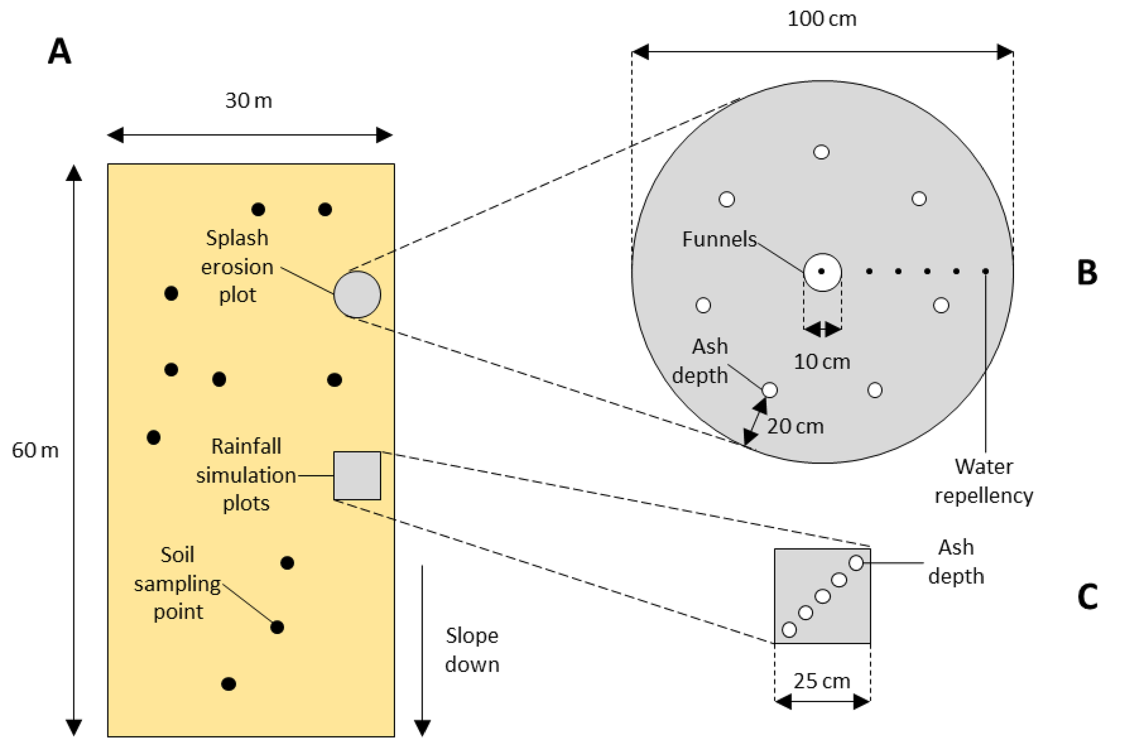

Figure 3. A: experimental area and location of soil sampling points; location of splash and runoff plots is not shown; size of plots is not proportional. B: splash erosion plots and location of points for monitoring water repellency and ash depth. C: rainfall simulation plots and location of points for measuring ash depth. Grey-shaded areas were homogeneous in color and depth (± 5 mm) of the ash layer at the beginning of the experiment.

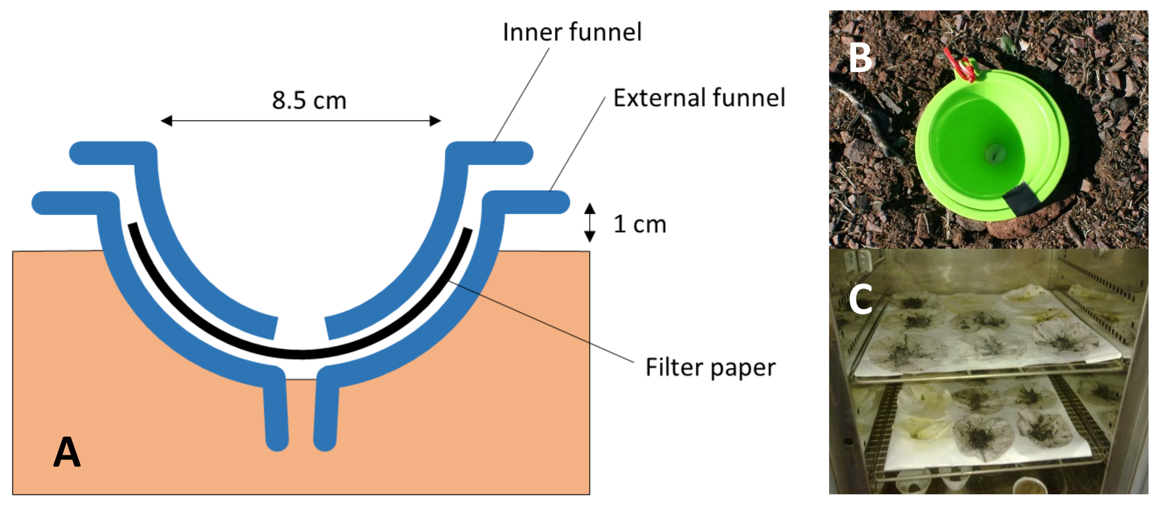

Figure 4. A: description of the system for collection of sediments displaced by splash erosion. B: the system inserted in the ground. C: filter papers with sediments during oven-drying.

2.5 RAINFALL SIMULATION

30 plots (25 cm × 25 cm) were selected on wettable ash (RW) and other 30 plots on water-repellent ash (RR) (Figure 3-C). Rainfall simulation experiments were carried using a Kamphorst portable simulator. Prior to rainfall simulations, the thickness of the ash layer was measured using knitting needles in five points evenly distributed on the diagonal of the experimental area (Figure 3-C) and the mean value was considered representative of each plot. During the simulations, water drops (5.9 mm, 0.106 g, on average) fell from an average height of 40 cm with a constant intensity of 60 mm min^{-1} during 10 min over the experimental area (0.0625 m^2). A gutter was used to direct runoff water to a container placed in a hole dug in the ground. Runoff water was collected periodically for calculation of runoff volume. The runoff rate was calculated as the proportion (%) of runoff water collected in relation to the total amount of water used in each test (60 L m^{-2} min-1 × 10 min × 0.0625 m^2 = 37.5 L).

2.6 DATA ANALYSIS

Analysis of normality and homogeneity of all variables was performed using the Shapiro-Wilk and Brown-Forsyth tests, respectively. When the null hypothesis was accepted, parametric tests and statistics were used (ANOVA, post hoc Fisher's least significant difference -LSD- test, Student's t-test, Pearson's correlation coefficients, average, standard deviation and regressions). If a variable did not satisfy both conditions, non-parametric tests and statistics were used (Spearman's rank correlation coefficient, mode, median and range). STATGRAPHICS (Centurion version 16 StatPoint Technologies, 1982-2011) software was used for all analyses.

3. RESULTS

3.1 CHANGES IN ASH PROPERTIES

Figure 5 shows the distribution of ash depth immediately after burn. Both in water-repellent and in wettable areas, the thickness of the ash layer decreased from ~30 (November, 2012) to ~1 mm (May, 2013) during the study period. This behavior of the ash layer is in agreement with previous research, which has shown the ephemeral character of ash during the postfire. Although the initial thickness of the ash later depends on the spatial variability of fuel and fire severity, wind and water erosion may cause an intense redistribution of ash particles after burn. Also, compaction, bioturbation, lixiviation and illuviation processes may cause changes in ash depth.

The intensity of ash water repellency varied between 0 (very wettable) and 5 (very strong) at the beginning of the experiment (Table 1). In the wettable ash areas, water repellency varied between very wettable (0) and wettable (1). Figure 6 shows the distribution of water repellency classes in the water-repellant ash areas (median EPT = 4, range: 2-5). Differences in ash water repellency are caused by type of fuel (in our experiment, shrub cover and composition was homogeneous) and fire severity. As hydrophobic organic residues are the cause of water repellency, differences in fire severity are suggested as the cause of the spatial pattern of wettable/water-repellent ash. As measured in splash erosion plots under field conditions, the intensity of water repellency in water-repellent ash areas decreased with time from strong, median EPT = 4, to wettable, 1 (Table 1).

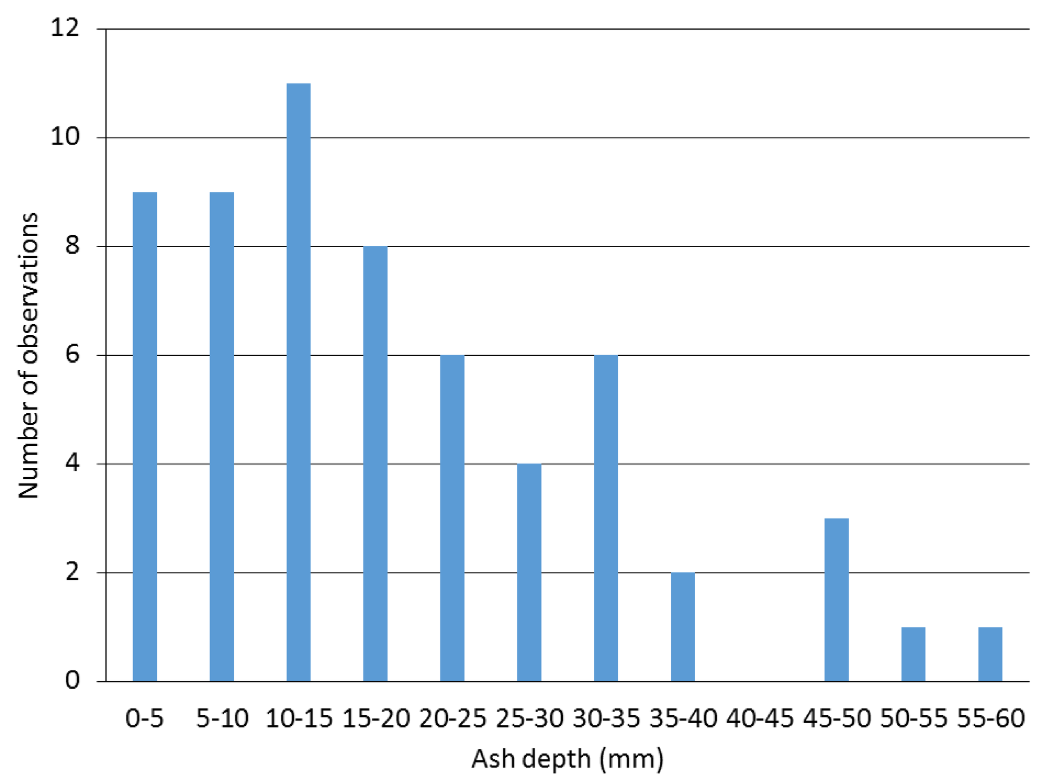

Figure 5. Distribution of ash depth classes in the study area.

Table 1. . Water repellency (median EPT class and range between parentheses) of the neighbour area (5 cm radius) in originally water-repellent and wettable areas, depth of the asy layer (mean ± standard deviation, mm) and amount of sediment displaced by splash erosion (mean ± standard deviation, g). Results of the ANOVA test (p-value) for sediment displaced are shown. Mean values followed by different letters within the same column show significant differentes (p ≤ 0.05). N = 15 in all cases.

Date	Water-repellent ash areas			Wettable ash areas		
	WR	Depth	Sediment	WR	Depth	Sediment
10/11/2012	4 (2, 5)	30.0 ± 5.8	3.90 ± 0.44	1 (0, 1)	28.9 ± 5.6	1.29 ± 0.12
20/12/2012	3 (1, 4)	18.1 ± 7.0	5.28 ± 0.69	1 (0, 1)	18.3 ± 6.0	1.48 ± 0.17
20/01/2013	2 (1, 3)	9.8 ± 4.1	10.61 ± 1.34	1 (0, 1)	11.4 ± 5.2	3.06 ± 0.39
20/02/2013	2 (1, 3)	4.8 ± 2.4	14.20 ± 1.75	1 (0, 1)	7.2 ± 2.9	4.32 ± 0.47
20/03/2013	2 (1, 3)	3.1 ± 1.9	16.97 ± 1.66	1 (0, 1)	4.2 ± 2.8	4.96 ± 0.52
20/04/2013	1 (1, 2)	1.9 ± 1.3	19.91 ± 2.16	1 (0, 1)	2.7 ± 1.8	6.10 ± 0.58
20/05/2013	1 (1, 2)	1.2 ± 0.9	21.74 ± 3.27	1 (0, 1)	1.4 ± 0.8	6.14 ± 0.69
All dates	2 (1, 5)	9.9 ± 10.7	13.23 ± 6.70	1 (0, 1)	10.6 ± 10.1	3.91 ± 1.94
ANOVA, p-value		0.0000	0.0000		0.0000	0.0000

3.2 SPLASH EROSION

For the ash-covered water repellent area, the results of all samples showed significant differences between them. On average, the number of displaced sediment was 13.23 ± 6.70 g. During the first four months after the fire, the amount of sediment displaced by splash increased rapidly up to 264.10% (from 3.90 ± 0.44 to 14.20 ± 1.75 g). By contrast, during the last three months, the number of displaced sediments remained high, but growth was lower, only 28.11% (from 16.97 ± 1.66 to 21.74 ± 3.27 g).

In the case of the area covered with hydrophilic ash, the amount of sediment was much smaller, as well we consider all samples together (t = -13 to 7017, p-value = 0.000), as individually (average values fluctuated from 1.29 and 6.14 g). During the first two sampling after the fire, the values did not differ from each other (1.38 ± 0.18 g on average). Subsequently, the amount of sediment collected grew slowly until the last two samples (6.12 ± 0.63 g on average).

Several authors have suggested that ash protects soil from the direct impact of raindrops and thus reduce splash sediment dispersion. However, there is very little information about the effect of hydrophobicity on splash erosion. Our results show that sediment displacement increased with time, as the depth of the ash layer decreased, and that water repellency contributed to increased splash erosion rates.

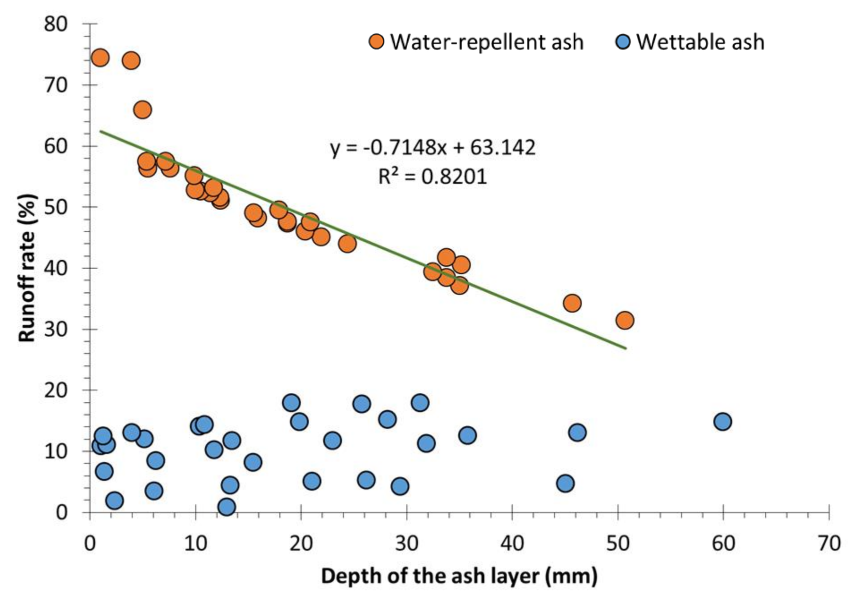

Figure 6. Runoff rate versus depth of the ash layer in water-repellent and wettable ash areas.

3.3 RAINFALL SIMULATION

Although no significant differences were found between the thickness of the ash layer from wettable (18.69 ± 15.06 mm) or water-repellent areas (18.49 ± 12.78 mm), significant differences were found for runoff coefficients (p = 0.0000). While in the water repellent ash, the runoff coefficient showed an average value of 49.9 ± 10.08% in the wettable areas this value decreased to 10.28 ± 4.86%.

Runoff coefficient from wettable areas is independent of the thickness of the ash layer (Figure 6). Low runoff coefficients observed, suggest that despite the saturation of the ash layer with water precipitation, a general process of infiltration was favored (higher to 80%). In the second case (water repellent ash), clearly shows how the runoff rate decreases with the ash layer thickness.

Compared to the previous case, the process could be more complex. For one, the runoff rate is much higher than the case of the wettable ash, which can be simply explained by delayed infiltration. In addition, the runoff rate decreases with increasing ash layer thickness. This suggests that, after a certain time in contact with water, the hydrophobicity is destroyed and the infiltration is enhanced. When the thickness of the ash layer is higher, a slow incorporation of water which is absorbed by the ash, and can infiltrate soil progressively is allowed. This mechanism explains as well the much higher generation of run-off rate on the water repellent layer as the increase of the infiltration rate when the thickness of the ash layer is increased.

At the working scale, these results agree with previous works in which it has been found that the ash is a key factor in the study of soil erosion affected by fire at pedon scale (1 m^2). However, it is not clear what is the influence of the ash layer on slope or basin scale. Due to the particle size of the ash, it is often suggested that it may contribute to the occlusion of the soil pores, forming a sealing surface that facilitate runoff generation. However, in this work it has been assumed that the effect occurs as well in the hydrophilic ash as in the water repellent ashes, so that differences in runoff generation should be conditioned only by the ash layer capacity to absorb and store water (conditioned by its thickness) and their degree of hydrophobicity. Due to the high heterogeneity of the ash layer, further studies should aim to assess connectivity of water and sediments to improve the knowledge about the influence of ash on erosion, along with other elements such as leaves debris and other wastes partially burned.

5. CONCLUSIONS

Ash plays an important role to protect soil in the post-fire. In this work has also been shown that the intensity of water repellency of the ash, as a result of the biomass and soil organic matter combustio degree, conditions very significantly the hydrological response after fire.

Results of this research show that ash protects soil from splash erosion, particularly in the case of hydrophilic ash. The presence of a water-repellent ash layer, however, in contrast to hydrophilic ash, increases the mobilization and sediment loss.

Water-repellent ash layer presence, increases runoff rate generation. The runoff rate is directly proportional to the intensity of the water repellency. However, during the rain test simulation it has been observed that even with strongly hydrophobic ash, the increase in the thickness of the ash layer contributes to the storage of water, which infiltrates slowly in the soil, thereby decreasing the run-off generation and the erosion risk.

During the post-fire precipitation, a hydrophilic ash layer acts absorbing large amounts of water and maintaining the runoff rate generation reduced at 20%, even as high intensity of precipitation as was used in this assay (350 mm h^{-1} for 10 minutes).

Although fire can increase the soil erosion risk, results suggest that, at plot scale, ash may acts protecting soil from erosion risk.

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