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EFFECTS OF FIRE AND VEGETATION COVER ON HYDROLOGICAL CHARACTERISTICS OF A MEDITERRANEAN SHRUBLAND SOIL

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Abstract

An experimental study based on the effects of fire on soil hydrology was developed at the Experimental Station of “La Concordia” (Valencia, Spain). It is located on a calcareous hillside facing SSE and composed of nine erosion plots (4 x 20 m). In summer 2003, after eight years of soil and vegetation recovery from previous fires in 1995 (with three fire treatments: T1 high intensity fire, T2 moderate intensity, and T3 not burned), experimental fires of low intensity were again conducted on the plots already burned, to study the effects of repeated fires on the soil water infiltration, soil water content and runoff.

Infiltration rates and capacities were measured by the mini-disk infiltrometer method (MDI), assessing the effects of vegetation cover by comparing the under canopy micro-environment (UC) and it´s absence on bare soil (BS), immediately before and after the fire experiments. Soil properties like water retention capacity (SWRC), and water content (SWC), were also determined for the different fire treatments (T1, T2 and T3) and micro-sites (UC and BS). Hydrological parameters, such as runoff and infiltration rate, were monitored at plot scale from July 2002 to July 2004. In the post-fire period, data displayed a 20% runoff increase and a decrease in infiltration (18%).

Differences in the steady-state infiltration rate (SSI) and infiltration capacity (IC) were tested with the MDI on the different treatments (T1, T2 and T3), and between the UC and BS microsites of each treatment. After fire, the SSI of the UC soil declined from 16 mm h^{-1} to 12 mm h^{-1} on T1, and from 24 mm h^{-1} to 19 mm h^{-1} on T2. The IC was reduced by 2/3 in the T1 UC soil, and by half on T2 UC soil. On the bare soil of T1 and T2, the fire effect was minimal and higher infiltration rates and capacities were reached. Therefore, the presence/absence of vegetation when burnt influenced the post-burnt infiltration patterns at soil microscale. On the T3, different rates and capacities were obtained depending on the microsites (UC and BS), with higher SSI (25 mm h^{-1}) and IC (226 mm h^{-1}) on BS than on UC (SSI of 18 mm h^{-1} and IC of 136 mm h^{-1}).

The SWRC and SWC were recovered from 1995 to 2003 (prior to the fires). The 2003 fire promoted high variability on the SWC at pF 0.1, 2 and 2.5, and the SWRC on burned soils were reduced. To summarise, the IC and SSI post-fire decreases, were related to the lower infiltration rate at plot scale, the significant differences in the SWRC between burnt and control treatments, and the increase in the runoff yield (20%).

According to the results, the MDI was a useful tool to characterize the soil infiltration on the vegetation patches of the Mediterranean *maquia*, and contrary to other studies, on the UC soil, the infiltration rate and IC, when soil was dry, was lower than that obtained on BS. Once the soil gets wet, similar values were found on both microenvironments.

Key words: Infiltration, hydrology, mini-disk infiltrometer (MDI), experimental fires, vegetation cover, Mediterranean

Introduction

Wildfires degrade the vegetation cover that protects the soil from the rain´s aggressiveness and erosion processes (Martin and Moody, 2001). Fire consumes litter layer and small bushes, leading to a complete change in vegetation and topsoil structures. Peak rainfall after fire, generates runoff and less water is retained as a ponded one, resulting in reduced resistance times and reduced total infiltration (Ferreira *et al.*, 2008).

Mediterranean soils under shrubland vegetation are often shallow and are located on slopes prone to erosion. In these conditions, the post-fire environment of the surface horizons is a determining factor in establishing the amount of mineral soil exposed to raindrop splash, overland flow, and the development of water repellent soil conditions (DeBano *et al.*, 1998). Physical and chemical changes in the upper soil horizons, induced by fires, greatly affect other properties such as aggregate stability (Andreu *et al.*, 2001), water retention capacity (González-Pelayo *et al.*, 2006), soil bulk density, porosity, permeability (Hubbert *et al.*, 2006), water repellence (Arcenegui *et al.*, 2007), wetting patterns (Robichaud, 2000) and thus soil water infiltration (Letey, 2001). The combustion process also turns the litter and duff layers into ash and charcoal, which can seal soil pores (Neary *et al.*, 1999) and therefore decrease hydraulic conductivity (Robichaud, 2000) and soil infiltration capacity (Rulli *et al.*, 2006).

Additionally, the Mediterranean environments are subjected to strong seasonal climatic fluctuations which modify the soil conditions, and as consequence, hydrological processes (Cerdà, 1996). On Mediterranean hillslopes, either the static or the dynamic soil properties are not uniformly distributed (Bergkam and Cammeraat, 1996) and many of them vary in patches related to micro-topography and vegetation (Bochet *et al.*, 2006; Gimeno-García *et al.*, 2001). In doing so, soil water infiltration in semi-arid areas is highly dependent on the dynamic soil characteristics such as organic matter, root systems, macropores, vegetation cover, soil crust formation, soil aggregation (Bergkam and Cammeraat*,* 1996), soil water content (Rulli *et al.*, 2006), rock fragment size, percentage and geometry (Poesen *et al.*, 1990). The spatial and temporal variability of these soil properties are subjected to the discontinuous distribution of vegetation and the complex interactions between plant and soil surface (Kutiel *et al.*, 1995; Gimeno-García *et al.,* 2001; Bochet *et al.*, 2006). As a result, the plant environment influences soil surface properties and hence, soil water infiltration and redistribution (Pierson *et al.,* 2001). Thus, the upper soil layer characteristics are determinant to establish the soil water infiltration and therefore the post-fire changes in the upper horizon are relevant to understand hydrological processes on burned slopes.

For that reason, the aim of this research is to quantify variations in soil hydrological parameters (infiltration rate and capacity, soil water content, and soil water retention capacity) under natural field conditions and after a repeated fire, and to consider the effect of the previous presence or absence of vegetation cover on the soil surface hydrological properties.

2. Materials and Methods

2.1. Study area and experimental set-up

The study has been carried out in the Permanent Experimental Field Station of "La Concordia", located on a forested area ceded by the Valencian Government (Generalitat Valenciana). It is placed at 50 km NW of the city of Valencia (39º45' N and 0º43' W) at an altitude of 575 meters a.s.l. (Figure 1). The Station represents a forested hillside facing SSE, with an average slope of 30% and consists of a set of nine erosion plots. Each plot is 4 m wide and 20 m long (80 m^2), with similar soil type, slope gradient, rock outcrops and vegetation cover characteristics. The selection of each plot was made after intensive monitoring of its soil, vegetation (number of individuals of each species, height and diameter) and morphology patterns and based on 58 transects slope dispersed every two metres (Andreu *et al.,* 2002).

Plots were closed, bounded by bricks and positioned parallel to the slope. At the foot of each plot, a 2 m wide collector ran into a 1500 litre tank to record all runoff and sediment produced during each rainfall event. Inside each main tank, there was a 30 litre tank to concentrate the runoff and sediments yielded in the collection. Runoff generation and the infiltration rate (mm h^{-1}), were monitored in each plot and for each erosive rain event occurred during the two year study period (July 2002 to July 2004) (Figure 2).

The meteorological characteristics were registered by an automatic meteorological station placed half way up the slope in the central part of the Experimental Station. A CS700 tipping bucket rainfall gauge recorded the rainfall volume (mm), the rain intensity (calculated for the maximum volume of precipitation occurring in 30 minutes) as I_{30} (mm h^{-1}), and duration (minutes) for each rainfall event occurred between July 2002 to July 2004. All the rain events were registered and the erosive rain events were only considered if they produced measurable runoff in the tanks. The mean annual precipitation in the area was around 400 mm, with maximum rain in autumn and spring and minimal rain in summer. The average temperatures ranged between 13.3ºC in the coldest month (January) and 25.8ºC in the hottest one (August).

Soil belongs to a Rendzic Leptosol type (FAO-UNESCO, 1988), developed on Jurassic limestone. Some of these soil characteristics are described in Gimeno-García *et al.* (2007). The soil has a variable depth of no more than 40 cm, good drainage and an important microbiological activity, confirmed by frequent and discontinuous soil pores (Rubio *et al.,* 2003). Soil surface is characterised by the existence of cracked stones and a high superficial stoniness ($\cong$ 65 %).

The shrubland vegetation is a scattered matorral (maquia) of medium height with *Globularia alypum, Rosmarinus officinalis, Ulex parviflorus, Cistus clusii, Thymus vulgaris, Rhamnus lycioides, Stipa tenacissima,* and *Quercus coccifera*, as the dominant species. This vegetation resulted from the degradation of the original *Rhamnus lycioides-quercetum cocciferae* association.

2.2. Fire treatments

In 1995, a random design of three plots for each fire intensity treatment was used. The different fire intensities were achieved by adding different amounts of biomass from the surrounding shrub vegetation: 4 kg m^{-2} for the high intensity fire (T1) and 2 kg m^{-2} for the moderate intensity fire (T2). The fuel load was spread uniformly on the plots creating fuel continuity. The remaining three plots maintained unburnt to be used as control (T3). A complete description of the fire performance and soil temperature results is given in Gimeno-García *et al.* (2004).

The repeated fires were performed on the 17th and 18th of July 2003. After eight years of recovery, the six plots previously burnt in 1995 were burned again without any biomass addition, to simulate the natural characteristics of a repeated fire. Only a small quantity of straw (0.25 kg m^{-2}) was sparsely added to achieve fire continuity on the slope.

The soil surface temperatures and fire duration were measured by means of thermo-sensitive paints and thermocouples. In 1995, statistically significant differences between the average temperatures and the medium values of residence time (soil temperatures greater than 100ºC) were observed between T1 (439 ºC and 36 minutes) and T2 (232 ºC and 17 minutes) (Gimeno-García *et al.,* 2004).

The average soil surface temperature in the 2003 fire reached 170ºC, and the mean values of residence time of temperatures greater than 100ºC for all the plots were around four minutes. With this fire behaviour, and according to the classifications established by DeBano *et al.* (1998) and Robichaud *et al.* (2000), these repeated fires were classified as a low severity. However, we have conserved the plots denomination from the 1995 fires (T1, T2 and T3) to check if the 1995 treatments influenced the results of 2003, and also to differentiate between the treatments.

2.3. Infiltration measurements (Minidisk infiltrometer, MDI)

The determination of the infiltration rate in Mediterranean field conditions requires a greater number of measurements due to it´s high spatial variability (Kutiel *et al.,* 1995). For that reason we chose to use the minidisk infiltrometer (MDI) (Decagon Devices, Pullman, WA; radius 1.59 cm) as it was used by several authors (Angulo-Jaramillo *et al.,* 2000; Lewis *et al.,* 2006), and because it is easily transportable, it is easily fitted to make slope measurements (because its relatively small diameter), and because it is a non-destructive methodology that allow us to repeat the measurements in the same spot, being comparable if they are done with the same soil moisture conditions.

Infiltration measurements were performed under a pressure of -2.0 cm of water using the method proposed by Zhang (1997). It is quite simple and works well for measurements of infiltration into dry soil. The method requires measuring accumulative infiltration *vs*. time and finding the results using the method

$$I = C_1 + C_2\sqrt{t} \qquad (1)$$

where C_1 (m s^{-1}) is related to hydraulic conductivity, C_2 (m $s^{-1/2}$) is related to soil sorptivity and t (s) is the time. The hydraulic conductivity of the soil (k) is then computed from

$$k = \frac{C_1}{A} \qquad (2)$$

where C_1 is the slope of the curve of the accumulative infiltration *vs.* the square root of time, and A is a value relating the van Genuchten parameters for a given soil type to the suction rate and radius of the infiltrometer disk. A is computed from:

$$A = \frac{11.65(n^{0.1}-1)\exp\left[2.92(n-1.9)\alpha h_0\right]}{(\alpha r_0)^{0.91}} n \geq 1.9$$

$$A = \frac{11.65(n^{0.1}-1)\exp\left[2.92(n-1.9)\alpha h_0\right]}{(\alpha r_0)^{0.91}} n < 1.9 \qquad (3)$$

where n and α are the van Genuchten parameters for the soil, r_o is the disk radius, and h_o is the suction at the disk surface. The van Genuchten parameters for the 12 texture classes were obtained from Carsel and Parrish (1988). The sandy-loam soil texture computed an A value of 5.2.

Before measuring the infiltration, each minidisk infiltrometer was subjected to an ultrasonic bath to avoid soil particles plugging the semi-permeable plastic disk pores. By doing this, the reproducibility of the measurements was checked before using the apparatus on soil located in the area of the experimental station but outside of the plots. Soil water content was also measured before each infiltration test by a ThetaProbe type ML2x (Delta-T Devices Ltd, Cambridge, UK).

Even though the minidisk infiltrometer is a useful tool in water infiltration studies, the great spatial variability on soil properties, the discontinuity at the hillslope hydrology, and its operation in the preferential flow of micropores (Decagon Devices, Inc. 2006), implies the need of a large number of measurements for the complete slope hydrological characterisation. However, the measurements carried out through time always in the same soil spots, allow us to know the micro-scale soil infiltration and sorptivity evolution and thus, to quantify the impact on soil surface of an external agent as fire.

The steady-state infiltration (SSI) is defined as a part of the infiltration curve with little slope variation with time during the experiment (Martin and Moody, 2001). In this way, the infiltration measurements were performed during 20 minutes and they were also theoretically extrapolated to 60 minutes to check differences between both time spaces. Results showed no statistically significant differences, and therefore, the 20 minutes were considered enough time to reach the steady-state conditions.

The patchy distribution of the vegetation allowed us to compare the measurements under canopy (UC) and on bare soil (BS) microsites. By doing this, four infiltration measurements at each plot were made: two under canopy (UC) and two on bare soil (BS), with a total of 36 tests for each period (before fire and after fire). The field work was carried out on 14th and 15th of July 2003, 3 days before the experimental fires performance. After the fires, the tests were performed on the 27th and 28th July. In nearly all cases, the infiltration measurements were made under antecedent soil moisture <5%, and always in the same place for each plot. Prior to each infiltration test, the ashy residue and superficial stones lying on the soil surface were carefully removed to facilitate the intimate hydraulic contact between the mineral soil surface and the water source.

The SSI and the infiltration capacity (IC, maximum rate of water transmission into soil) for each microsite, plot and treatment were calculated. The ratio of infiltration rates on burnt *vs.* pre-burnt soils (Martin and Moody, 2001) was obtained. It could be a useful tool for comparing the effects of fire on soil and on the hydrological conditions of the tested microsites.

Analysis of variance (ANOVA) and Tukey's test at $p<0.05$, were performed to detect differences in the soil infiltration rate between vegetation cover (UC) and on bare soil (BS) on the different treatments, before (BB) and after fire experience (AB).

2.4. Soil sampling and analysis

A total of seventy two soil samples were taken before and immediately after the fire. The sample depth was 5 cm from the surface of under canopy (UC) and on bare soil (BS) microsites. Samples were taken close to the infiltration measurement points. After this procedure, the samples were air-dried, screened with a fraction diameter < 2 mm and stored in plastic boxes for analysis.

Soil water retention capacity (SWRC) was inferred from the soil water content (SWC) analysis. The SWC was calculated at a pressure head of -0.5 kPa, -10 kPa, -33 kPa, -330 kPa, and -1500 kPa (pF 0.1, 2, 2.5, 3.5 and 4.2, respectively), using the pressure plate membrane method (Hillel, 1980). Results were expressed in percentage of volume (%) and the pF curves were drawn (Figure 5). Soil core volume was 1.16 cm^3 and three replications per samples were made (n=216). The bulk density (ρ_b) was obtained by the dry weight/soil core volume.

SWRC was calculated for each soil sample using the equation:

$$SWRC=(\theta_{10} - \theta_{1500})^* \rho_b \qquad (4)$$

where θ_{10}, θ_{1500} are gravimetric water volumes at -10 kPa (pF 2) and -1500 kPa (pF 4.2), respectively, and ρ_b is the bulk density of soil samples (Hillel, 1980).

3. Results

3.1. Rainfall pattern

In the decade between 1994-2004, high rainfall variability was recorded at the La Concordia Experimental Station. The precipitation volume ranges between 204 mm in 1998 and 556 mm in 2002 (Campo *et al.,* 2006), making 380 mm, the average precipitation for that decade.

This study, as previously mentioned, was focused between July 2002 and July 2004. We have taken into account the pre-fire year and the erosive rain events registered between July 2002 and July 2003. In this elapsed time, twelve erosive rain storms were recorded compared to the eighteen in the post-fire year (July 2003-July 2004) (Figure 3). The rain intensity (I_{30}) and the duration of rainfall in the pre-fire year were in general, more homogeneous than in the post-fire events. Rain volume reached 390.4 mm and the average I_{30} was 6.2 mm h^{-1}, with a maximum of 21.2 mm h^{-1} and a minimum of 1.6 mm h^{-1}. Whereas, in the post-fire year, the rain volume measured was 285 mm and the average I_{30} was 13.4 mm h^{-1}, with a maximum of 65.4 mm h^{-1} and a minimum of 2.2 mm h^{-1}. Twelve days after the repeated fire, in the rain event occurred on 30th July, there was a peak of rain intensity. In addition, the next three rainstorms had I_{30} between 20 to 40 mm h^{-1}, and denoted major rain aggressiveness after the experimental fires (Figure 3). The average time duration of rain events in post-fire year was 534 minutes per event compared to 1515 minutes per event in pre-fire year.

3.2. Runoff trends

Runoff rates on burnt plots increased after the 2003 fire and showed statistically significant differences in relation to the pre-fire levels. On the control plots (T3), no differences in runoff rates appeared between pre- and post-fire periods (Figure 4a). In the pre-fire year, the total runoff for T1 and T2 yields 4.9 L m^{-2} and 5.4 L m^{-2}, respectively. Whilst, on the control plots the runoff was 1.3 L m^{-2}. Before the 2003 fire, between the burnt (T1 and T2) and control (T3) treatments, a difference of 75% still remained, even though these runoff values were on the same order of magnitude.

One year after the 2003 fire, the T3 maintained the same pre-fire runoff values, however, on the burnt ones, these values sharply increased, on average from 5.1 L m^{-2} to 27.8 L m^{-2}.

The differences between the fire treatments were of 10% (T1, 26.2 L m^{-2} and T2, 29.4 L m^{-2}), but the difference between burnt and control plots increased until 95% (27.8 L m^{-2} on burnt plots and 1.5 L m^{-2} on control ones). We also highlight the peaks of I_{30} in the early rain events occurred after the low intensity fire (Figure 3). In the first four rain events, the average I_{30} increases up to 20 mm h^{-1} (even values up to 60 mm h^{-1} were recorded on the 30th of July of 2003) and the runoff produced in burnt plots represented the 65% of the whole runoff yielded in the post-fire year. Whereas, in the control plots, the runoff generated in the first four rain events represented the 55%. According to the results, differences of one order of magnitude were reached between the burnt and control treatments (Figure 4a), denoting the changes in the soil hydrological behaviour and also the importance of the I_{30} peaks after fire.

3.3. Pre and post-fire hydrological conditions

The values of infiltration rate at the plot scale supports these findings on the runoff trends. In the pre-fire year, insignificant statistical differences were observed between treatments, 2.78 mm h^{-1} in burned plots and 2.82 mm h^{-1} in the control ones. At the end of the post-fire year, the infiltration decreased in the burnt plots, showing statistically significant differences relative to the control ones: 5.6 mm h^{-1} and 5.2 mm h^{-1} in T1 and T2, respectively, and 6.6 mm h^{-1} in T3 (Figure 4b).

On the other hand, after a fire disturbance in a shrubland area, one soil quality indicator could be the soil water retention capacity (Boix-Fayos, 1997). According to this indicator, we notice that before the fire experience, no statistically significant differences between burnt and control treatments appeared (Table 1). Hence, before the 2003 fire, some hydrological properties as infiltration rate at the plot scale and SWRC, were substantially recovered in the burnt plots, showing similar conditions to those of the control ones (Figure 4b and Table 1).

The degrading effect of fire affected the SWC and SWRC (Figure 5 and Table 1). Instead of the slight rise on the after burnt SWRC, there is statistical evidence of less water content in T1 and T2 relative to those on T3. Also the data revealed high water content variability at low pF and thus, the gravitational water content increased in contrast to the capillary and hygroscopic one (Figure 5).

3.4. Effects of fire and presence/absence of vegetation on the steady state infiltration (MDI)

3.4.1. Fire effects

The fire impact on soil surface generated a decrease in the infiltration rates; T1, from 19.6 to 17.2 mm h^{-1}, and T2, from 22.3 to 21.5 mm h^{-1}, even though there is no significant statistical evidence (Table 2).

According to Martin and Moody (2001), the burnt/not burnt ratio on the SSI, provides a relative measurement of the fire effects on soil infiltration and it is useful for comparing disparate sites. Ratios of 0.88 in T1 and 0.96 in T2, reflected a slight decreasing trend of the SSI, which confirmed its relatively small change.

In relation to the infiltration capacity (IC) and previous to the fire, similar values were reached in T1, T2 and T3. The decline occurred after the fire disturbance was clear and in the T1 and T2, the IC decreased by 50% and 33%, respectively (Table 2). Meanwhile, on T3 the IC did not change and, despite the fact that the IC was almost the double, the SSI (21.7 mm h^{-1}) was almost the same as the one obtained in T1 and T2.

3.4.2. Vegetation effects

3.4.2.1. Natural undisturbed treatment

The patchiness of vegetation on the plots of “La Concordia” describes the variability of topsoil properties. The interspaces between plants (BS) in T3, displayed greater SSI and IC than the UC soil (Table 3). The statistical analysis did not detect differences in SSI, but the greatest values in the bare soil could be related to the clear difference in the infiltration capacity between both microsites (Table 3), with 60% more IC in BS than in the UC soils.

To check the natural water repellence gradient on the UC soil, the Figure 6 draws the infiltration rate over time for the vegetated and non-vegetated soil. The curve can be divided into two sections. Primarily, the initial exponential decrease in the first five minutes (maximum soil sorptivity), and secondly, a linear infiltration behaviour (from minute 5th to minute 20th) as the soil moisture increases. Hence, in the first step (infiltration rates at minute 5th), statistically significant differences ($p<0.05$) between microsites (UC/BS) were obtained: 24.5 mm h^{-1} in UC and 44.1 mm h^{-1} in BS. As the infiltration test runs, the soil wetness increases and when the steady-state (minute 20th) was reached, no statistically significant differences between microsites were obtained: 17.9 mm h^{-1} in UC and 25.4 mm h^{-1} in BS (Figure 6). Therefore, on the compared microsites (UC and BS), the main differences on the infiltration trials occurred in the first five minutes of the test, which could be considered as the influence of water repellence on the UC microsites.

3.4.2.2. Post-fire changes

Robichaud and Waldrop (1994), define fire impact as a magnitude in the alteration of soil properties, which highly depends on the amount of vegetation residue and litter consumption. The study of the variations in the SSI and IC could reflect this effect. Relative to the SSI, differences between microsites (UC and BS) were obtained in the pre-fire infiltration trials on T1 and T2. In T1, 30% less water infiltration was obtained under shrubland compared to the ones on the bare soil. In T2, the IC and the SSI were always larger in the BS microsites than in the UC ones, which only exceeded those of BS (24 mm h^{-1} in UC and 20 mm h^{-1} in BS) (Figure 7) in the last minutes of the test.

The fire impact produced a decrease in infiltration, mainly in the UC microsites. In the UC soil of T1 and T2, the ratios after burned/before burned (AB/BB) were of 0.76 and 0.79 respectively. Comparing microsites (UC and BS), the post-fire differences also increased in T1 (14%) and T2 (6%) (Table 3). On the UC microsites, a marked decrease in the initial stages (at minute 5th) was found. Although at the SSI (minute 20th), the difference regarding the pre-fire values were substantially reduced (Figure 7). The results on the IC seem to be clear, where a decrease of almost 67% in T1 and 42% in T2 (Table 3) occurred and directly affected the water infiltration in the initial stages.

The results obtained on the bare soil, indicate a small fire influence in these areas. The statistical analysis did not detect significant changes between pre- and post-fire conditions on the SSI and on the IC (Table 3). In addition, on BS of T2, a slight increase occurred in the SSI. A different response took place on T1, where no increase in the SSI occurred, and the change relating to post-fire conditions was minimal (Table 3). The burned/unburned SSI ratio on T1 bare soil was of 0.96, while on the infiltration capacity, the mean ratio was of 0.6. On T2, the SSI ratio showed an increase, but the infiltration capacity showed practically no change after the fire disturbance.

4. Discussion

4.1. Rainy periods and runoff behaviour

The precipitations in the Mediterranean basin denote a wide inter-annual variability, especially in rainfall volume and intensity (Gimeno-García *et al.,* 2007). The rain intensity variability on La Concordia Experimental Field Station during 2002-2004 ranged from 1.6 to 91.8 mm h^{-1}. During a year before the 2003 fire, the storm characteristics displayed soft rain intensities (I_{30} ranges between 1.8 mm h^{-1} to 21.2 mm h^{-1}) and long durations. This fact, together with the 30-40% vegetation recovery since 1995, and the negative and exponential relationship between plant cover and runoff (Gimeno-García *et al.*, 2007), facilitated a decrease in the runoff rates during the year 2002. However, the high superficial stoniness (up to 60%) and the income of new litter that could create barriers (Cerdà, 2001; Pierson *et al.*, 2001), were the other factors that promoted a high ponding infiltration and less runoff. Prior to the 2003 fires, the runoff rates in burnt plots were recovered and the values were in the same order of magnitude as on the control plots.

Meanwhile, the post-fire average I_{30} (13.6 mm h^{-1}) and the short elapsed time between fire impact and first rain storms, have directly influenced the runoff trends on the burnt plots, during the first post-fire year (Campo *et al.*, 2006; González-Pelayo *et al.,* 2006; Gimeno-García *et al.,* 2007). Thus, the runoff rates in burnt treatments increased in one order of magnitude compared to the pre-fire values and to the control ones, reporting differences of 95% relative to the T3. Equally, Campo *et al.* (2006) described a runoff divergence of one order of magnitude between this burnt and a non-affected Mediterranean ecosystem. Scott (1993) calculated differences in the runoff up to two orders of magnitude after a wildfire in South African mountains and, Ferreira *et al.* (2008) listed runoff increases of 1 and 2 orders of magnitude depending on the study scale, catchment and plots.

Focussing on the rain events, data reflected that 65% of the runoff was recorded during the early storms which occurred after the fire. Sala *et al.* (1994), Andreu *et al.* (2001) and Gimeno-García *et al.* (2001 and 2007) obtained similar trends and, Rubio *et al.* (1995) indicates the four first months after fires as the most critical period for runoff production in Mediterranean areas. After the 2003 experimental burning, the short elapsed time (twelve days) between the fire impact and the first rainstorm, the post-fire soil surface conditions, together with average I_{30} values of rains up to 20 mm h^{-1}, were the key factors in the one order of magnitude runoff increase.

4.2. Fire influence on some hydrological properties

The decrease of the infiltration at plot scale, the high variability of SWC at low pF values and the significant differences between burnt and control SWRC, are in agreement with the findings of Cerdà (1998), whom, after fire disturbances in a carbonated bedrock soil, found a negative relationship between soil water content (SWC) and infiltration rate. Lower levels of SWRC were also found by Boix-Fayos *et al.* (1997), in similar soil and vegetation burned areas.

In addition to these tendencies, Badía *et al.* (2003) and Rulli *et al.* (2006), found a decrease in the saturated hydraulic conductivity of burnt soils, which is closely linked to the infiltration process (Robichaud, 2000). In other terms, Andreu *et al*. (2001) also reported a post-fire degradation effect, but only with a soil aggregate fraction higher than 2 mm. In studies in the laboratory muffle furnace, García-Corona *et al*. (2004) connected the effects of low temperatures (<220ºC) to changes in the aggregation pattern and presence of water repellency. Therefore, fire impact on soil surface imply alterations on the topsoil structural characteristics (soil cohesiveness, bulk density and compaction), which are directly related to the soil infiltration capacity (Cammeraat and Imeson, 1998).

Consequently, post-fire changes on the SWRC and SWC (Table 1 and Figure 5), are partially associated with the soil structure and aggregation of the soil particles (Boix-Fayos, 1997; Badía *et al.,* 2003; González-Pelayo *et al*., 2006). Therefore, post-fire reduction in soil infiltration must be linked with changes in hydrological parameters, which are partially due to the degradation of soil structure as a result of burning (Imeson *et al.,* 1992). A concomitant factor associated with the infiltration decrease in burned areas, could be the incorporation of hydrophobic compounds on soil surface after the fire impact (Pierson *et al.,* 2001; Shakesby and Doerr, 2006; Ferreira *et al.,* 2008), together with the crusting processes in soil pores by the addition of ashes and detached particles (Neary *et al.,* 1999).

This data reflects that the major variations on the SWC occurred in the soil fraction involved at low retention forces, pF 0.1, pF 2, and pF 2.5 (Figure 5). At these pF values, the amount of water depends primarily on the coarse pore sizes used in capillary and gravity movement of water, and hence, it is strongly affected by soil structure (Hillel, 1980). The greater SWC variability on samples taken after fire disturbance could indicate the soil surface structural changes reported after fire, and are in accordance with the lower infiltration rate, the significant differences in the SWRC between burnt and control treatments, and the increase in the runoff yield.

4.3. Fire and vegetation effects on the infiltration (MDI)

4.3.1. Changes on SSI induced by fire

The burnt/non-burnt ratios of SSI, reflect the soil behaviour on burned calcareous Mediterranean soils. In this study, ratios of 0.88 in T1 and 0.96 in T2 were measured, which agree with the observation of Kutiel *et al.* (1995), whom obtained ratios ranging in 0.85 to 1, in Mount Carmel forest, Israel. On the other hand, Imeson *et al.* (1992), in studies in a post-fire Mediterranean forested plain (Catalonia, Spain), obtained infiltration rates between 15 and 20 mm h^{-1} in a post-fire environment, showing the characteristic water infiltration curve into the soil (Figure 6 and 7), that seems to be related with humus type and fire impact.

Instead of the decrease in the infiltration rate, the post-fire IC reduction was clear. Robichaud (2000) and Rulli *et al.* (2006), also found a decline of hydraulic conductivity from pre- to post-fire soil conditions of about 40% and 60%, respectively. The first suggested that it was caused by the development of fire induced water repellent conditions. Whilst, Imeson *et al.* (1992) also noticed a drop in the IC after fire and argued that it was due to the ground cover reduction, the formation of a water repellent layer and the soil pores being clogged by the ash particles and/or fine sediment. Therefore, it appears to be clear that fire contributes to diminish the soil water infiltration, which it is directly linked with the IC, and the processes involved in its decline.

It was observed that values lower than 1 in the SSI and IC ratios, and the post-fire soil surface conditions, are related to the runoff yield at the plot scale, which increased in one order of magnitude relative to pre-fire values. On the other hand, the reduction in half of the IC in the T1 and T2, relative to the T3 and the pre-fire values, could also be an indicator of the fire impact degree on the hydrological soil surface properties of the affected soil. The importance of the IC is associated with the first steps of the infiltration process, because when the soil is dry and a rainstorm occurs, the IC is one of the relevant parameters for the runoff production.

4.3.2. Natural and burned vegetation effects on soil

4.3.2.1. Infiltration processes on non-burnt soils

The different infiltration behaviour between vegetated and bare soil appears to be related to the first steps of water entry into the soil (Figure 6), when soil sorptivity is at its maximum. Consequently at the 5th minute of the infiltration test, double values of infiltration were found in BS relative to the UC ones. However, at the 20th minute (steady-state) no differences were found. By this, the diverse soil surface properties of vegetated and non vegetated sites (Kutiel *et al*., 1995; Bochet *et al.,* 2006), might to be implicated during the first stages of the infiltration test. Similar soil behaviours were described by Letey (2001), which related the soil sorptivity with the water entry into soil, and partially linked the low water infiltration with water repellent soil conditions facilitated by litter and magnified by fire impact. Also taking into account comparable soils, Arcenegui *et al.* (2007) and Mataix-Solera *et al.* (2007), reported natural soil water repellence in the upper soil layers in alkaline soil conditions under Mediterranean shrubs. They noted that the type and quantity of litter controls the persistence of hydrophobicity and thus, directly influence the infiltration processes. Verheijen and Cammeraat (2007), also determined a repellence gradient from shrub species tussocks to the plant interspaces (BS). Consequently, this natural hydrophobic soil gradients, could affect the hydrological response of Mediterranean slopes characterized by patchy shrubland vegetation. Thus, the more hydrophobic soil surface conditions under the bushes canopy (Arcenegui *et al.*, 2007; Mataix-Solera, *et al.*, 2007; Verheiten and Cammeraat, 2007), retards soil water infiltration by the micropores fluxes (involved in the minidisk measurements), mainly in the first stages of the infiltration test, where the highest infiltration capacity (IC) has been reached in this study.

At the end of the infiltration tests, at the steady-state, similar values on the vegetated (UC) and non vegetated (BS) microsites were reached (Figure 6). It could be related to the decrease of hydrophobic soil behaviour with its wettability (DeBano *et al.,* 1998). Cammeraat and Imeson (1999) and Robichaud (2000), also noticed linear water infiltration behaviour as the soil moisture increases. In vegetated soil with dry conditions (before minute 5th), hydrophobicity could play a role in the decrease of the infiltration capacity (Table 3) and, as a result, in the SSI. Also, when the steady-state was reached and the soil water content increased, the stable water infiltration rate depended on other soil properties.

4.3.2.2. Influence of burnt vegetation on water infiltration

Multiple factors bring about the reduction in SSI in burnt soils in relation to unburnt ones (Martin and Moody, 2001). Letey (2001) and Shakesby and Doerr (2006), describe reductions in soil infiltration by water repellence induced by fire. Neary *et al.* (1999) and Martin and Moody (2001) describes sealing processes on pores by fine soil and ash particles, altering soil superficial porosity. On the other hand, Mataix-Solera and Doerr (2004), observed that finer aggregate fractions exhibited a higher degree of hydrophobicity than the coarsest fraction on a calcareous Mediterranean burnt soil. Finally, Campo *et al.* (2008) describes on UC microsites after the early 1995 fires, a decreasing trend on the macro-aggregate quantity and an increase of the micro-aggregate one. As a consequence, in burnt soils under shrubland canopies, the probable increase of the hydrophobic micro-aggregate fraction combined with the ashy residue, that could plug soil pores, implied a decrease in the infiltration capacity and hence, on the steady-state infiltration (Table 3).

In contrast, on the bare soil, the fire impact was minimal and the changes in the infiltration were negligible. Pierson *et al.* (2001), after a rangeland firestorm in a bush forest range in northwest Nevada (USA), concluded that fire had little influence on the infiltration of the plant interspaces. Furthermore, Robichaud and Waldrop (1994), describe that the fire progression on the slope creates a mosaic pattern of duff consumption and some unburnt areas, due to the spatial variability of the duff thickness and vegetation cover on the slope, and thus some non-vegetated areas are not affected by thermal impact. On bare soil microsites, the major infiltration capacity and SSI could be explained by the lack of stand vegetation acting as a hydrophobic source by the partial decomposition of organic matter after a light fire (Letey, 2001).

5. Conclusions

In the case study, eight years after the early fires in 1995 is enough time for the soil to recover some hydrological properties as soil water content and soil water retention capacity. Differences on runoff yield still remain close to 75%.

The higher runoff yields after 2003 fire disturbance were directly influenced by the low infiltration capacity measured after burning. Runoff increased in one order of magnitude (up to 20 times) during the post-fire year. A relevant factor on runoff generation was the distribution of the rainfall events during the early weeks after fire (I_{30} greater than 20 mm h^{-1} in the first four rainstorms). The runoff produced in these four early rain events, represented 65% of the whole post-fire year runoff, denoting the importance of the I_{30} and the elapsed time between fire and the first aggressive rainstorm.

The natural variability in the steady-state infiltration rate and infiltration capacity at the patchy micro-scale, can be strongly affected by the presence or absence of vegetation. Contrary to other studies, on soil under canopy, the infiltration rate and infiltration capacity, when soil is dry, is lower than that obtained on bare soil. Once the soil gets wet, the steady-state infiltrations are similar on both microenvironments.

On the burnt soils and depending on the microsite, different responses on the infiltration rate and capacity were obtained. The soil under canopy showed a significant decrease of the steady-state infiltration related to the important decline of the infiltration capacity. This drop is involved in the early stages of the infiltration process. On the other hand, the bare soil is less affected and showed a slight change in both parameters. Therefore, the infiltration pattern in burnt areas changes in relation to the non affected ones, and as global consequence, the soil water storage decreases at the plot scale.

5. Acknowledgements

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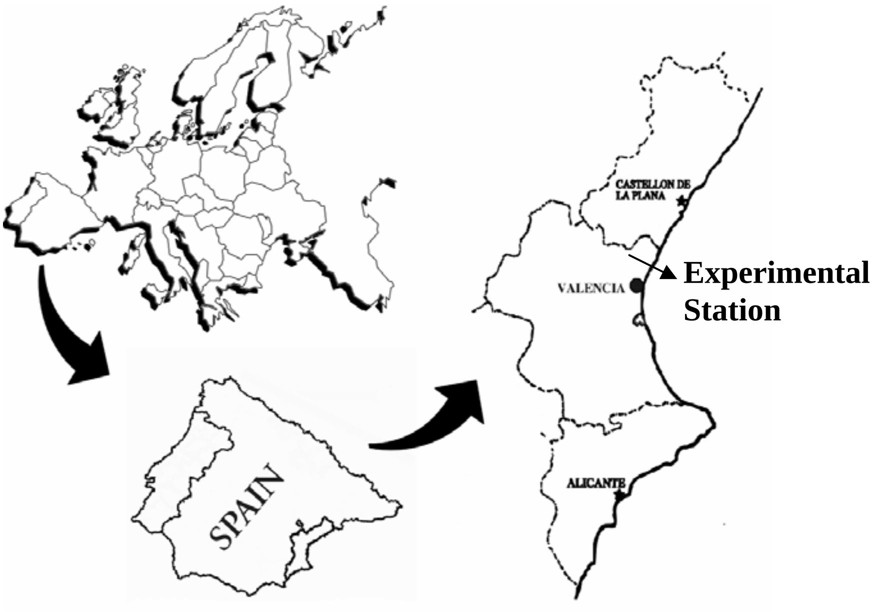

Figure 1. Geographical location of the Experimental Station of La Concordia (Llíria-Valencia, Spain).

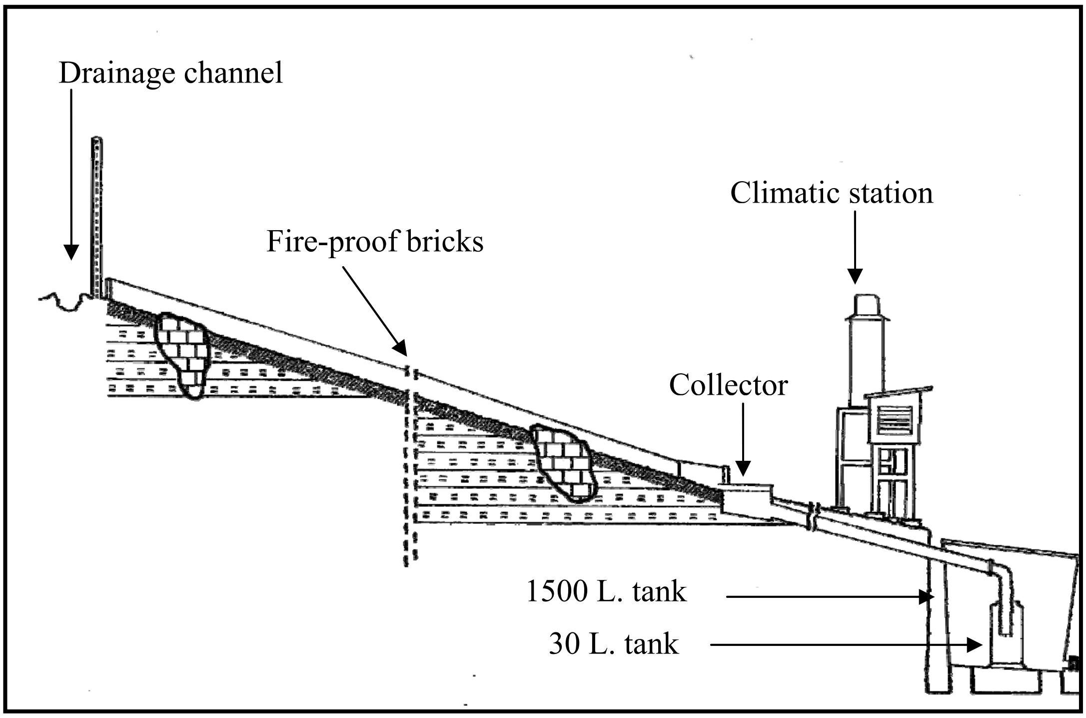

Figure 2. Erosion plot design installed in the La Concordia Experimental Station

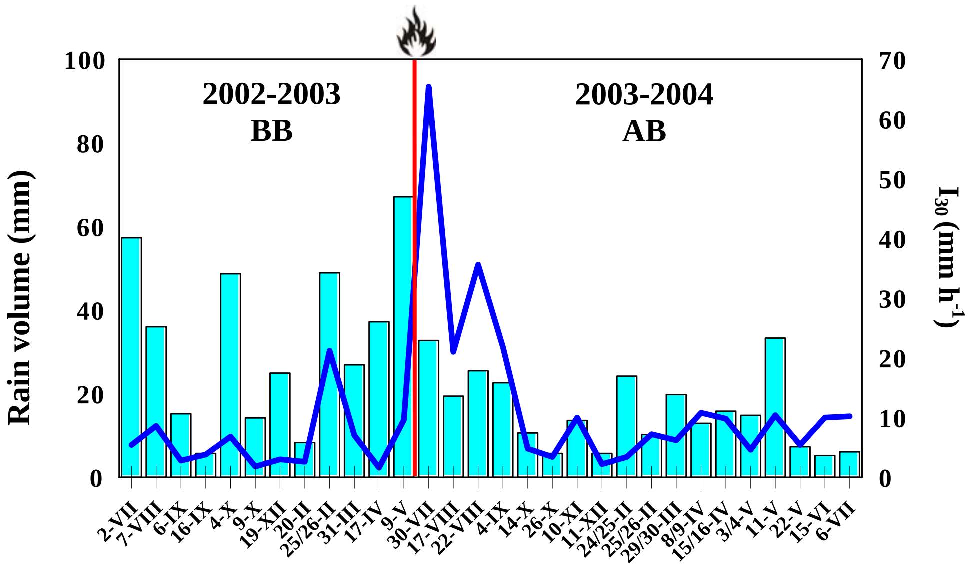

Figure 3. Erosive rain events occurred during the studied period. Rain volume (mm) in bars and I_{30} (mm h^{-1}) in line. BB, before burnt. AB, after burnt.

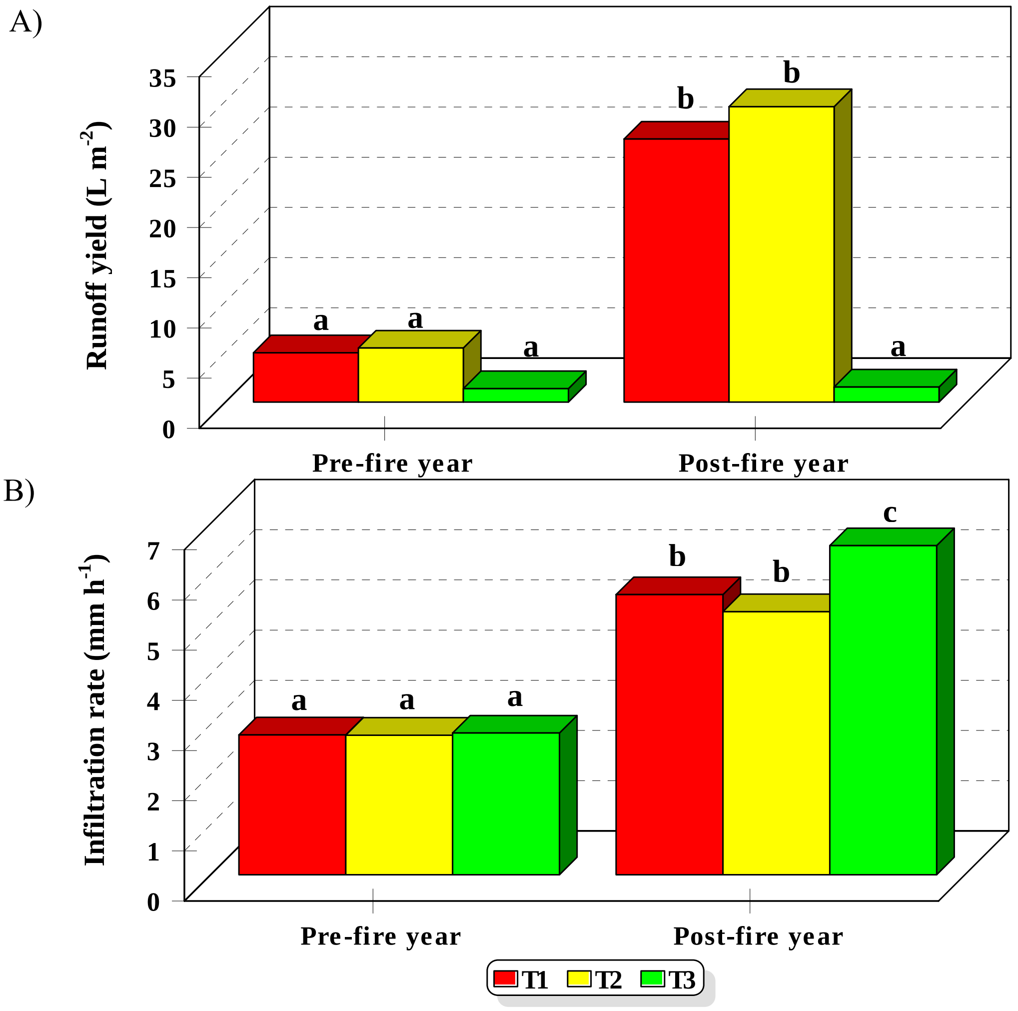

Figure 4. Runoff yielded (L m^{-2}) (A), and infiltration rate (mm h^{-1}) (B) at the plot scale, recorded in the pre- (2002-2003) and post-fire (2003-2004) years. T1, high intensity treatment; T2, moderate intensity treatment; and T3, control. Values not sharing the same letter indicate statistically significant differences according to Tukey´s test ($p<0.05$)

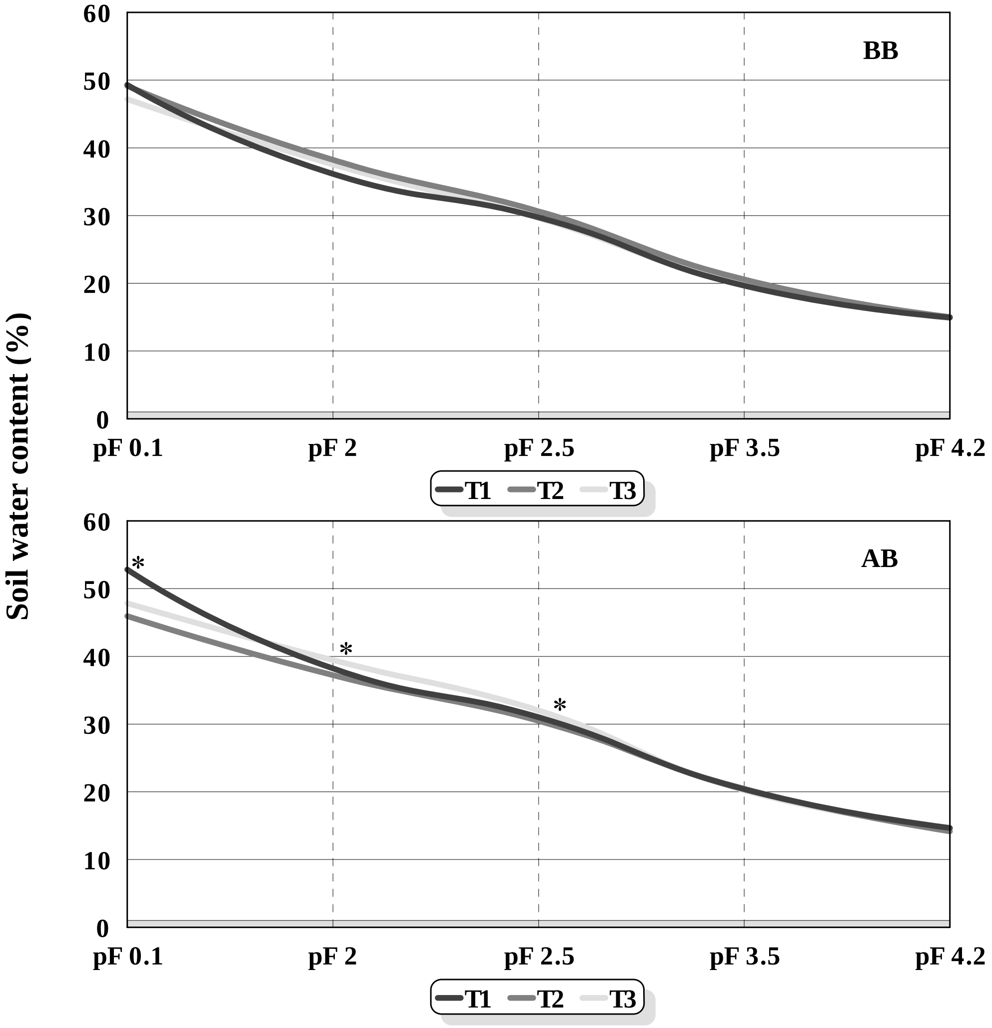

Figure 5. Soil water content (%) extracted by pF curves. BB means before burnt, AB means after burnt. T1, high intensity treatment; T2, moderate intensity treatment; and T3, control. *, Means statistical significant differences between fire and control treatments detected by Tukey's test ($p<0.05$).

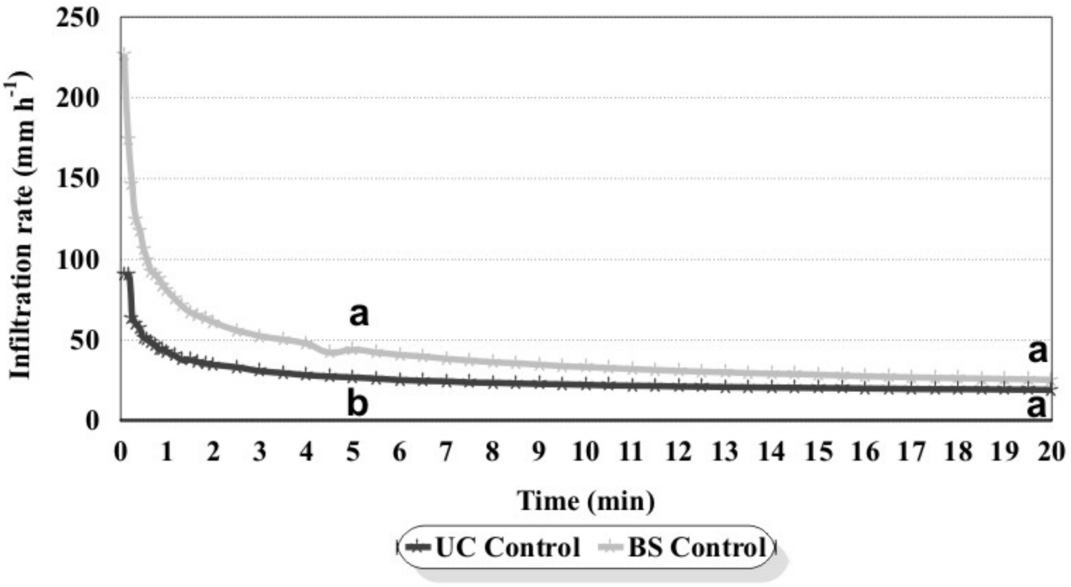

Figure 6. Infiltration rate (mm h^{-1}) over time in T3 (control treatment). UC, under canopy. BS, bare soil. Different letters among UC and BS curves, at 5th minute and at 20th minute, display statistical significant differences detected by Tukey's test ($p<0.05$).

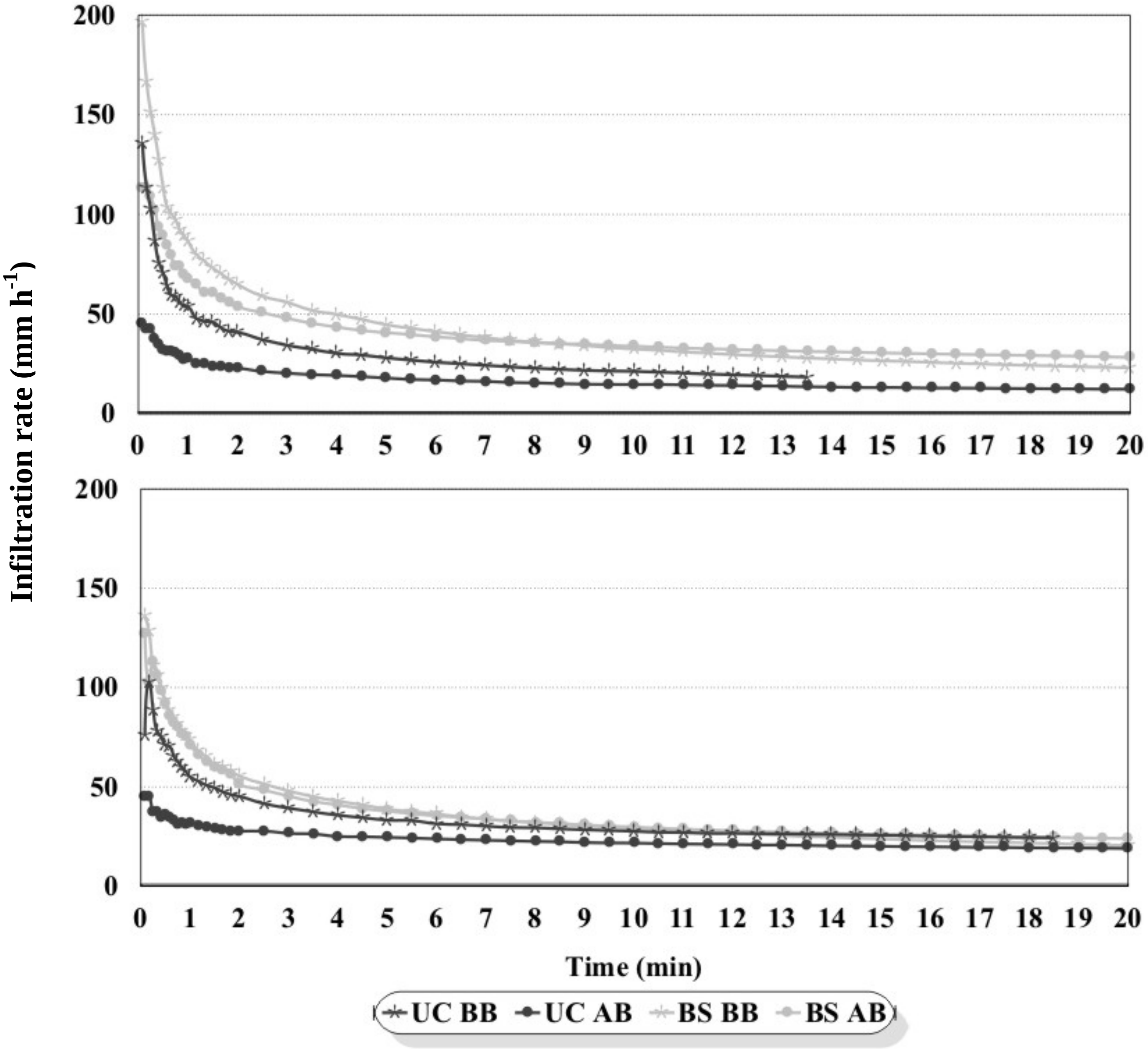

Figure 7. Infiltration rate (mm h^{-1}) over time. T1 and T2 are high and moderate fire intensity treatments, respectively. UC, under canopy. BS, bare soil. BB, before burnt. AB, after burnt.

Table 1. Soil water retention capacity (%) obtained from samples taken before (BB) and after (AB) the 2003 burnt, depending on the fire treatments: T1, high intensity; T2, moderate intensity; and T3, unburned. N=72.

	T1	**T2**	**T3**
BB	21.3 a	23.2 a	22.6 a
AB	23.6 a	22.7 a	25.6 b

[a] Values with the same letter, in the same rows, indicate no statistically significant differences detected by Tukey’s test ($p<0.05$).

Table 2. Steady-state infiltration (SSI, mm h^{-1}) and infiltration capacity (IC, mm h^{-1}), obtained by the minidisk infiltrometer method (MDI), depending on the different fire treatments (T1, high fire intensity; T2, moderate fire intensity; and T3, unburned). BB and AB mean before and after the 2003 experimental fire, respectively. N=72.

		T1	**T2**	**T3**
SSI (mm h^{-1})	**BB**	19.6	22.3	21.7
	AB	17.2	21.5	21.7
	Ratio AB/BB	0.88	0.96	1.00
IC (mm h^{-1})	**BB**	166.2	119.4	158.7
	AB	79.3	86.1	158.7
	Ratio AB/BB	0.48	0.72	1.00

Table 3. Average steady-state infiltration rate (SSI, mm h^{-1}) and average infiltration capacity (IC, mm h^{-1}) measured by means of minidisk infiltrometer method (MDI). T1, high fire intensity; T2, moderate fire intensity; and T3, unburned. BB and AB mean before and after the 2003 experimental fire, respectively. UC, under canopy and BS, bare soil. N=72.

		T1		**T2**		**T3**	
		UC	**BS**	**UC**	**BS**	**UC**	**BS**
SSI (mm h^{-1})	**BB**	16.3	23.0	24.1	20.5	17.9	25.4
	AB	12.3	22.1	19.0	24.0	17.9	25.4
	Ratio AB/BB	0.76	0.96	0.79	1.17	1.00	1.00
IC (mm h^{-1})	**BB**	136.0	196.5	102.8	136.0	90.7	226.7
	AB	45.3	113.4	45.3	127.0	90.7	226.7
	Ratio AB/BB	0.33	0.58	0.44	0.93	1.00	1.00