Hydrological Properties of Mediterranean Soils Burned with Different Fire Intensities

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ABSTRACT

The influence of vegetation cover on soil hydrological properties and its response to the impact of different fire intensities, in a Mediterranean forest environment, has been evaluated. The study was carried out in the Permanent Experimental Field Station of La Concordia (Lliria-Valencia, Spain), on a set of nine erosion plots (4 x 20 m). The Station is located on a calcareous hillside S-SE oriented, with soils of Rendzic Leptosol type and supporting Mediterranean shrubland vegetation. All runoff generated and sediment produced in every rain event was collected from each plot. The set up includes a system of sensors for the continuous monitoring of climatic parameters (air temperature and humidity, rain volume, intensity, etc).

In June 1995, a set of experimental fires were carried out on the Station. Three of the plots were burned with high intensity fire, three with moderate intensity and the remainders were left unaltered. Soil water content and water retention capacity (WRC) were measured in the different plots and in two different vegetation covers: under canopy (UC) and in bare soil (BS). The pF curves were also obtained for each fire treatment.

During a year after the fires (June 1995-June 1996) great differences in runoff generation between fire treatments and the control plots were observed.

No significant differences were detected on water retention capacity between soils UC and BS, in the burned plots. However these differences appeared in the control plots, giving values for UC and BS of 0.130 cm^3 cm^{-3} and 0.180 cm^3 cm^{-3}, respectively. Plots corresponding to the high fire intensity treatment showed values of WRC significantly higher than those of the moderate intensity and of the control treatments.

The pF curves show that the values of water volume, at the different pressure points studied, were slightly greater on UC soil. Values obtained for BS samples are higher in the

fire treatments, showing significant differences in respect to the control plots at pF 1 and 2. These differences were also observed for UC soil, but in this case at pF 2, 2.5 and 4.2.

Keywords:

1. INTRODUCTION

In Mediterranean areas, shrubland vegetation is often structured in a spotted spatial configuration, playing a significant role in controlling runoff generation and soil loss. The interaction between vegetation development, soil surface properties and water movement strongly influences the structure of Mediterranean ecosystems (Cammeraat *et al*., 1999). Theses patterns could change as a result of fire (Moreno, 1999).

Forest fires have become a common phenomenon during summer in many European Mediterranean countries. Their effects are more evident on environments like those characteristic of the Mediterranean area (Rubio and Recatala, 2005; Trabaud, 1990). The immediate consequences are the loss of protective vegetation cover and a strong visual impact on the landscape.

The soil environment, during and after fire is affected directly by the input of heat and ashes. In the field, the effects of these factors are concomitant, making the identification of individual causes of changes in soil properties, such as degradation of organic matter or changes in aggregate size distribution, between others, difficult (Giovannini and Luchesi, 1997).

Post-fire conditions on soil surface are of key importance because they determine its response to raindrop splash, overland flow and the development of water repellent soil conditions (De Bano, 1981).

One of the most useful ways to study the effects of fire on the soil system is carrying out fires in experimental plots. With this approach, it is possible to know and measure soil conditions before, during and after the fire experiment and to improve knowledge about the hydrology of the zone affected by different intensities of fire (Rubio *et al.*, 1994).

The aim of this study is to evaluate post-fire changes in hydrological properties on a typical Mediterranean slope comparing fire affected and not affected soil. The evolution of soil response to runoff processes was also studied in each rainfall event for a year after the fire experiments.

2. MATERIALS AND METHODS

2.1. Study Area

This work was carried out in the permanent Experimental Station of La Concordia (Lliria-Valencia, Spain), 50 km NW of Valencia city (Figure 1). It is 575 m above sea level, on a forested hillside South-South East facing, with a sclerophyllous shrub cover regenerated after a previous wildfire occurred in 1978. The most abundant species include *Rosmarinus officinalis*, *Ulex parviflorus*, *Quercus coccifera*, *Rhamnus lycioides*, *Stipa tenacissima*, *Globularia alypum*, *Cistus clusii* and *Thymus vulgaris*.

Climatically the area belongs to the dry ombroclimate of the lower mesomediterranean belt, according to Thornthwaite's classification. The average annual precipitation is around 400 mm with two maximums, autumn and spring, and a dry period from June to September. Mean monthly temperatures range from 13.3ºC in January to 25.8ºC in August.

The soil is a Rendzic Leptosol (FAO-UNESCO, 1988), or Calcic Xerochrept type according to Soil Taxonomy classification (Soil Survey Staff, 1990), developed on Jurassic limestone. This soil has a variable depth, always less than 50 cm, abundant stoniness (≅ 40%) and good drainage.

2.2. Experimental Set-Up

The Station consists on a set of nine erosion plots; 4 m wide x 20 m long each, with similar characteristics such as soil morphology, slope gradient, rock outcrops and vegetation cover. The selection of each plot location was made after intensive surveys of the vegetation, soil and morphology patterns, based on across slope transects every two metres.

Plots were oriented parallel to the slope and bounded by bricks. At the foot of each plot, a 2 m wide collector ran into a 1500 L tank to record all runoff and sediment produced during each rainfall event. Inside each tank there was a 30 L tank to concentrate the sediments produced, facilitating their collection.

A random design of two different fire intensity treatments, with three plots each, was used. These different fire intensities were achieved by the addition of different amounts of fuel load to the plots of each treatment, 40 t ha^{-1} to reach the high intensity fires and 20 t ha^{-1} for the moderate intensity ones. The fuel necessary to obtain the two fire intensities was taken from the surrounding area using vegetation similar to that present on the plots, and its quantity was calculated using a modification of the method proposed by Etiene and Legrand (1994). The remaining three plots were maintained unburnt to be used as control. The temperatures on soil surface and their duration were measured, on each square metre, by means of thermosensitive paints and thermocouples. The mean soil surface temperatures reached were 439 ºC for high fire intensity plots and 232 ºC for the moderate intensity ones, and the residence time in soil of temperatures greater than 100ºC was 36’22” and 17’45” in each fire treatment, respectively (Gimeno-García *et al.*, 2000).

2.3. Soil Analysis and Measurements

Soil samples were taken from the first 5 cm of the soil surface before and immediately after fire. These were taken from under canopy (UC) and bare soil (BS). After that, they were air-dried, screened to remove the fraction > 2 mm diameter and stored in plastic boxes for analysis. The mean surface volumetric water content before fire experience was 0.08 cm^{-3} cm^{-3}.

Soil Water Content (SWC) was calculated for the potentials: 0, -10, -33, -300, and -1500 KPa, or pF 1, 2, 2.5, 3.5, 4.2, using the pressure membrane method (Richards, 1947). Soil Water Retention Capacity (WRC) was calculated for each soil sample using the equations of McLaren and Cameron (1996):

$$\textbf{(a) } WRC=(\theta_{10} - \theta_{1500})*\rho_b \qquad \textbf{(b) } WRC=(\theta_{33} - \theta_{1500})*\rho_b$$

Where WRC is Water Retention Capacity, θ_{10}, θ_{33}, θ_{1500} are gravimetric water volumes at -10, -33, and -1500 KPa, and ρ_b is the bulk density of soil samples. The results were obtained for volumetric units in percentages.

Water Retention Capacity with field capacity at -10 KPa and -33 KPa, was calculated for the different plots, and the pF curves were also determined.

Climatic parameters and the intrinsic characteristics of the different rainfall events were monitored by a logging system of sensors with GSM transmission of data. Runoff generation dynamics were monitored in each rain event during the studied period. Rainfall intensity was calculated for the maximum volume of precipitation occurring in 30 min (I_{30}).

Soil organic matter content was determined by oxidation with potassium dichromate (Jackson, 1958). Electrical conductivity was measured in soil saturation extracts by the method of Richards (1964). Aggregate stability was assessed using a wet-sieving procedure (Primo and Carrasco, 1973). Calcium carbonate content were determinated by the Bernard calcimeter method (MAPA, 1986), and pH was determined in saturated paste (Richards, 1954).

Standard statistical analyses were applied at 95% of signification level. Analysis of variance and Tukey's test at α=0.05 were used to detect differences in WRC according to the different fire treatments and vegetation cover. Climatic parameters were also analyzed with ANOVA´s test.

3. MAIN RESULTS AND DISCUSSION

3.1. Rainfall characteristics

Total rainfall collected during the one year period after the experimental fires (June 1995-June 1996) was 386.62 mm. The total volume of erosive rainfall, with runoff production, was 321.26 mm distributed in 24 events, showing an average I_{30} of 10.38 mm h^{-1}. The maximum value of I_{30} was 35.36 mm h^{-1} on 18th September, coinciding with the period when the most aggressive rains in the Mediterranean region usually occurs (Perez Cuevas, 1994). The lowest value was 1.4 mm h^{-1} on 15th December (Figure 2A).

In winter, the total rain was 172.8 mm (distributed in 15 events), similar to autumn and spring together (148.46 mm in 9 events), but the duration of storms was three times higher than in the rest of year (average of 641 min and 216 min, respectively) (Figure 2B). Moreover, duration was 72% higher and the I_{30} was 70% lower in winter than in the rest of the study period and, as a consequence of this, two periods according rain characteristics can be differentiated during the year of study: the last dates of summer 1995 plus autumn and spring 1996 (period 1), and winter 1995/96 (period 2).

3.2. Hydrological trends

In Table 1 are reported some soil characteristics analyzed after the fire experience, distinguishing between vegetation cover (under canopy and bare soil) and fire treatments.

During the first year after the fire experiment, there are marked differences in runoff generation between fire treatments and control plots. Plots affected by high intensity fire give 80% more runoff than control plots, meanwhile on plots affected by moderate intensity there is 74% more runoff than on control ones (Figure 3). Benavides-Solorio (2001), shows that runoff rates after the impact of fire on soil produce an increase of even three orders of magnitude in erosion.

However, if these data are divided according the two periods defined by rain characteristics, important differences in runoff yield between treatments and periods can be observed. As it was explained above, period 1 is characterized by erosive rains of medium/high I_{30} (average= 18.49 mm h^{-1}) and short duration. Period 2 show rains of low I_{30}

(average= 5.51 mm h^{-1}) and long duration, with high soil water content during this period and low runoff values. In this way, runoff in period 2 was 57%, 65%, 18% lower than in period 1 for the plots affected by high intensity, moderate intensity and control, respectively (Figure 4A). It is possibly explained because the soil profile had not been completely saturated, favouring lower infiltration rates than period 1 but similar for the different fire treatments (Figure 4B), according to the observations made by Cerdà (1996) on similar environments.

The data obtained for the burned soils are in agreement with those obtained by different authors (Rubio *et al*., 1997; Andreu *et al*., 2002), which indicate that in burned soils the main factors that control runoff are the I_{30} and the rain distribution during the year, so a direct relation between runoff yield, rainfall volume and intensity was observed. Furthermore, some authors like Lavee *et al*. (1998); Boix Fayos (1998); and Puigdefabregas (1999), conclude that in the Mediterranean environment and in natural conditions, runoff rate is highly dependent on rain regime and antecedent soil moisture conditions. Robichaud (2000) also observed that the rain characteristics after a wildland fire are partially responsible for the runoff rates generated. So, low rainfall intensities could facilitate a gradual wetting of the soil profile, favouring changes or the disappearance of the hydrophobic substances generated on topsoil after the fire, allowing then a normal infiltration rate. This could be the reason for the difference in infiltration rates between the treatments in period 2. The differences in the rainfall distribution through the year of study influence the hydrological trends in runoff yield and in infiltration rate (Figure 4).

3.3. Water Retention Capacity

The soils burned with high intensity fire showed values of WRC significantly higher than those of the moderate and control treatment (Figure 5). After the fire experiment, the burned plots presented homogeneous conditions on WRC for the different vegetation cover, although in BS samples the WRC was slightly lower than in UC samples (Figure 5).

These results could indicate changes in physical properties at the soil surface (Andreu, 2001; Giovannini, 1994). These changes could be produced in particle-size distribution and aggregation by the re-agreggation of clay-size particles into sand-size (Giovannini and Lucchesi, 1997). When the WRC is calculated on the basis of a matric potential of -33 KPa, the possible effect of the water held by the sand-sized particles is eliminated, and the differences between fire treatments disappear. The fire effect could favour high water holding at low pF values. Between the values -10 KPa and -33 KPa, the water content held is 75% and 55% higher for high and moderate intensity treatment, respectively, than control values (Figure 5). Then, there is a significant amount of water held in soil at low pF values for the high intensity treatment. This water is probably retained in the gaps generated by the re-aggregation of clay particles into sand size particles. Guber *et al*. (2003), classifying aggregates by size, using the average water content at -10, -33 and -1500 KPa, found that larger aggregates show the greatest variation of water content and the greatest values for this parameter.

Only control plots show significant differences between vegetation cover on WRC (Figure 5). Soil samples taken from bare soil show higher WRC, which is possibly due to the high superficial stoniness that covers the major part of the soil surface (a mean of 59 ± 3% of surface stoniness). Then, the evapotranspiration rates could be lower because rock fragments block the upward movement of water to the soil surface where evaporation can occur (Nobel, 1992). Because of this, the water retained between these pF values is upmost in the bare soil. Bellot *et al*. (1999), found that under canopy soil, and in a Mediterranean environment, not all the rainfall is received by the soil surface since the shrubland canopy interception reduces soil water content due, among others factors, to the major evapotranspiration rates generated by vegetation.

Cerdà (1998) and Bellot (1999), found that depending on the shrubland type developed on the same soil, aggregate stability and soil water content can change. So, in natural unburned areas the WRC depends, mainly, on the vegetation type and on soil characteristics.

3.4. pF curves

Table 2, shows significant differences between burnt and control treatments for all pF points in UC, except for pF 1, and pF 3.5. In BS the differences between fire treatment values and control ones were only appreciable at low pF values, so the characteristics of the BS samples make easier the physical re-aggregation of clay-size particles to sand-size particles after fire impact than in UC soil (Molina *et al.*, 1998; Llinares, 2001). The soil UC in control plots retains more water than the soil UC and BS in the plots affected by the impact of fire. The pF curves for the high intensity treatment did not show significant differences between UC and BS (Table 2), which could indicate that the pass of fire makes homogeneous soil conditions, as it was observed by Boix Fayos (1997). In the moderate intensity treatment, there are significant differences only for pF 1 and 3.5; meanwhile, for the control plots significant differences were observed for pF 4.2. Those differences between UC and BS on control samples could be due to a reorganization in the microaggregate fraction because at this pF values (pF 4.2), the main factor that possibly determines the matric water retention are the texture and the specific surface of the soil material that join water and soil by adsorption forces (Hillel, 1980).

The values of water content for BS samples of fire treatments are higher than those of control samples. In this way, the fire effect on bare soil in relation to its hydrological properties could bring about, initially, an increase in the water content mainly at low pF values (pF 1, 2). This increase shows significant differences for pF 1 and 2 (Table 2).

The fact that values of water content in BS samples increase probably depends, among others factors, on structural changes in topsoil after the fire. These structural changes are related to an increase in the macroaggregates fraction favoured by particle cementation processes (Molina *et al*., 1998; Llinares, 2001; Andreu, 2001).

The possibility of a macroaggregates increase in soil surface layers could explain the volume of water retained at low pF values by the soils affected by fire. At these values, the amount of water depends primarily on the capillary effect and the pore-size distribution, and hence, it is strongly affected by soil structure (Hillel, 1980). The rise in the macroaggregate fraction on soil surface accompanied by the decrease of microaggregates, immediately after the fire experiment (Molina *et al*., 1998; Llinares, 2001), could probably produce an increase on pore volume and water content of soil. These large aggregates present the greatest variations in water content and the greatest values in this parameter (Guber *et al*., 2003).

4. CONCLUSIONS

The rain distribution during the year after the experimental fires shows clearly two different periods. One is characterized by medium/high intensity and low duration rains in spring and autumn, and the other, in winter, with rains of long duration and low I_{30} characteristics.

The impact of fire on soil has important hydrological consequences in the most aggressive rainfall period (spring and autumn). The differences in runoff generation between this period and winter are above 20% for control plots and 60% for the burned plots. These values emphasize the importance of rainfall characteristics in the immediate period after the fire experiments.

The hydrological properties of soil are also affected by the impact of fire. It produced the homogenization of water retention capacity values between vegetation covers (under canopy and bare soil), and the increase in water content of the bare soil in burned plots versus control ones at low pF values. This increase in water content at low pF values could indicate structural changes in the soil surface.

In relation with water retention capacity, the pF curves show substantial differences between UC and BS. In some points of the pF curves there are higher values in BS than in UC (statistically not significant). However in the pF range between 3.5 and 4.2, on control plots, the values of soil water retention under canopy soil are slightly higher than on bare soil.

In the Mediterranean area, the impacts of fires are magnified by the changing characteristics of the rain regime. This fact and the increase in frequency of forest fires could favour the progressive ecosystem degradation and the increase of desertification risk.

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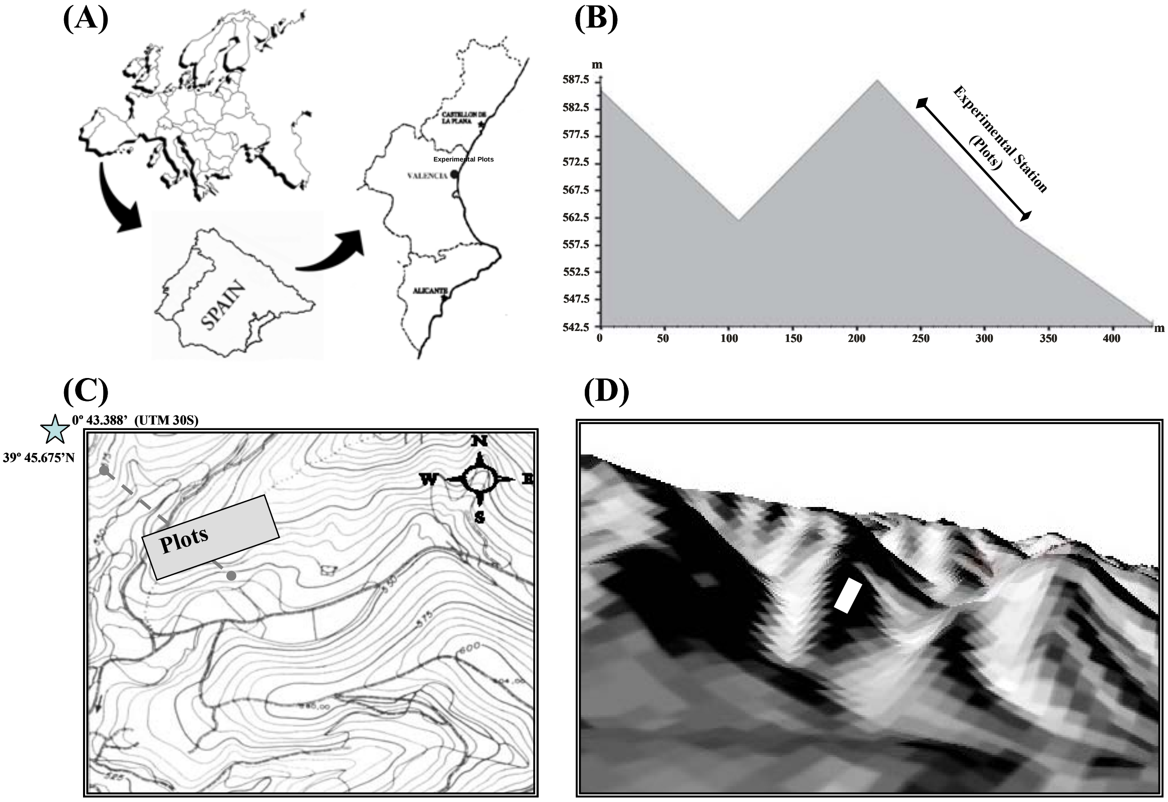

Figure 1. (A) Geographical location of the Experimental Station of La Concordia (Llíria-Valencia, Spain). Morphological characteristics of the study area: (B) Profile with altitudes and distances. (C) Topographic map with altitudes and coordinates. Grey broken line indicates the profile B. (D) Digital terrain model with the location of the plots (white rectangle).

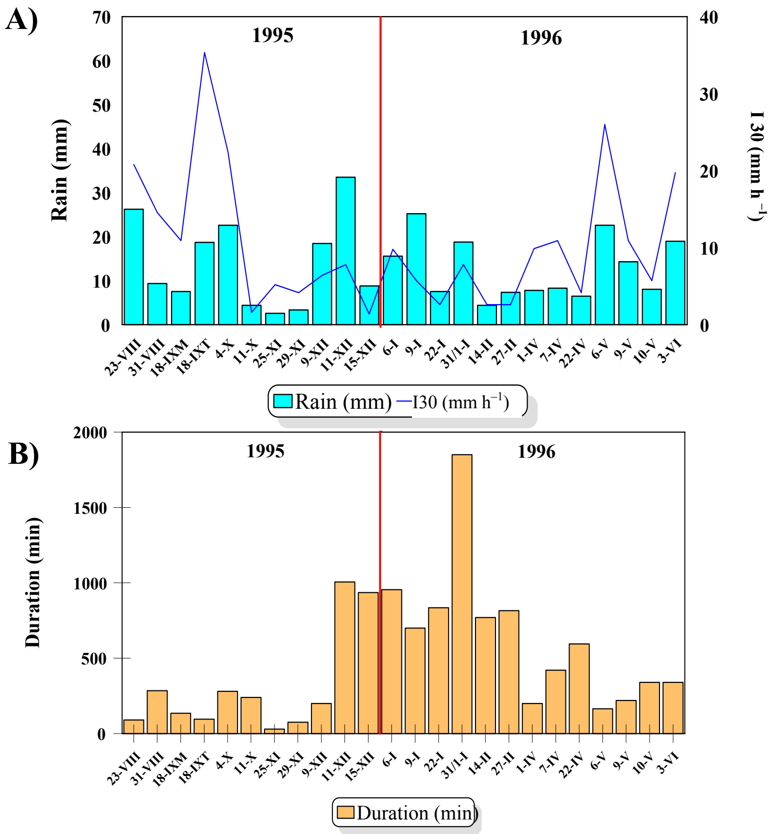

Figure 2. Volume (A), intensity (A), and duration (B), of erosive rains occurring during the studied period.

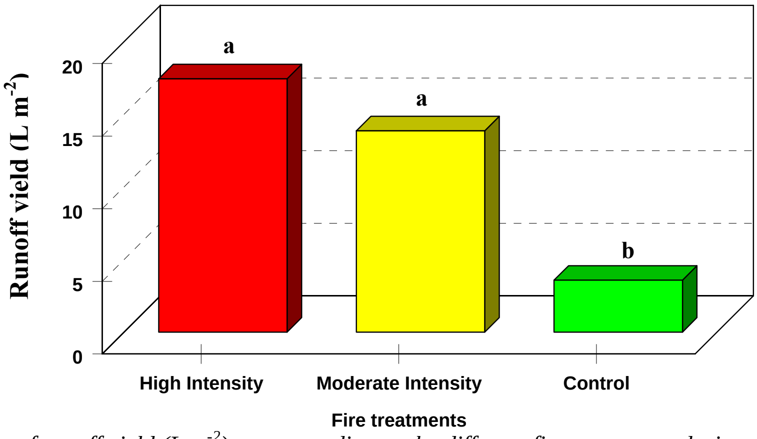

Figure 3. Total values of runoff yield (L m^{-2}) corresponding to the different fire treatments during the studied period. Values not sharing the same letter indicate significant differences between fire treatment using Tukey´s test ($P<0.05$).

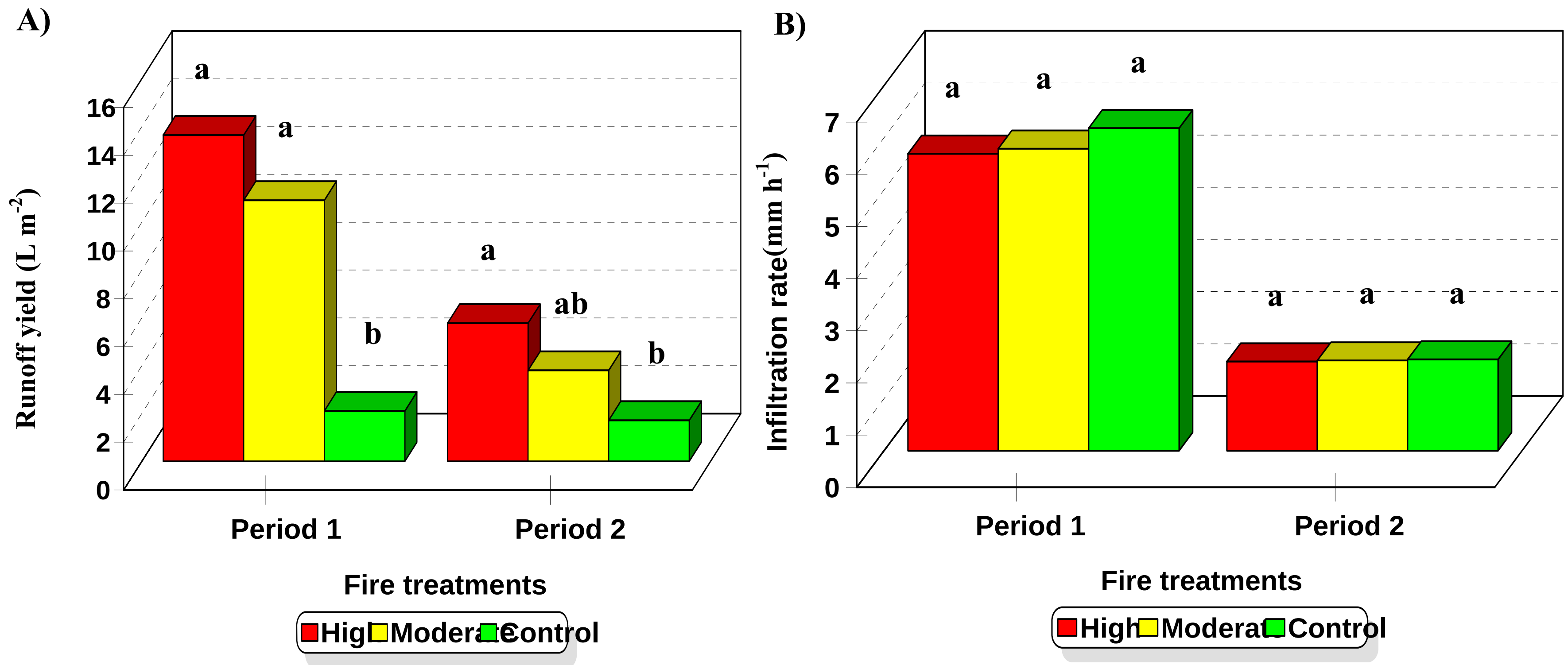

Figure 4. Total values of runoff yield (L m^{-2}) (A) and infiltration rate (mm h^{-1}) (B), for the different treatments and periods described during 1995-96. Values not sharing the same letter indicate significant differences between fire treatment using Tukey´s test (P<0.05).

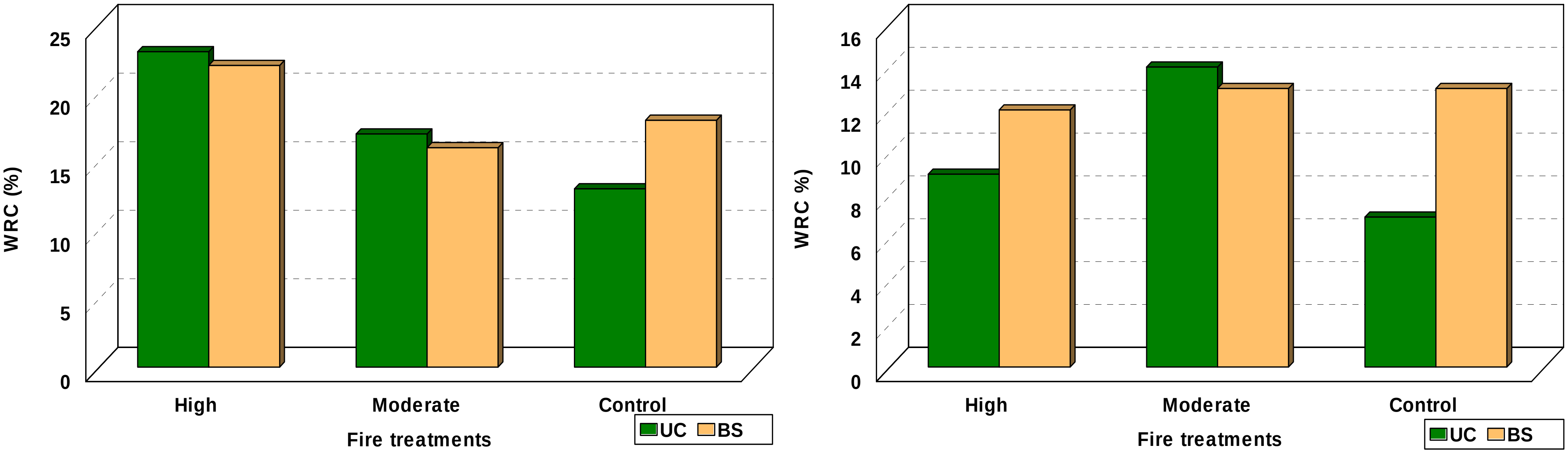

Figure 5. Water Retention Capacity (WRC) calculated at matric potentials of -10 KPa and -1500 KPa (left side), and calculated at matric potentials of -33 KPa and -1500 KPa (right side), for the different fire treatments and vegetation cover, immediately after the fire experiment (1995). UC (under canopy), BS (bare soil). Values not sharing the same letter indicate significant differences for the different vegetation cover (lower case) according to the Tukey´s test. Differences between treatments are also showed (capital letter) according to the Tukey´s test (P<0.05).

Table 1. Summary statistics for temperatura data (Cº) measured with the thermosensitive paints

Fire treatment	**High (4Kg m^{-2})**			**Moderate (2Kg m^{-2})**		
Plots	1	4	8	2	6	7
N	80	80	80	80	80	80
Mean (Cº)a	417.78 a	448.09 a	434.91 a	239.90 b	239.46 b	217.54 b
Median	420	454	420	226	226	198
SD	118.78	132.63	147.32	90.71	91.58	81.61

[a] Different lower case letter among High and Moderate treatments indicates statistically significant difference at $P<0.05$

Table 2. Mean values of some soil properties for each fire treatment and vegetation cover in 1995, after fire experiment.

Before fire experience

Vegetation cover	A.S. (%)	pH (water)	E.C.(dS/m)	CO3Ca (%)	O.M.(%)
UC	-	7.29a	1.14a	45.42a	12.11a
BS	-	7.5b	0.61b	50.15b	8.49b

After fire experience

Vegetation cover	Treatment	A.S. (%)	pH (water)	E.C.(dS/m)	CO3Ca (%)	O.M.(%)
UC	High	33.68a	7.20a	3.59a	45.85a	12.85a
UC	Moderate	31.59a	7.34a	2.51ab	46.94a	11.85a
UC	Control	35.32a	7.33a	1.04b	45.65a	12.33a
BS	High	28.13a	7.21a	2.71a	48.35a	9.57ab
BS	Moderate	23.46a	7.38ab	1.70b	49.01a	11.18a
BS	Control	23.53a	7.52b	0.68c	49.00a	7.98b

UC, Under Canopy; BS, Bare Soil. A.S., aggregate stability; E.C., electrical conductivity; CO_3Ca, calcium carbonate; O.M., organic matter. Values not sharing the same letter in columns indicate significant differences between fire treatment for the different vegetation cover, using Tukey´s test ($P<0.05$).

Table 3. Water Content (%), for the different vegetation cover and treatments for the soil samples taken after the fire experiment.

Levels of comparision		pF 1	pF 2	pF 2.5	pF 3.5	pF 4.2
UC	High I	47.79a	38.56a	24.49a	22.44a	15.67a
	Moderate I	48.76a	32.96b	30.03b	22.48a	15.64a
	Control	47.52a	34.35b	27.46ab	23.81a	20.87b
BS	High I	45.37a	37.09a	27.30a	22.95a	14.95a
	Moderate I	52.05b	31.78b	28.71a	24.28a	15.72a
	Control	47.47ab	33.19b	28.24a	22.65a	14.99a

Levels of comparision		pF 1	pF 2	pF 2.5	pF 3.5	pF 4.2
High Intensity	**UC**	47.79a	38.56a	24.49a	22.44a	15.67a
	BS	45.37a	37.09a	27.30a	22.95a	14.95a
Moderate Intensity	**UC**	48.76a	32.96a	30.03a	22.48a	16.64a
	BS	52.05a	31.78a	28.71a	24.28b	15.72a
Control	**UC**	47.52a	34.35a	27.46a	23.81a	20.87a
	BS	47.47a	33.19a	28.24a	22.65a	14.99b

(UC) Under canopy; (BS) Bare soil. A) significant differences in water content between fire treatments depending on vegetation cover, and B) significant differences in water content between vegetation cover depending on fire intensity treatments, for different pF values according to ANOVA´s test. Values not sharing the same letter in a column indicate significant differences for the different treatment and vegetation cover, judged using Tukey´s test ($P<0.05$).