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Changes in soil hydraulic conductivity after prescribed fires in Mediterranean pine forests

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Abstract

Prescribed fire removes or reduces the plant material that is prone to forest fires by creating fuel discontinuity and minimising fire intensity. This forest management tool potentially impacts Mediterranean ecosystems hydrological response by influencing water infiltration into soil. As direct measurements (e.g. by infiltrometers) of unsaturated infiltration in soil subjected to prescribed fires are scarce, this study has evaluated changes in soil hydraulic conductivity (SHC) using Minidisk infiltrometer after prescribed fires in representative plots of forests in the Iberian Peninsula under Mediterranean semi-arid conditions: (i) pure forest of Black pine Arnold ssp salzmannii; (ii) mixed forest of Maritime and Black pine; (iii) mixed forest of Aleppo and Maritime pine. The results have shown that fire reduced the organic layer thickness and its organic matter content. Consequently, after the prescribed fire the water content of burned plots was always lower than in untreated soils; conversely, the reverse soil behaviour was noticed before applying fire. Compared to the untreated soils, and with very few exceptions, prescribed fire did not cause significant changes in SHC. No general patterns in the comparisons between treatments (burned/unburned soils), in time evolution after fires and in the interactions between these effects were detected. This means that the SHC of burned soils followed the temporal variations of untreated soils. The lack of significance of these differences between treatments could be due to the low-fire severity and the limited effect of temperature in the mineral layer on soil hydraulic properties. This effect was expected and agrees with other studies. Overall prescribed fires did not alter SHC in Mediterranean forest ecosystems under unsaturated conditions since fire was of low-severity.

Keywords: Prescribed burning; soil infiltration; low-intensity fires; hydrologic properties; mini-disk infiltrometer.

1. Introduction

The use of prescribed fires is a tool commonly used to prevent the occurrence and impact of wildfire in Mediterranean forest ecosystems. Prescribed fires noticeably eliminate, or at least reduce, fuel for fire by creating discontinuity under trees in areas with little forest canopy. This helps minimise the danger of large fires, and thus acts as a defence in the forest areas potentially prone to wildfires (Ferreira et al., 2005; Finney et al., 2005). As prescribed fires tend to be of low-intensity, low-severity and patchy in nature, their effects depend on the type and amount of fuel load and soil moisture (Alcañiz et al., 2018).

The viability of prescribed fires for land managers in charge of taking wildfire prevention measures is linked to competitive costs compared to alternative forest defence measures, such as mechanical or manual forest cleaning (Rodríguez y Silva, 2004). In spite of these economic advantages, often many ecological aspects of prescribed fires are not thoroughly considered, such as the possible changes induced in the biotic (e.g., soil micro-organisms and vegetation renovation) and abiotic (e.g., soil properties) components of forest ecosystems (Plaza-Álvarez et al., 2017; Sagra et al., 2017). The nutrient cycling of forests is relatively stable within short-term minimizes the loss of nutrients from these wildland systems in the absence of any major disturbance such as fire (Neary et al., 2005). Fire has been shown to affect the physico-chemical and biological properties of soil, as widely documented in the interesting and comprehensive reviews of Alcañiz et al. (2018)), Cawson et al. (2012), (Certini, 2005; DeBano, 2000; Neary et al., 1999)). Since our understanding of these effects is still limited, the number of studies examining prescribed fires and their effects on the soil has increased in recent years since their use in vegetation management has become more common for forest protection from wildfires or with his role in recovering natural pastures (Alcañiz et al., 2018).

However, more research is needed to better understand and explain by a quantitative approach the potential impacts of prescribed fires on the hydrological response of soils subjected to the prescribed fires. For instance, a detailed description of the relationships between the thermal regime during prescribed fire, measured in field experiments, and the hydrological parameters of the affected soils is necessary (Fernández et al., 2008). In particular, a detailed knowledge of the water infiltration capacity of soils is of fundamental importance in Mediterranean forest areas (Lucas-Borja et al., 2018). These areas are subject to frequent and intense rainstorms, which cause high-magnitude flash floods with strong erosion power with soil degradation risks (Bombino et al., 2009; Fortugno et al., 2017; Zema et al., 2014). Prescribed fires may aggravate these risks, whose control requires proper countermeasures, since ~~a~~ reduced infiltration increases overland flow, which, in its turn, generates a potential increase in erosion rates after fire (Robichaud and Waldrop, 1994).

In Mediterranean areas, the effects of prescribed fires on soil hydrological parameters, erosion or water quality have been investigated mainly in the Iberian Peninsula (e.g., (Badía et al., 2017; Fernández et al., 2008; Úbeda et al., 2009; Vadilonga et al., 2008); Plaza-Álvarez et al. (2017) in Spain; Stoof et al. (2015) and Fonseca et al. (2017), in Portugal). However, the majority of these studies have evaluated the changes in soil hydraulic conductivity due to prescribed fires using indirect measures (e.g., by evaluating infiltration as the difference between precipitation and runoff after rainfall simulations; Fernández et al., 2008; Vadilonga et al., 2008) rather than by direct and local infiltration measures. Direct measurements have instead been taken in other environmental contexts (e.g., Robichaud (2000a), in Montana and Idaho, USA; Kennard and Gholz (2001b), in Bolivia; Savadogo et al. (2007), in Burkina Faso, West Africa), where however the precipitation patterns and amounts as well as the soil hydrological properties differ from those of Mediterranean areas. Such studies have generally shown lower soil infiltration rates after prescribed fires.

To bridge this gap, the present study evaluates the effects of prescribed fires on soil infiltration by direct measurements in the most representative forests of the Iberian Peninsula under Mediterranean semi-arid conditions. To this end, the changes in the soil parameters that influence water infiltration and hydraulic conductivity were measured at the plot scale throughout one year after forest litter cleaning by prescribed fire in three common pine forests of central Spain (Aleppo, Maritime and Black pine). These field campaigns should confirm or reject the working hypothesis of this study that prescribed fires decrease infiltration rate thereby increasing surface runoff rates in forest soil. If such hypothesis is rejected, the study could demonstrate that low-severity fires do not significantly alter soil hydrology of Mediterranean forests; therefore, the related result is important to support decision making to reduce the most dangerous hydrological effects of fire in forest ecosystems.

2. Materials and Methods

2.1. Study areas

The study areas were described in (Plaza-Álvarez et al., 2018; Plaza-Álvarez et al., 2017). These correspond to 3 pine forests more common in Spain: (i) pure stand of *Pinus nigra* Arnold ssp salzmannii ("PN") located in Beteta (province of Cuenca); (ii) mix stand of *Pinus pinaster* Aiton with *Pinus nigra* Arnold ssp salzmannii ("PPPN") located in El Pozuelo (province of Cuenca); (iii) mix stand of *Pinus halepensis* Miller with *Pinus pinaster* Aiton ("PHPP") located in Lezuza (province of Albacete) (Table 1).

Table 1

These three areas have continental Mediterranean climate of which PN is the more humid zone with mean annual precipitation around 650 mm and organic layer with 14,0±6,1 cm depth, followed by PPPN (mean annual precipitation between 550-600 mm and organic layer depth 9,1±4,0 cm); PHPP is the most dry and hot (the mean annual precipitation is around 450mm) and with poorer soils (with organic layer depth of 4,1±2,2 cm).

In these forest zones, the fuel model was "TU1 according to the classification of Scott and Burgan (2005). The understorey was formed by little trees of *Quercus faginea* Lam. and *Quercus ilex* subsp. ballota (Desf.) and shrub of *Quercus coccifera* L., *Juniperus oxycedrus* L., *Thymus* sp. and *Rosmarinus officinalis* L in PHPP, and in PPPN there are *Quercus faginea* Lam. and shrub primarily of *Cistus laurifolius* L. acompained of *Rosa canina* L., *Prunus spinosa* L., *Crataegus monogyna* Jacq., *Juniperus oxycedrus* L. and. *Lavandula* spp. In PN the understorey was *Genista scorpius* L., *Arctostaphylos uva-ursi* L., *Juniperus communis* L., *Rosa canina* L., *Amelanchier ovalis* Medik. and *Lavandula* spp. The tree density was 595±141, 667±125 and 1281±256 to PHPP, PPPN and PN respectively. The mean slope was less 13 % in all plot of the three study areas. Soil texture (0-5 cm) is clay in PHPP and PN (mainly alkaline) and loamy-sand in PPPN (with a neutral pH).

2.2. Experimental design

Six experimental plots were established at each study site. Three plots were subjected to prescribed fire treatment and the remaining three (not burned) were taken as control.

Therefore, nine burned plots and nine untreated (control) plots (3 study areas x 3 treated/untreated plots) were available.

The Regional Forest Service of Castilla-La Mancha, which is appointed with the management of forest areas, applied the prescribed fires in spring 2016. Prescribed fires were carried out manually. Fire lines, separated one from another by a space of 1 metre, were established perpendicularly to the wind direction and in the opposite direction. The objective of the fire was to burn leaves and bushes without affecting trees. The small space between burning lines means that fire intensities were not high. Each experimental plot was 50 metres by 50 metres. Of this total area (2500 m^2), only a strip of 30 x 30 m was sampled to avoid the edge effect on the burned plots. At each study site, plots were selected and established after a preliminary characterisation (slope, exposure, vegetal characteristics of trees, shrub and herbaceous layers), and the main soil physico-chemical properties were measured. This characterisation ensured homogeneous plots for the subsequent temporal analysis of the soil hydraulic conductivity (SHC).

2.3. Soil sampling and laboratory analysis

The main topsoil properties (0-5 cm) were determined on six samples per plot two days before the prescribed fire, again seven days after and also 1 year after the prescribed fire. A total of 324 soil samples (6 samples × 6 plots × 3 study areas x 3 dates) were collected. In the same samples, pH (by a potentiometric sensor on the 1:5 soil water sample), OM (by Walkley and Black method, 1934) and texture (by the densimetric method of Bouyoucos, 1927, described by Gee and Bauderi, 1986) were determined (Table 2).

2.4. Fire temperature measurements

The temperatures during the prescribed fire were measured. Thermocouples that took continuous measurements were placed on the ground. Six datalogger HOBO UX120 4-channel Analog Loggers (Onset HOBO, Massachusetts, USA) were used. All the outlets had a thermocouple, of which three were placed on the ground. One of them was placed in the OM layer, another on the soil surface and another was buried in mineral soil at a depth of 2 cm. In this way it was intended to see how heat was transferred in soil.

The maximum soil temperatures induced by prescribed fires were very different at the topsoil for the three experimental sites (160ºC at PHPP, 264ºC at PPPN and 361ºC at PN). The maximum soil temperatures were below 50ºC in the mineral soil layer (43ºC at PHPP, 35ºC at PPPN and 37ºC at PN), whereas the temperature at the 5-cm soil depth for the three experimental areas barely increased (1ºC), as shown in more details by Plaza-Álvarez et al. (2017).

2.5. Soil temperature, water content and hydraulic conductivity measurements

Soil temperature (ST) and soil water content (SWC) were continuously measured at a depth of 1-2 cm in the mineral soil during the 1-year monitoring, data can be viewed in Plaza-Álvarez et al. (2018); sensors were removed during the prescribed fire and relocated to the same place upon cooling down soil after prescribed fire. To measure SWC, a sensor "Vegetronix VG400" was used, while a TMC20-HD temperature sensor measured ST. Six sensors per plot were placed (three temperature sensors and three moisture sensors), which were connected to a datalogger (UX120 4-channel Analog Logger, Onset HOBO, Massachusetts, USA).

SHC was measured in both plot types (burned and control) by the Mini-Disk Infiltrometer (MDI, Decagon Devices, Inc. Pullman, W.A., 2016), commonly used for field measurements, given its small size and easy handling (Robichaud et al., 2008). MDI measurements were taken following the procedures suggested in the MDI technical manual and by Robichaud et al. (2008). The technical manual also reports the components and modalities for using the device.

In each experimental plot, litter layer was removed by a small shovel on the soil surface and a cut was made at a depth of 1-2 cm to leave a horizontal and smooth surface to place the MDI. The volume of water infiltrated in the MDI was recorded every 30 seconds for no less than 10 minutes.

The soil infiltration rates were estimated from the measurements taken by the MDI records, adopting equations (1) and (2) proposed by (Zhang, 1997). Firstly, the measured cumulative infiltration values (I, [m]) were fitted against the measurement intervals (t, [s]) by equation (1):

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

and the coefficients C_1 [m s^{-1}] and C_2 [m s $^{-1/2}$] were thus estimated by interpolation. Coefficient C_1 is related to soil hydraulic conductivity, and C_2 is its absorption capacity (Decagon Devices, Inc. Pullman, W.A., 2016). Then the SHC (k, [mm h^{-1}]) was calculated by the following equation:

$$k = \frac{C_1}{A} \tag{2}$$

Where, coefficient A is a value relating to the Van Genuchten parameters (n and α) for a certain soil type to the suction rate (h_0) and the infiltrometer disk radius (2.25 cm). According to n, α and h_0 (this latter assumed in this study to be equal to -2 cm) values for the experimental soils, the following values of A were taken (Decagon Devices, Inc. Pullman, W.A., 2016): (i) 4.1 for the clay soil at PHPP and PN; (ii) 2.8 for the loamy-sand soil at PPPN.

2.6. Statistical analysis

A two-way ANOVA was applied to evaluate the statistical significance of the changes in SHC after prescribed fire at each study site, assuming as factors: (i) time (days after fire, "DAF"); (ii) treatment (prescribed fire; or no treatment).

All the plots were considered spatially independent in all cases. An independent Fisher's minimum significant difference test (LSD) was used for the *post hoc* analysis comparisons. A $p < 0.05$ level of significance was adopted. The statistical analysis was performed by version 3.2.4 of the R Project for Statistical Computing.

3. Results

About soil texture, noticeable and significant increases in clay content (+15.3%) and decreases in sand (-20.2%) and loam (-34.8%) fractions took place after fire at the PN stand, although these values were returned to previous values to burning in the second soil sampling (1 year later). The other soils experienced slight and not significant texture changes (Table 2). The organic layer depth dropped significantly just after the prescribed fire (by 4, 3 and 2 cm, in stands PN, PPPN and PHPP, respectively), but, it was increased 1 year after the fire by the accumulation of litter. Soil pH was slightly increased, but without any significant difference, this data can be viewed in Table 2.

Regard to the OM of soils, before the prescribed fire, the PN stands showed the highest value (18.0±3.6%), PPPN had OM of 8.6±2.3%, while the lowest value (4.3±1.3%) was measured at PHPP. As expected, the treatment by prescribed fire reduced slightly the OM of soil but without statistical significance, with OM values after the prescribed fire of 16.3±3.4% (PN), 6.1±2.0% (PPPN) and 3.9±1.3% (PHPP) (Table 2). One year after the prescribed fire, in burned plots the OM values were similar to just after fire values.

The values of SHC measured before the prescribed fire did not show any significant difference among the plots of each study area. This revealed a common starting point to compare the effects of the fire treatment on this soil hydrological property. SHC was generally higher in the clayey soils (on average 10.1 and 13.7 mm h^{-1} at PN and PHPP, respectively) compared to the loamy-sand soil (6.0 mm h^{-1} in PPPN).

The ANOVA applied to the effects of treatments (prescribed fire or no treatment), the time elapsed after fire and their interactions on SHC showed that: (i) the prescribed fire significantly affected the soil hydraulic conductivity only in the PN forest stand; (ii) the effect of time elapsed after fire was significant at sites PPPN and PHPP; (iii) in these latter forest types, the treatment-DAF interaction on SHC was not significant, whereas the opposite was observed in the PN plots (Table 3).

Table 3

At two experimental sites (PN and PPPN) SHC remained almost constant throughout the observation period. Instead, a sudden increase (49.1 mm h^{-1}, compared to SHC measured immediately before or after the fire, equal to 10.0 and 6.36 mm h^{-1}) was noticed in summer - 43 days after fire - for the plots covered by PHPP; subsequently, the natural SHC was recovered (Figure 1).

Figure 1

The comparison between the two treatments (prescribed fire *versus* control plots) highlighted no significant differences in SHC few days after fire, with two exceptions: (i) on day 33 after the fire in the PN forest stand; (ii) at the PHPP site 10 days after burning (Figure 1). In these situations, SHC of the site subjected to prescribed fire was 80% lower (PN) and even 112% (PHPP) higher than the values measured in the control plots.

4. Discussions

4.2. Effects of fire on soil physico-chemical properties

This study showed that, compared to pre-fire conditions, soil texture was not significantly modified by prescribed fire in our forest stands, except for the clay content, which noticeably increased in the PN stand, but returned to normal values in the next sampling so this difference could be due the random chance sampling after fire since particle-size distribution of soil is not directly affected by fires at lower intensity (Oswald et al., 1998), as found in the other forest stands (PPPN and PHPP) of this study. The slight decrease in the clay fraction surveyed in the PPPN stand - although not significant - is in accordance with the findings of (Díaz-Raviña et al., 2012) and other authors, who reported how fire passage may change particle size distribution, such as an increased sand fraction accompanied by reduced clay and silt fractions.

Changes in soil pH were not significant. These results comply with the findings of Marcos et al. (2009), who, on occasion of a low-intensity prescribed fire of heath lands in three acid soils (pH = 4.3) in the Cantabrian mountains (NW Spain), did not observe any significant differences of pH between burned and control soils (0-5 cm soil thickness), in spite of the basicity (pH of 8.5-9.5) of the ashes covering mineral soil (Badía et al., 2017).

Also, other authors found that the pH values remain unaltered after fire (Alcañiz et al., 2016; Lavoie et al., 2010; Meira-Castro et al., 2015; Switzer et al., 2012; Valkó et al., 2016). Normally, the burn events that did not change pH values were low-intensity and severity prescribed fires applied periodically (every 2 years or more) or single treatments carried out once rather than annually (Alcañiz et al., 2018). However, increases in pH are common after fire (Arocena and Opio, 2003; Granged et al., 2011; Neill et al., 2007; Scharenbroch et al., 2012; Switzer et al., 2012; Úbeda et al., 2005). These increases in pH, reported in both field (e.g. Giovannini (1994)) and laboratory experiments (e.g. Fernández et al. (1997)), have been attributed to the complete OM oxidation during fire, to the release of cations in all fire types

(Fisher and Binkley, 2000), to OH losses (Arocena and Opio, 2003; Certini, 2005) and to the presence of carbonates, base cations and oxides in the ash formed and deposited in soil during fire (Ekinci, 2006).

Our prescribed fires altered other soil characteristics, particularly organic layer thickness (by -40% on average) and OM content (by -16% on average), presumably due to litter burned during the prescribed fire. However, the OM changes in the soil (0-2 cm) were not significant compared to the unburned soils.

A reduced organic layer thickness has also been found after prescribed fire also by Fernández et al. (2008). The most intuitive change that soils undergo during burning is loss of OM (Certini, 2005). Depending on fire severity, the impact on OM consists in slight distillation (volatilisation of minor constituents), charring or complete oxidation. Substantial OM consumption begins within the 200–250 °C range and is completed at around 460 °C (Giovannini et al., 1988), while partial OM consumption occurs at 200–250 °C and complete consumption at 460 °C (Certini, 2005).

In the burned plots, the maximum temperatures recorded on the mineral soil surface during burning had to be high enough to start either destroying mineral soil OM or fine roots or enhancing hydrophobic layer formation (DeBano, 1981; DeBano et al., 1998; Giovannini et al., 1990). However, the fact that heat barely penetrated soil and the lack of significant differences in soil bulk density suggest that these changes, if occurred, are probably minor.

4.3. Effects of fire on soil hydrological properties

Soil moisture affects the soil infiltration rate and its propensity to reduce the soil hydrological response (Keizer et al., 2008; MacDonald and Huffman, 2004). The comparison of SHC surveyed during the 1-year monitoring period both in the unburned and burned plots do not show that the prescribed fire induced significant changes in soil hydrological properties, except in PN where the prescribed fire treatment showed significant differences. Few weeks after fire at the two clayey sites (PN and PHPP) the SHC was different from the control zone. In one case (PHPP site), the burned soil showed a higher SHC than the control soil (Figure 1). These occasional differences should be attributed mostly to the natural variability of soil hydraulic properties rather than to a direct influence of fire effects, since, the SWC of the burned plots was less than in the control plots in all study zones (Plaza-Álvarez et al. al., 2018) but was not correlated with SHC because in the case of PN 5 DAF when SWC was significantly lower than in the control area, SHC was lower than in the control area, but not significantly, and in PHPP 10 DAF SWC was significantly lower than in the control zone while SHC was significantly higher in the burned area than in the control zone.

The increase in SHC recorded in the clayey soil at PHPP in early summer may be due to the effects of the soil micro-cracks surveyed at the site and to soil particle aggregation (generating macro-voids into the surface), which could have increased the water infiltration into the soil surface (Figure 1). It is well-known that soil aggregates can be formed, disintegrated and re-added depending on the environmental conditions (Hillel, 1998), it is also known that the superficial hydrophobicity of the soil could contribute to the stability of the soil below the surface since, according to (Sullivan, 1990), hydrophobicity slows down the wetting process and therefore stabilizes the deeper aggregates. Thus, the increase of superficial soil hydrophobicity in summer (Plaza-Álvarez et al., 2018) in these areas could have maintained the aggregation of clays facilitating water being infiltrated into soil. The higher organic layer thickness and OM values of the soil at PN stand may have avoided cracking of this clayey soil and reduced water infiltration.

The similarity in the hydrological behaviour of soils affected by prescribed fires and the untreated ones was confirmed by the contrasting results in the analysis of the effects of treatments, time elapsed after the fire and their interactions on SHC. Indeed, prescribed fire significantly changed SHC (also synergically with time, as the significant interaction effect shows) in the PN forest stand (clayey soil), (Table 3). These contrasting results about changes in SHC between the soils subjected to prescribed fires or unburned soils somewhat reflects those reported by many authors. Some researchers have shown minimal effects on infiltration rates of bare soil subjected to low-intensity fire, but reduced SWC (González‐Pelayo et al., 2010). Cawson et al. (2012), when analysing the actions of prescribed fire on surface runoff and erosion as water infiltration effects, evidenced that a high proportion of studies report that the impacts of fires are minimal. For instance, (Robichaud, 2000b) in areas subjected to a low-severity burn of Montana and Idaho (USA) found constant runoff rates, which, in turn, indicates constant SHC values despite variations among plots. In the same environmental context, the within-year variability in the infiltration between the burned and unburned conditions across sites of Idaho (USA) was minimal, but the between-year variability in infiltration was significant (Pierson et al., 2008). Vadilonga et al. (2008) in Catalonia (East Spain) and Fernández et al. (2008) in Galicia (North Spain) detected minor and nonsignificant changes in the infiltration of the soils subjected to low-intensity fires, such as prescribed fires. Lack of fire effects on soil OM and saturated conductivity can be explained by the soil temperatures not being high enough to alter these soil properties (Stoof et al., 2015).

As regards SHC variability in time, our findings at the PPPN and PHPP sites contrast with the majority of literature experiences, which report that the hydraulic conductivity of burned soil worsens immediately after fire (e.g. due to some negative effects, such as increased soil water repellence, reduced soil aggregate stability, or burning OM, Prats et al., 2016; Santana et al., 2014; Shakesby, 2011). For instance, (Robichaud et al., 2008; Robichaud et al., 2013), using MDI, found low immediate post-fire infiltration rates, but higher values for this hydrological parameter one year after the wildfire on a loamy soil. The reduced water infiltration capacity immediately after fire compared with the pre-fire situation has also been attributed to the soil hydrophobicity generated by lipid compounds released from burned plant material, whose persistence in soil is variable depending on fire severity and the environmental conditions after fire (Are et al., 2009; Hubbert et al., 2006; Imeson et al., 1992; Woods and Balfour, 2010). Therefore, these Authors suggest to conduct controlled burns during drier soil conditions.

5. Conclusions

In order to evaluate whether, and by what degree, soil hydrological properties are affected by low-intensity fires, unsaturated hydraulic conductivity of soils subjected or not to prescribed fires was monitored over a 1-year period in three pine forests (*Pinus halepensis*, *Pinus pinaster* and *Pinus nigra*), these being the most representative forests in the Iberian Peninsula.

The prescribed fires were of low intensity with mean temperatures between 160 and 361 ºC. Fire reduced the organic layer thickness but no the organic matter of soil. Compared to the untreated soils, the prescribed fire did not significantly modify soil hydraulic conductivity, with a few exceptions. No general patterns of soil hydraulic conductivity between treatments (burned/unburned soils), with time elapsed after fires and with interactions between these factors were detected, which means that the hydraulic conductivity of burned soils follows the temporal variations of untreated soils. The lack of significance of these differences could be due to low-fire intensity. This effect was expected and is also reported in other studies.

Overall, our this research demonstrates that prescribed fires do not alter soil hydrological properties (in particular the unsaturated soil hydraulic conductivity) in Mediterranean forest ecosystems, provided that a low-intensity fire is applied. This study provides a better understanding of the changes in hydrological characteristics caused by different fuel management techniques, which is important to help land managers make the best choices to reduce fire hazards in hydrological consequences terms (also in view of facing the effects in future climate change scenarios, which forecast increased precipitation erosivity).

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Changes in soil hydraulic conductivity after prescribed fires in Mediterranean pine forests

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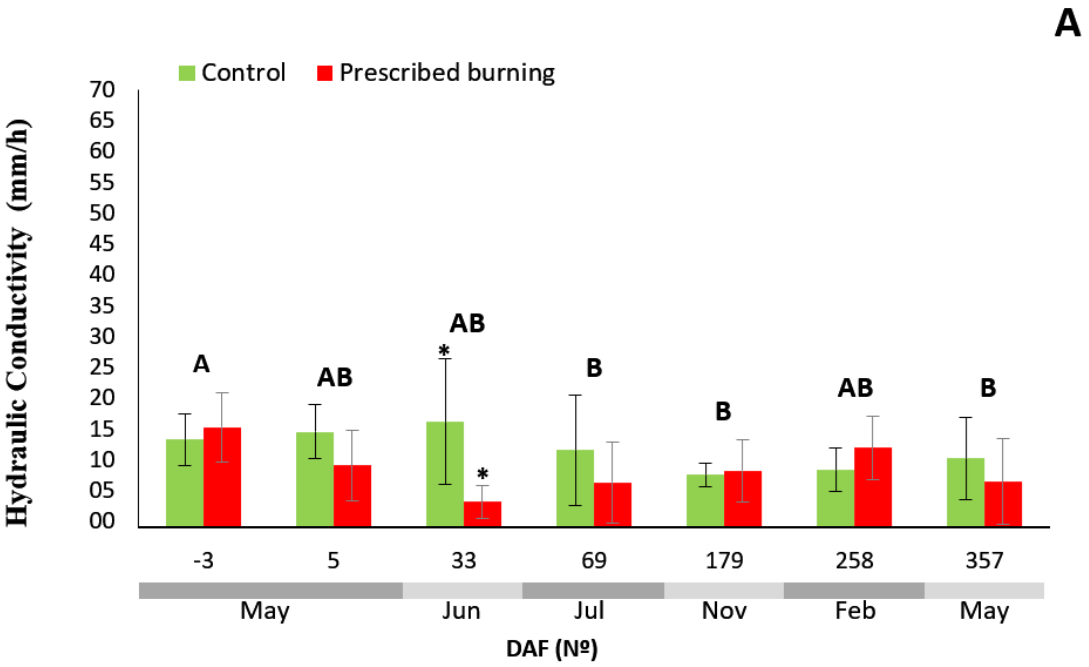
FIGURES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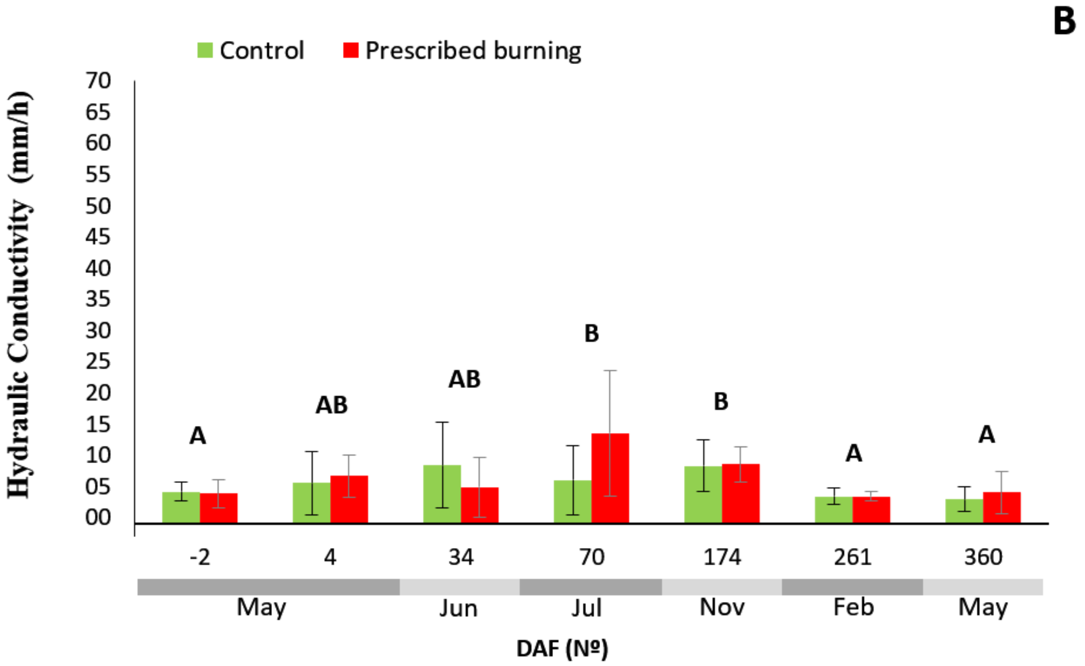
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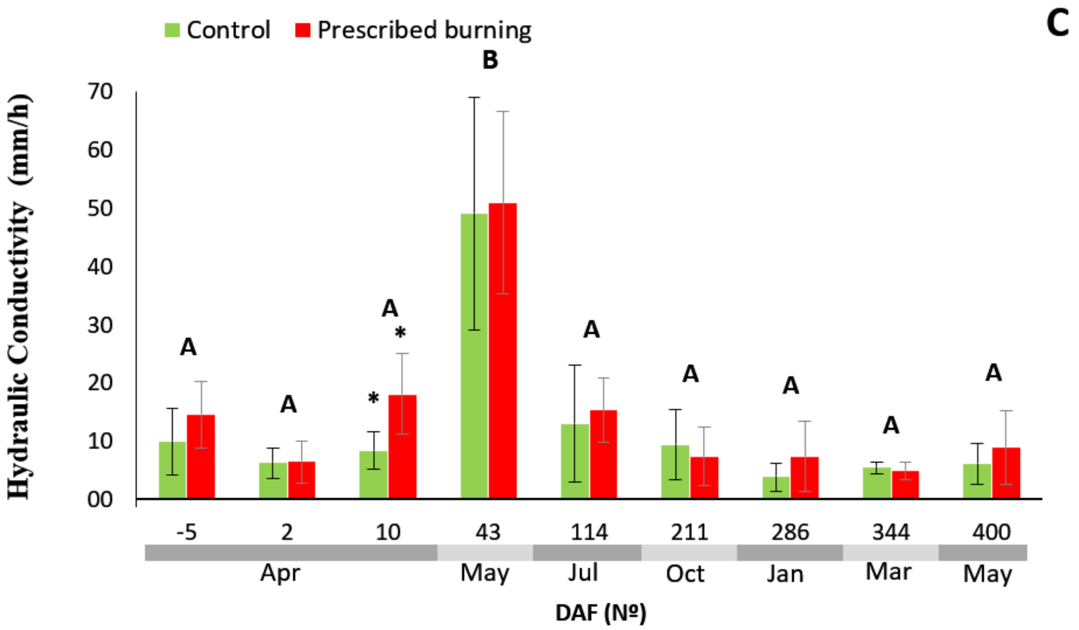

Asterisks (*) indicates significant differences between control and burned area at the same monitoring date, while capital letters indicate significant difference among the different monitoring dates (at $p < 0.05$).

Figure 1 - Temporal evolution of soil hydraulic conductivity (SHC, mean ± standard deviation) in (a) PN (pure *P. nigra* stands), (b) PPPN (mixed *P. pinaster* and *P. nigra* stands), and (c) PHPP (mixed *P. halepensis* and *P. pinaster* stands).

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TABLES

Table 1 - Morphological characteristics of the studied sites (Castilla La Mancha, Spain).

Site (municipality)	**Forest type**	**U.T.M. coordinates**	**Min-max altitude (m a.s.l.)**	**Mean slope (%)**
Beteta	PN	X: 575451 E Y: 4489248 N	1.000-1.050	4.2±1.3
El Pozuelo	PPPN	X: 561373 E Y: 4490691 N	1.250-1.300	5.0±2.2
Lezuza	PHPP	X: 557588 E Y: 4306475 N	1.000-1.050	10.2±2.3

Notes: PN = Black pine; PPPN = Maritime and Black pine; PHPP = Aleppo and Maritime pine.

Table 2 - Main soil properties of the burned plots in studied sites (mean ± standard deviation, n = 18 samples) (Castilla La Mancha, Spain).

Forest type	**Main soil texture**	**Sampling time**	**Organic layer depth (cm)**	**OM content (%)**	**pH**	**Texture (% w/w)**		
						sand	**silt**	**clay**
PN	Clayey	Before fire	14.0±6.1 a	18.0±3.6 a	7.3±0.4 a	32.6±6.2 a	25.3±6.4 a	42.1±8.6 a
		Just after fire	10.0±5.0 b	16.3±3.4 a	7.8±0.5 a	26.0±5.3 a	16.5±4.5 b	57.4±9.7 b
		1 year after fire	12.2±4.4 ab	16.4±4.1a	7.6±0.4 a	29.9±4.3 a	23.3±5.2 ab	46.8±6.8 ab
PPPN	Loamy-sand	Before fire	9.1±4.0 a	8.6±2.3 a	6.9±0.3 a	82.3±5.2 a	8.7±3.2 a	9.0±2.0 a
		Just after fire	6.2±3.1 b	6.1±2.0 a	7.0±0.4 a	86.9±4.2 a	6.1±2.6 a	7.0±1.7 a
		1 year after fire	6.9±3. ab	6.0±1.8 a	6.9±0.4 a	80.3±3.9 a	9.2±4.1 a	10.5±3.4 a
PHPP	Clayey	Before fire	4.1±2.2 a	4.3±1.3 a	7.6±0.5 a	31.2±4.5 a	27.3±3.9 a	41.5±7.1 a
		Just after fire	2.4±2.1 b	3.9±1.3 a	7.7±0.3 a	30.4±7.9 a	25.1±3.7 a	44.5±9.5 a
		1 year after fire	3.2±2.3 ab	3.8±1.4 a	7.8±0.5 a	30.1±3.2 a	23.4±2.4 a	46.5±5.2 a

Notes: PHPP = Aleppo and Maritime pine; PPPN = Maritime and Black pine; PN = Black pine; OM = organic matter; different letters indicate significant (at $p < 0.05$) differences before and after fire.

Table 3 - ANOVA of the SHC for each study zone (PN, PPPN and PHPP) (Castilla La Mancha, Spain).

Factors	**Sum of squares**	**Degree of freedom**	**F-value**	**P-value**
PN				
T	195.5	1	5.54	<0.05
DAF	356.9	6	1.68	>0.05
T x DAF	582.4	6	2.75	<0.05
Residual	2471.7	70		
PPPN				
T	17.84	1	0.86	>0.05
DAF	450.49	6	3.63	<0.01
T x DAF	196.37	6	1.58	>0.05
Residual	1447.43	70		
PHPP				
T	164.5	1	1.27	>0.05
DAF	18918.1	8	18.29	<0.001
T x DAF	268.6	8	0.26	>0.05
Residual	11630.5	90		

Notes: PHPP = Aleppo and Maritime pine; PPPN = Maritime and Black pine; PN = Black pine; T = treatment (prescribed fire versus control soil); DAF = time elapsed (number of days after fire).