Variability of hydraulic conductivity and water repellency of soils with fire severity in pine forests and reforested areas under Mediterranean conditions

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Short title: Soil hydrology after wildfire in pine forests and reforested areas

Abstract

The effects of fire on soil hydraulic conductivity (K) and soil water repellency (SWR) have been mainly studied by field experiments in forest areas burned by wildfires with a given severity, while the variability of K and SWR with the fire severities has been less investigated. To fill this gap, the changes in the K and SWR with fire severity (adapted from Vega et al., 2013) and soil depth (1 and 5 cm below the ground surface) have been evaluated in two forest ecosystems (natural stand of pine and reforested areas) of Castilla La Mancha (Central Eastern Spain) and compared to unburnt areas. A significant influence of the fire severity on the infiltration rates was found, and this influence was different between the natural stand of pine and the reforested areas. Compared to the unburnt soils, the highest reduction of the K (80-90%) and SWR levels were found for the fires with low and intermediate severities at the soil surface, At the lower soil depth, the reduction of K and the SWR level due to fire were proportional to its severity. Moreover, the K of the soil surface layer was often higher compared to the water infiltration in the deeper layer. In the reforested areas, also low fire severities can noticeably reduce the surface K, despite the limited SWR, while the natural forests are less exposed to hydrophobicity in their surface soil layer. Overall, the study indicates the

need of primary and most urgent actions of post-fire management in reforested areas subjected to intermediate fire severities, in order to reduce the risk of flooding and erosion linked to a reduction in water infiltration and increase of soil repellency.

Keywords: pine natural stand; reforestation; water infiltration; hydrophobicity; soil organic carbon; post-fire management.

1. INTRODUCTION

Wildfires heavily impact on hydrological processes in forest ecosystems, since fire removes the vegetation cover, leaving the soil bare and thus exposed to erosion by rainfall (Moody et al., 2013; Shakesby, 2011). Moreover, several physico-chemical properties of soil are altered by fire, such as the infiltration rates and water repellency levels (DeBano, 1991; Leonard F DeBano, 1981). The changes in soil hydrology in forests result in increases in surface runoff and soil erosion rates, with heavy environmental on-site (e.g., soil loss, landslides) and off-site impacts (e.g., transport of entrained pollutants, damage of urban infrastructures) (Zema et al., 2021b).

The complexity of the hydrological processes in burned forests has been highlighted by many studies, as the result of several environmental and anthropogenic factors (e.g., climate, soil dynamics, vegetation, fauna, afforestation) (Pereira et al., 2018; Shakesby and Doerr, 2006; Zavala et al., 2014). Water infiltration plays a key role in the hydrological processes of burned forests, and the soil hydraulic conductivity (hereafter K) is the most important parameter that governs this process. Understanding this parameter is essential in forest soils of the Mediterranean semi-arid conditions, since in this environmental context the surface runoff and soil erosion are dominated by the infiltration-excess mechanism (Lucas-Borja et al., 2018). Moreover, the Mediterranean soils are generally shallow, with low aggregate stability and organic matter (OM) and nutrient contents (Cantón et al., 2011). In unburnt forest soils, K is widely variable, from 1 to 10^3 mm/h (Carlyle-Moses et al., 2018), and the fire enlarges this range of variability. Fire generally reduces K, and this effect depends on its severity (Inbar et al., 2014; Niemeyer et al., 2020; Zema, 2021). While the changes in K due to fires with low severity (such as the prescribed fires) are low or even negligible (Alcañiz et al., 2018a; Carrà et al., 2021), high-severity wildfires can modify the K by some orders of magnitude (DeBano, 1971; Doerr et al., 2003, 2000; Fernández et al., 2021; Zavala et al., 2014). Moreover, K can be further decreased by soil water repellency (SWR) (Imeson et al., 1992; Ritsema et al., 1997, 1993; Shakesby et al., 1993), which is primarily determined by the accumulation of long-chain organic compounds in or around soil particles. SWR in forest soils can be from negligible to extreme (Mao et al., 2019), and this effect strongly influences water infiltration (Cerdà and Doerr, 2007; Imeson et al., 1992; Plaza-Álvarez et al., 2019, 2018; Stoof et al., 2011). The simultaneous occurrence of low K and high SWR in the Mediterranean soils affected by wildfires results in Hortonian infiltration-excess overland flow during intense storms (Doerr et al., 2000) with excessive rates of surface runoff and soil erosion (Robichaud and Waldrop, 1994). The forest type (natural or reforested stand), age (young or old stands) and management (linked to forest operations) play an important role in driving the soil properties (Jarvis et al., 2013; Neary et al., 1999; Zema et al., 2021b, 2021a). Moreover, the soil changes may be variable along the soil profile: an abrupt change in one of these hydrological properties with the soil depth can alter water infiltration and therefore the hydrological response of soil to rainstorms. The heat released by a fire migrates from its surface to the deeper layers, and the fire effects on soil properties attenuate with depth.

A better understanding of the synergistic effects of SWR and K in burned soils of the Mediterranean forests is very important to setup strategies to reduce the hydrological impacts of fire and the related environmental hazards (Lucas-Borja et al., 2018; Plaza-Álvarez et al., 2018). Water infiltration and repellency in burned forests have been widely investigated across the Mediterranean ecosystems under a variety of pedological, climatic and management conditions (e.g., (Inbar et al., 2014; Neris et al., 2013; Wittenberg et al., 2011). These authors showed that a fire of a specific intensity of severity modify the infiltration rate and induce SWR of a given level, which in turn result in changes in runoff generation and often in altered erosion rates. Often these studies separately focus on one of these two important key variables. Less research is available on the relationships between the K and SWR under fires of different burn severities and in different forest ecosystem types (e.g., natural forests, reforested areas and forests subjected to management operations). Moreover, the hydrological effects of fire have been studied by field experiments carried out in forest areas burned by wildfires with a given severity, while the variability of K and SWR with the fire severities has been less investigated. It is well known that the magnitude of the soil changes mainly depend on the fire severity (i.e., the entity of changes in the burned ecosystem) (Certini, 2005; Zavala et al., 2014; Zema, 2021). Fire severity is considered as a key descriptor of the magnitude of the soil changes after fire due to its implications on the hydrological response (Fernández et al., 2020; Fernández and Vega, 2016; Fernández-Alonso et al., 2019). For low severity fires soil heating is negligible and the impact on soil properties is low, while the soils burned by high-severity fires can reach very high temperatures, and the impacts on soil hydrology can be extremely negative, such as strong water repellency and very low infiltration capacity (Pereira et al., 2018; Zema, 2021).

To fill this gap, this study explores the variability of the K and SWR with fire severity (from zero to five using a modification of the classification proposed by (Vega et al., 2013) in two forest ecosystems (natural stand of pine and reforested areas) of Castilla La Mancha (Central Eastern Spain); this variability was compared to the K and SWR values of unburnt areas selected in both pine and reforested zones. To our best knowledge, this is the first study that has simultaneously analyse the impacts of classes of fire severity on important hydrological properties of soils, and separately for undisturbed and managed forests. The research questions to which this investigation aims at replying are the following: (i) how and how much K and SWR vary with the fire severity and soil depth? (ii) are K and SWR different between the two forest ecosystems? The results of this study help land planners in prioritizing the post-fire management actions, according to the different hydrological hazards related to the fire severity and ecosystem type in burned forests of the Mediterranean environment.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located in the municipality of Liétor (province of Albacete, region of Castilla-La Mancha, Spain, 38º30'40.79" N; 1º56'35.02" W, Figure 1). Its elevation ranges between 520 and 770 m above the mean sea level. The climate is semi-arid, and it is categorized as type BSk according to the Köppen classification (Kottek et al., 2006)) with mean annual temperature and precipitation of 16.6°C and 321 mm, respectively. Soils are classified as Calcid Aridisols (Nachtergaele, 2001) with a sandy loam texture. The study sites are exposed to north-west and have a mean slope of 15-25%.

The forest area of the Albacete Province covers 613061 ha, 41% of the total area of the Province (1485000 ha). These forests are composed by pine and woods (60%), whereas the remaining areas are covered by shrubs and pasture (40%) (data source: Spanish Institute of Statistics, 2021). More information about the forest species composition is detailed in the studies by (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2022; Lucas-Borja et al., 2020; Lucas-Borja et al., 2020).

The dominant overstory vegetation in the study area consists of Aleppo pine (*Pinus halepensis* Mill.) with a shrub layer of kermes oak (*Querco cocciferae*) (Peinado et al. 2008). Before the wildfire, the stand density and tree height ranged from 500 to 650 trees/ha and from 7 to 14 m, respectively. The understory vegetation also includes *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus coccifera* L. and *Plantago albicans* L. The economic value of the understory species decreased in the mid of the 20th centrury, and this led to agricultural abandonment and reforestation by Aleppo pines of natural origin. Therefore, a mixture of natural pine (not affected by wildfire in the last 100 years) and reforested stands of Aleppo pine, about 60-70 years old composes the study area.

In more detail, the vegetation before the fire was heavily anthropized, with Aleppo pine trees of two different origins: (i) pine of natural origin in valley and shady areas, where moisture accumulates, and/or very steep and thus inaccessible areas; and (ii) reforested pine stands ('1980-90s) in areas of poor soils and steep slopes. It is important to mention that grasslands (especially *Macrohcloa Tenacissima* L.) were planted and cultivated in most of the study area some centuries ago. The shrublands can be considered as the main vegetation or species that accompanies the Aleppo pine, consisting of *Macrochloa Tenacissima* L. (*Helictotricho filifolii-Stipetum tenacissimae*), rosemary (*Anthyllido cytisoidis-Cistetum clusii*), Macroflora-rosemary (a mixture of the latter species) and Thymus (*Anthyllido onobrychoidis-Thymetum funkii*). All the shrubs and herbal layers are thermophilic species that significantly characterize the Mediterranean dry forests. More information about the vegetation in the study area can be found in (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2022; Lucas-Borja et al., 2020; Lucas-Borja et al., 2020).

In July 2021, a wildfire burned a large part of the forest areas, both pine stands and reforested zones. One week after the wildfire, a study area of 70 ha was selected, including both unburnt and burned forests, subjected to crown fire with 100% tree mortality (Figure 1). The soils of the study area are very homogenous with small spatial variability, as shown by the high similarity of the physico-chemical properties of the soils under different soil conditions (Table 1).

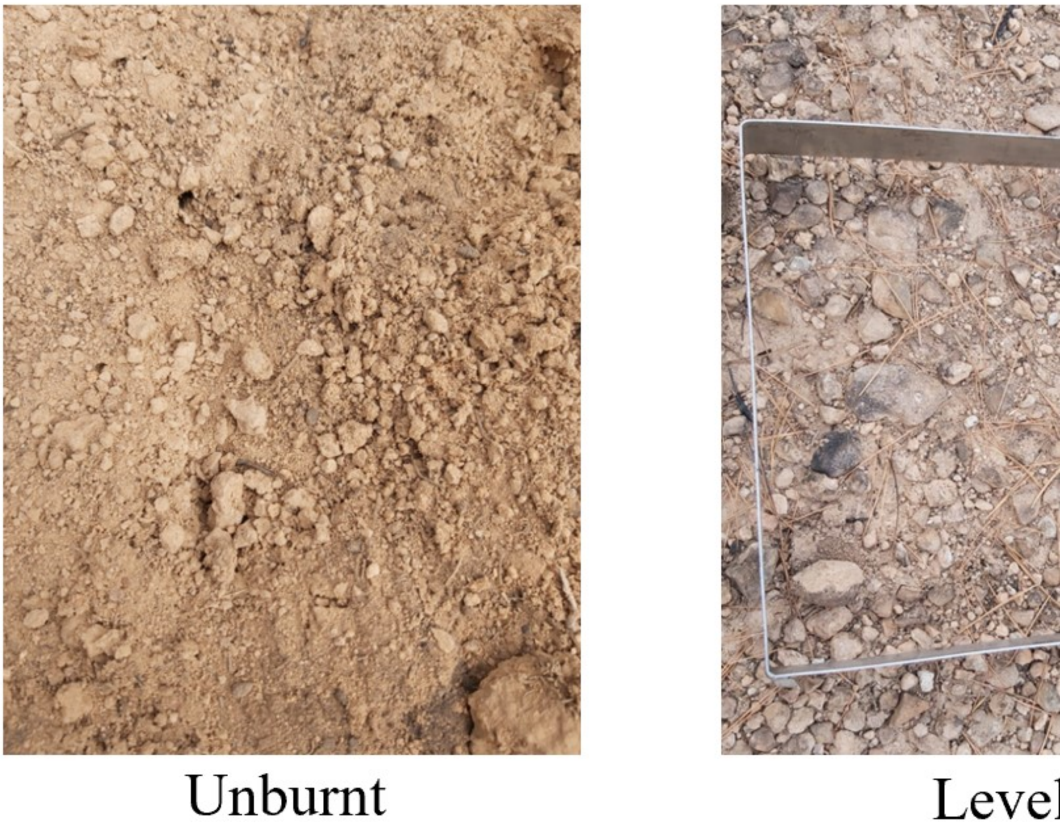


Figure 1 – Geographical location of Albacete province (a, upper figure) and the study site of Liétor (b, upper figure) (Castilla La Mancha, Spain) as well as photos showing soil burning severity levels (lower figure) in the study site.

Table 1 – Main physico-chemical properties of the study area (Liétor, Castilla La Mancha, Spain) according to the different soil conditions.

Soil property	**Soil condition**					
	Unburnt		**Low severity fire**		**High severity fire**	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
SaC (%)	42.80	2.41	42.85	1.19	41.43	1.72
SiC (%)	33.35	0.77	34.70	0.83	33.78	1.33
ClC (%)	23.85	2.18	22.50	0.70	24.75	0.39
pH	8.33	0.01	8.25	0.01	8.40	0.02
EC (mmhos/cm)	0.47	0.02	0.61	0.02	0.51	0.02
OM (%)	5.94	0.44	6.10	0.49	6.28	0.82
TN (%)	0.21	0.01	0.22	0.01	0.22	0.03

P (ppm)	13.75	1.52	16.00	1.34	14.50	3.03
K^+ (meq/100 g)	1.06	0.09	1.27	0.13	1.15	0.10
Na^+ (meq/100 g)	0.06	0.00	0.06	0.00	0.06	0.00
Ca^{2+} (meq/100 g)	45.86	0.71	48.42	0.84	48.39	1.14
Mg^{2+} (meq/100 g)	5.34	0.55	5.54	0.52	6.08	0.58

Notes: SaC = sand content; SiC = silt content; ClC = clay content; EC =electrical conductivity; OM = organic matter; TN = total nitrogen; P = phosphorous; K^+ = potassium; Na^+ = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium.

2.2. Experimental design

One week after the wildfire of 2021, and before the first rainfall event, the burnt area was delimited together with adjacent unburnt areas. In these areas (burned and unburnt), 80 sampling plots (each of 20 cm x 20 cm) were randomly installed as follows: 40 plots were established in the burned pine stand; the remaining 40 plots were identified in reforested areas. In both areas, the vegetation was fully burned by crown fire. Ten additional plots were selected in an unburnt area close to the zones affected by the wildfire, five in the pine stand and five in the reforested area. Since the values of K and SWR were very close for the two areas (difference lower than 5%), we considered one value of these properties for the unburnt areas (assumed as "control"). The minimum reciprocal distance among all plots was 300 metres, to avoid pseudo-replication.

The soil burn severity was assessed in each plot using a modification of the classification proposed by Vega et al. (2013). This classification consisted of the following levels of soil burn severity (Figure 1):

- Very low severity (Level 1): bare soil together with soil with limited burned litter, but limited duff consumption
- Low severity (Level 2): bare soil together with burned litter.
- Moderate severity (Level 3): Oa soil layer totally charred and covering mineral soil, with some ash and black carbon on the surface.
- Moderate to high severity (Level 4): forest floor completely consumed (bare soil), but soil organic matter not consumed and surface soil intact; Mostly grey soil colour (due to ash) on the soil surface
- High severity (level 5): forest floor completely consumed, soil organic matter of the soil surface consumed and soil structure altered within a depth of less than 1 cm; grey soil colour (with orange colour on the surface).

A "Level 0" of the soil burn severity was attributed to the unburnt soils.

Therefore, the experimental design consisted of three land conditions (pine stand vs. reforested area vs. unburnt forest) × five fire severities (class 1 to 5) × two soil depths (1 and 5 cm above ground) × four (pine stand and reforested area) or five (unburnt forest) replications, totalling 90 plots).

2.3. Measurement of soil hydraulic conductivity and water repellency

The K and SWR were measured in three points of each plot, randomly selected. The unsaturated K was estimated using a Mini-Disk Infiltrometer (MDI, (Devices, 2013)) (Robichaud et al., 2008a), and following the MDI technical manual and the procedure suggested by (Robichaud et al., 2008b, 2008a). In more detail, the litter layer was removed using a shovel on a small area of soil surface, which was subsequently leveled to place the infiltrometer and cleaned using a brush. Every 30 seconds after the start of each measurement, the volume of water infiltrated in the soil was recorded until the total water infiltration or a maximum time of 10 minutes. K was calculated using the equations proposed by (Zhang, 1997). The measured infiltrated water volumes (I, [m]) were regressed with the time intervals of 30 seconds (t, [s]) by equation (1):

$$I = C_1 t + C_2 t^{1/2} \quad (1)$$

C_1 and being a coefficient related to soil hydraulic conductivity [m s^{-1}] and a coefficient related to absorption capacity [m $s^{-1/2}$], respectively.
Equation (2) was used to estimate the K ([mm h^{-1}]):

$$K = C_1/A \quad (2)$$

where A is a coefficient that corresponds to the Van Genuchten's parameters (n and α) of a specific soil type for the suction rate (h_0, equal in this study to -2 cm) and disk radius (r, 2.25 cm) of the infiltrometer. For the experimental soil (of sandy loam texture), the values of A, n and α were equal to 3.91, 3.78 and 0.075, respectively (Devices, 2013).
The estimation of the SWR in field was carried out using the Water Drop Penetration Test (WDPT) method (Letey, 1969; Woudt, 1959). The method measures the time needed by a drop to infiltrate into soil. In this investigation, 15 drops of distilled water were left to drop from a pipette on the soil surface, and the infiltration time was recorded by a stopwatch.
The SWR was classified based on the measured values of WDPT, following the classification of (Bisdom et al., 1993):

i) non water-repellent or wettable soil (class 0, WDPT < 5 s);
ii) slightly water-repellent soil (class 1, 5 < WDPT < 60 s);
iii) strongly water-repellent soil (class 2, 60 < WDPT < 600 s);
iv) severely water-repellent soil (class 3, 600 < WDPT < 3600 s); and
v) extremely water-repellent soil (WDPT > 3600 s) with three sub-classes (class 4, 1 < WDPT < 3 h, class 5 (3 < WDPT < 6 h) and class 6 (WDPT > 6 h).

At the same time, the soil water content (SWC, e.g., Dekker and Ritsema, 1994; Lichner et al., 2013; Vogelmann et al., 2013), which influences SWR, was measured by a device (Vegetronix VG400, accuracy of 2%, measurement range 0-50%), placed on the soil surface and connected to a data logger (UX120 4-channel Analog Logger, Onset HOBO, Massachusetts, USA). All the SWR measurements with differences in SWC over 10% were discarded, in order to avoid SWR being biased by different SWC.

The WDPT values (and then the relevant SWR class was assigned to the land condition and severity) and K measured in each point of the plots were averaged for the following statistical treatment.

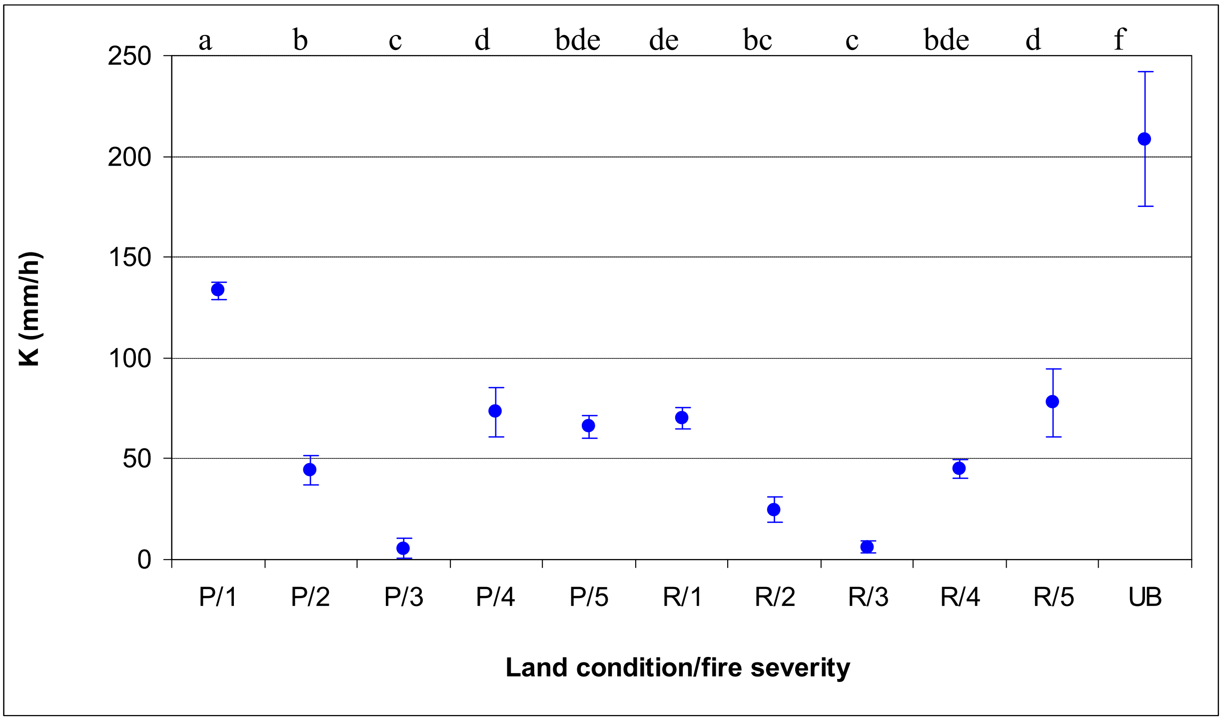
2.4. Statistical analysis

A 3-way ANOVA (ANalysis Of VAriance) was separately applied to K and WDPT values (individually assumed as response variables), assuming as factors the type of the forest ecosystem (unburned, natural stand of pine or reforestation), fire severity (levels 1, 2, 3, 4, and 5) and soil depth (1 or 5 cm below ground). The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the response variable. In order to satisfy the assumptions of the statistical tests (equality of variance and normal distribution), the data were subjected to normality Anderson-Darling's test or were square root-transformed whenever necessary. The statistical analysis was carried out using the XLSTAT release 2019 software.

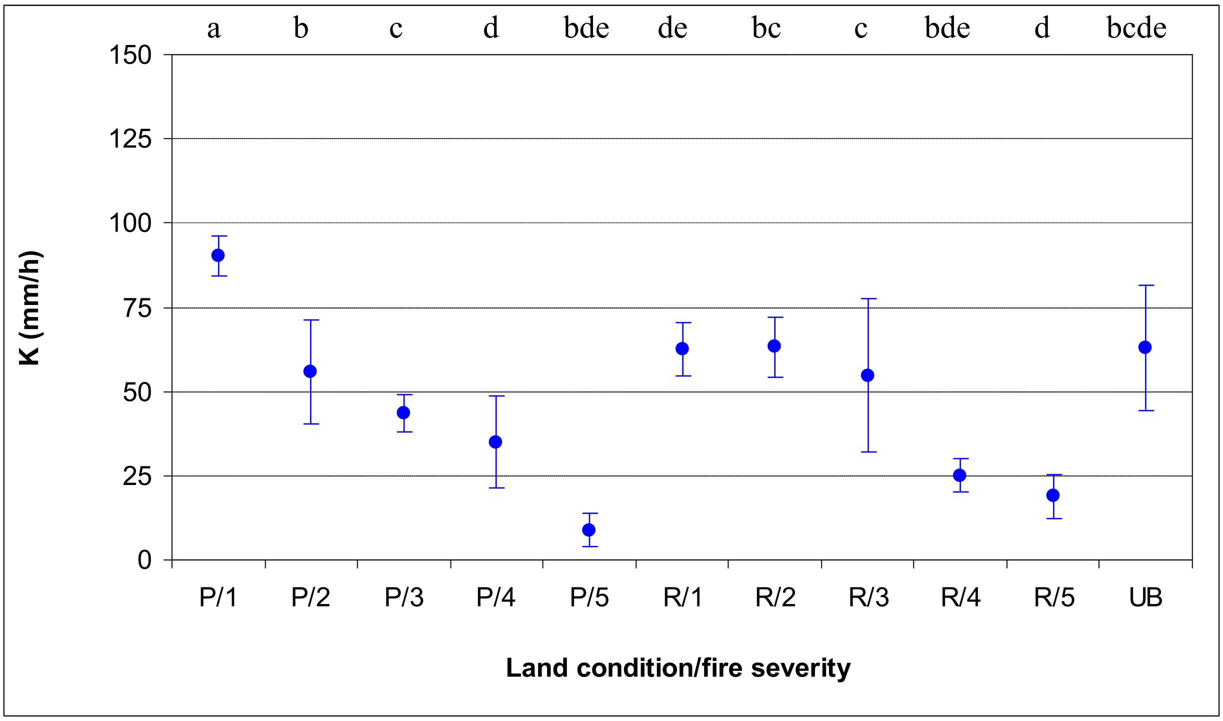
3. RESULTS

In the unburnt soils, the K was 209 ± 33.1 mm/h on the surface (1 cm of depth) and 62.9 ± 18.7 mm/h at 5 cm (data not shown). The 3-way ANOVA showed that all the analyzed factors (forest ecosystem type, fire severity and soil depth) and their interactions played a significant ($F > 16.359$, $p < 0.001$) influence on K, except the interaction among all the individual factors ($p = 0.078$). The results of ANOVA also showed that the K was on average significantly higher in the natural stand of pine compared to the reforested area, and at the soil surface compared to the deeper layer.

With reference to the superficial value, in the upper layer of the burned soils the K decreased with a fire severity between 1 and 3. In contrast, the soils burned by fires with higher severity (4 and 5) showed a K higher in comparison with those burned at fire severity of 2 and 3. The minimum K was measured at a fire severity of 3 for both the forest ecosystem types (5.6 ± 5.1 mm/h for natural stand of pine and reforested area). The variability of K was low, as shown by the coefficient of variation equal to 25.3%. It is worth to mentioning that, in the reforested area, the K of soils burned at severity of 5 (77.9 ± 17.0 mm/h) was close to the value measured for burning at severity equal to 1 (70.1 ± 5.0 mm/h) (Figure 2a).



(a)



(b)

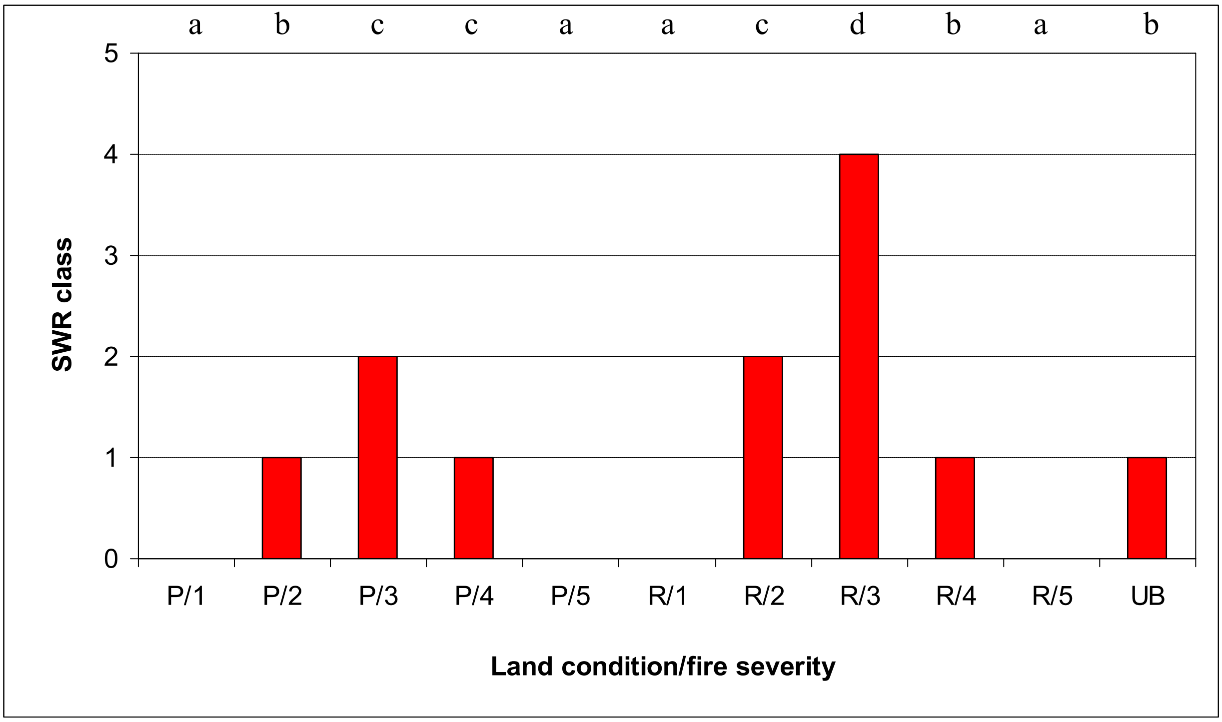
Figure 2 – Soil hydraulic conductivity (K) measured at 1 (a) and 5 (b) cm below the ground surface in two forest ecosystem types (P, pine; R, reforested area), and under five fire severities (1, 2, 3, 4 and 5) and unburnt soils (UB) in the study area (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among forest ecosystem type and fire severities, while the vertical lines are the error bars.

At a depth of 5 cm below the ground, the K was again lower compared to the value measured in the unburnt soil, and this decrease was monotonic. More specifically, while the decreasing trend was constant for the pine stand, the soils burned by fires with severity 4 and 5, and then subjected to reforestation showed a K significantly lower compared to the lower severities. The variability of K was similar as in the superficial layer (coefficient of variation equal to 26.5%). For both forest ecosystem types, the lowest K was measured at a burning severity of 5 (8.8 ± 4.9 mm/h, natural pine, and 18.9 ± 6.5 mm/h, reforestation) (Figure 2b).

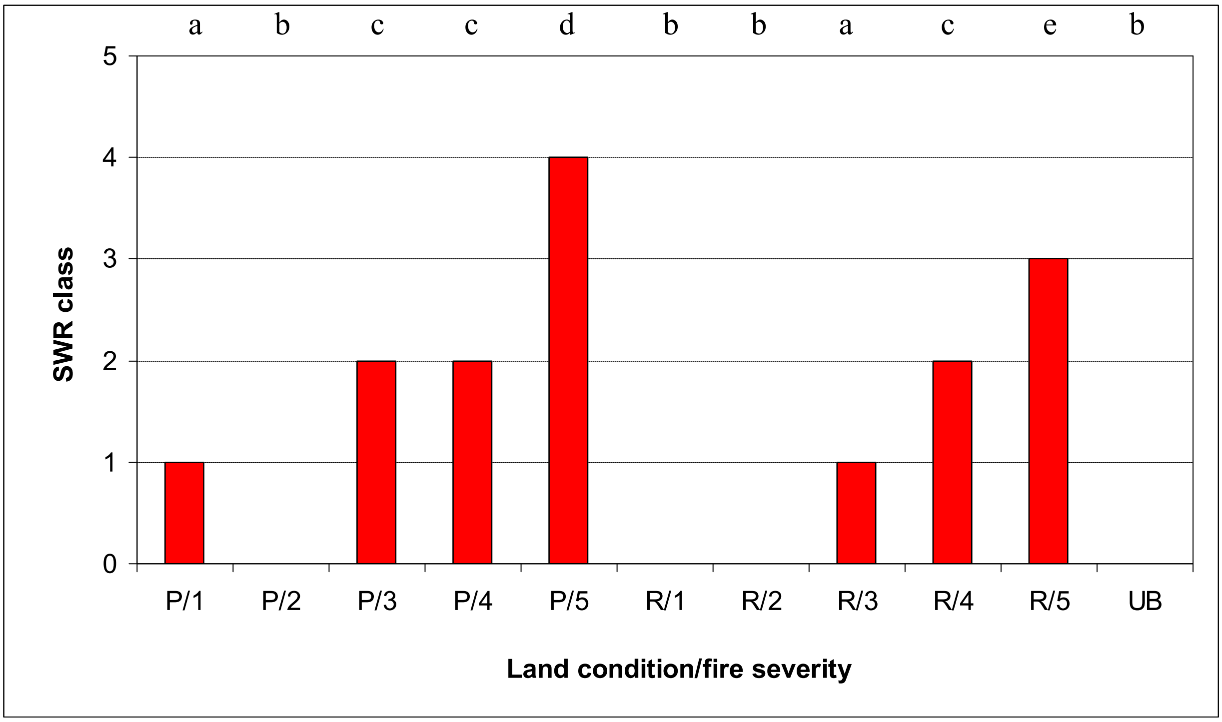
Concerning the SWR, the superficial and deeper layers of soils were non repellent (class 0, WDPT < 5 s) or slightly water-repellent (class 1, 5 s < WDPT < 60 s), respectively (data not shown). The 3-way ANOVA showed that none of the evaluated factors neither their interactions influenced the SWR, and therefore the differences in SWR among the various forest ecosystem types, fire severities and soil depths were not significant.

In the superficial layer and in the natural stand of pine, the soils were non or slightly water-repellent (classes 0 and 1, as the unburnt soils) at fire severities of 1, 4 and 5, and became strongly water-repellent (class 2) when the severity was 3. In the reforested area, the fire severity 1, 4 and 5 did not induce water repellency, while a strong and even an extreme repellency was surveyed in the soils burned at a fire severity of 2 and 3 (Figure 3a).

In the deeper layer, the SWR monotonically increased with the fire severity for both forest ecosystem types, except for the pine stand burned by fire with severity equal to 2, which did not show any repellency (class 0). In general, the fires with severity between 1 and 2 did not induce repellency or resulted in a slight repellency (classes 0 and 1), while the SWR was strong to extreme (classes from 2 to 4) in soils subjected to burning at severities between 3 (only in the deforested areas) and 5 (Figure 3b).



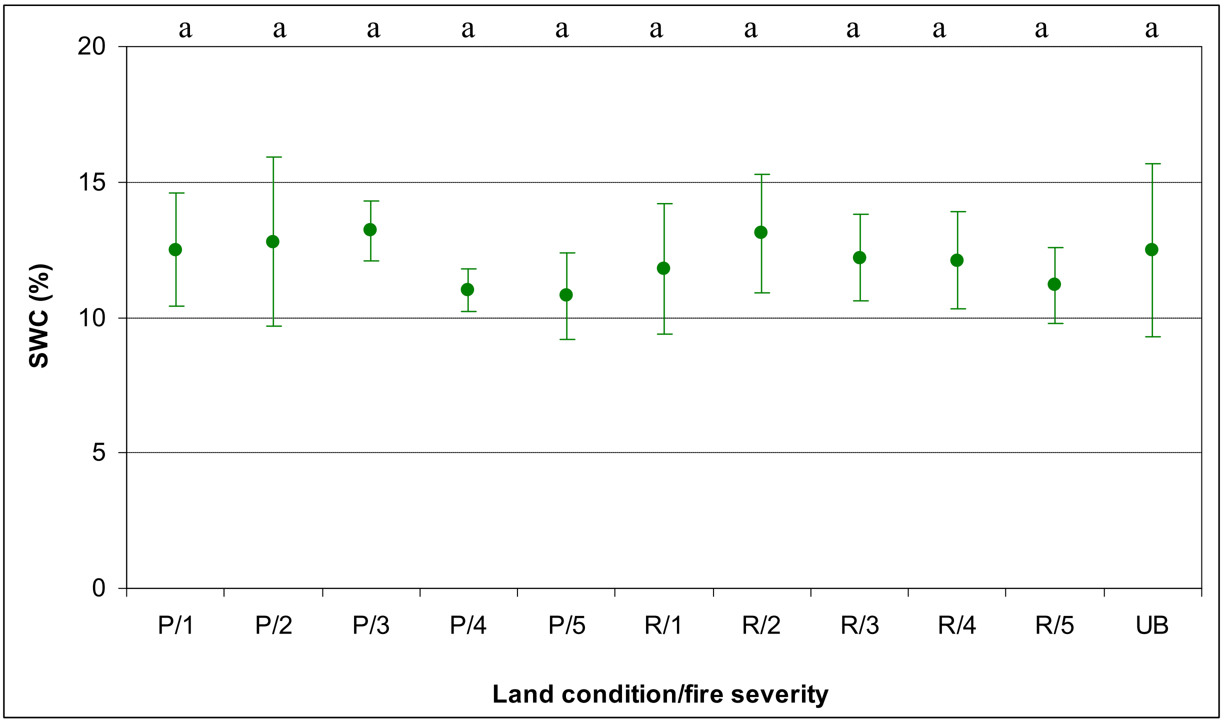
(a)



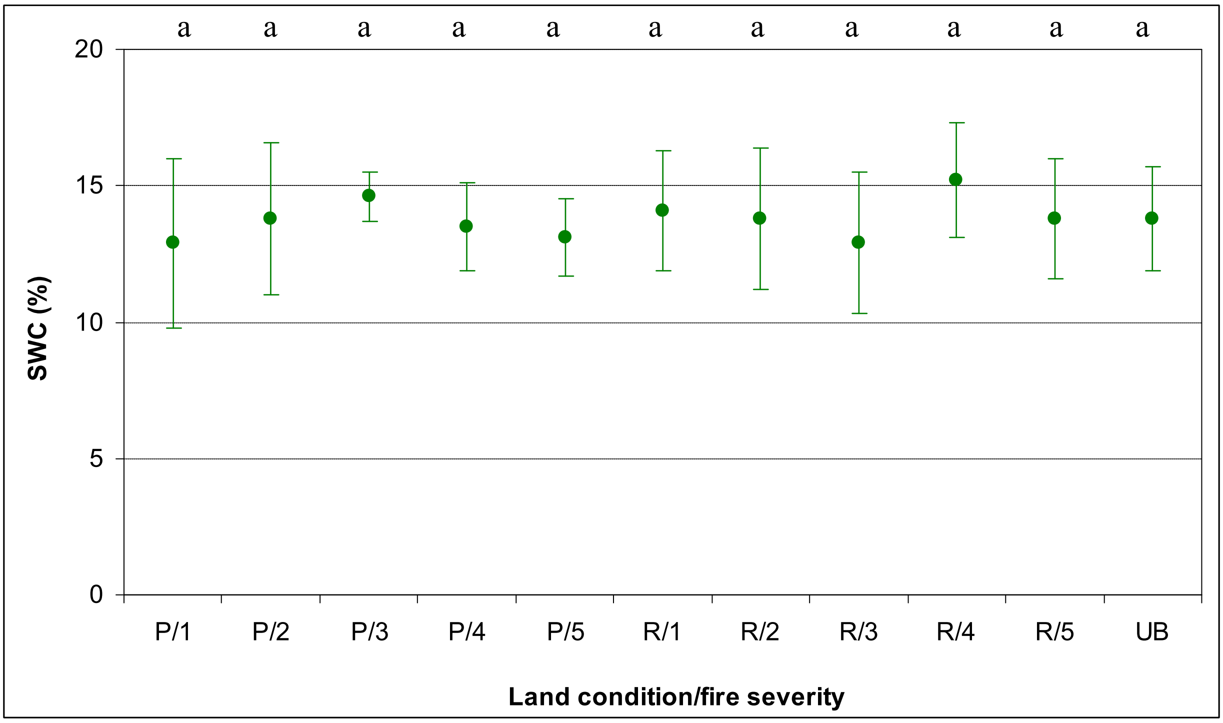
(b)

Figure 3 – Soil water repellency (SWR) class (referred to the WDPT values) measured at 1 (a) and 5 (b) cm below the ground surface in two forest ecosystem types (P, pine; R, reforested area) and under five fire severities (1, 2, 3, 4 and 5), and unburnt soils (UB) in the study area (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among forest ecosystem type and fire severities, while the vertical lines are the error bars.

The differences in SWC, which is a primary driver of SWR, were very low among the different land conditions and fire severity at both soil depths (Figure 4), and this allows the SWR comparability.



(a)



(b)

Figure 4 – Soil water content (SWC) measured at 1 (a) and 5 (b) cm below the ground surface in two forest ecosystem types (P, pine; R, reforested area), and under five fire severities (1, 2, 3, 4 and 5) and in unburnt soils (UB) in the study area (Liétor, Castilla La Mancha, Spain). Different letters

indicate significant differences among forest ecosystem type and fire severities, while the vertical lines are the error bars.

By regressing the K and SWR values separately for the two soil depths, coefficients of determination of 0.26 (1 cm below ground) and 0.67 (5 cm) were found. Only the latter correlation was significant at $p < 0.05$ (Figure 5).

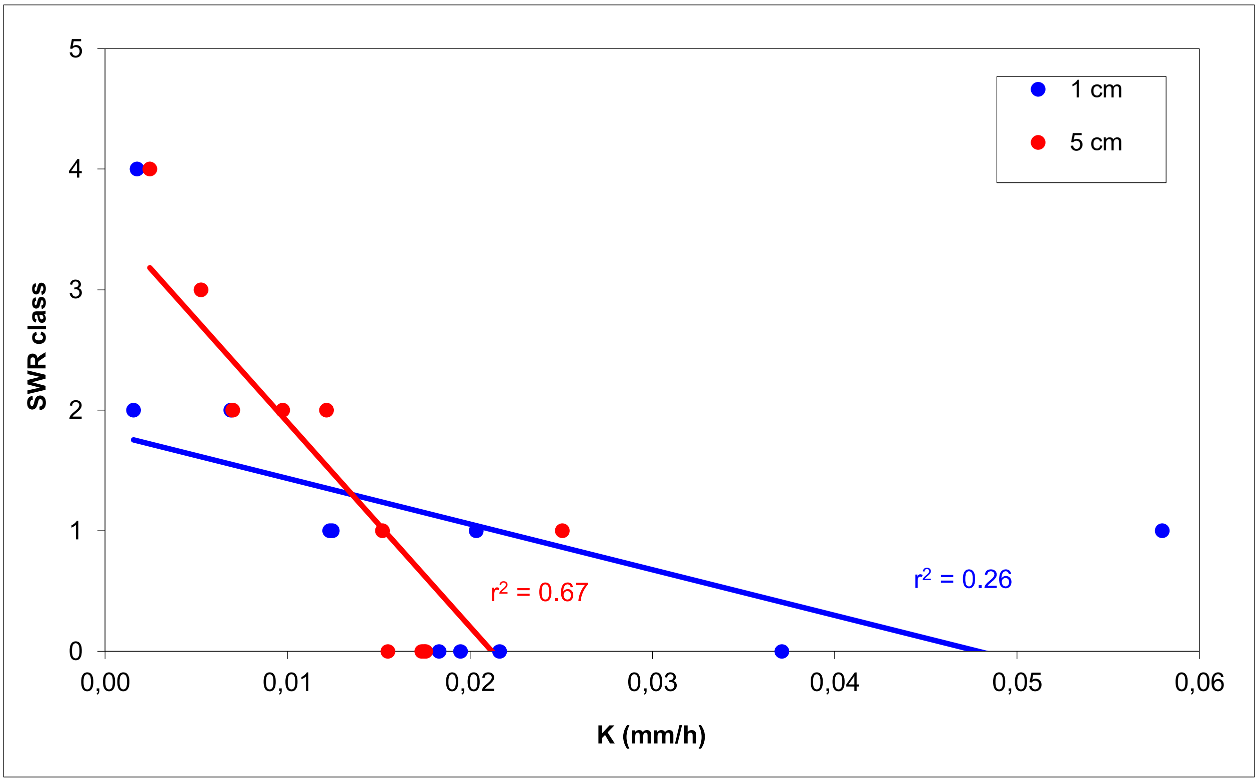


Figure 5 – Linear regression between the soil hydraulic conductivity (K) and soil water repellency (SWR) class (referred to the WDPT values) measured at 1 and 5 cm below the ground surface in two forest ecosystem types (pine and reforested areas), and under five fire severities (class 1, 2, 3, 4 and 5) and in unburnt soils in the study area (Liétor, Castilla La Mancha, Spain).

4. DISCUSSIONS

The importance of water infiltration and repellency in the hydrological response of forest soils, especially in semi-arid Mediterranean conditions, have been highlighted by several studies (e.g., (DeBano and Rice, 1973; Martínez-Zavala and Jordán-López, 2009; Wahl et al., 2003). The influence of these hydraulic properties on the hydrology forest soil is extremely important in burned areas, where fire may alter the undisturbed hydraulic conductivity by many orders of magnitude (Fernández et al., 2021; Pereira et al., 2018; Stoof et al., 2011; Zema, 2021). This means that a deep understanding of the variability of K and SWR with the fire and soil characteristics is essential to control and mitigate the hydrological hazard in forestlands. Identifying how the SWR patterns are modified as a function of fire severity in semi-arid environments can help land planners in the post-fire management of these ecosystems. Both the fire severity and soil depth significantly influenced the infiltration rates, and this influence was different between the studied forest ecosystems. At the soil surface of the burned soil of both natural pine stand and reforested area, the fire reduced the K by 80-90% even at a severity of 2, while this reduction was even 97% for wildfire with severity of 3 in comparison to the infiltration measured in the unburnt soils. Unless differences in K and SWR existed between burnt and unburnt plots pre-fire, it is likely thatfires with relatively low severity can play negative impacts on water infiltration at the soil surface with subsequent increased risks of surface runoff and erosion. In the soils burned at the highest severity, the fire destroys the SWR on the soil surface. The combination of lack of repellency and destruction of aggregates in the most severely burned soils is what increases the risk of erosion (Fernández et al., 2016; Fernández et al., 2021). At the lower soil depth, the fire induced reductions of K that were more or less proportional to its severity. At the 5 cm soil depth, the pine stand showed hydrological effects that were more tolerant towards a fire severity of 4, while the reduction in K was very high (-86%) at the highest severity (level 5) compared to the unburnt soils. In the reforested soils, the highest fire severities strongly reduced the K by 60-70%. It is worth to notice that, in some cases, the K of the soil surface layer may be higher compared to the water infiltration in the deeper layer, which means that the soil's capacity to allow water infiltration decreases with depth. This was observed in burned soils of both natural stand of pine and reforested area at the lowest (level 1) or highest (levels 4 and 5) fire severities. In contrast, at the intermediate fire severities (levels 2 to 3), the water infiltration strongly increases with the soil depth.

With reference to the effects of fire on SWR, while at the soil surface the highest SWR was found for the soils burned by fires with moderate severity (inducing the maximum reduction of K), in the deeper layer the hydrophobic effects increased with the fire severity. We should notice that the soils burned at the lowest (level 1) and highest (levels 4 and 5) severities did not exhibit strong SWR, and this confirms literature data. As a matter of fact, SWR does not noticeably change at temperatures under 200 °C, increases between 250 and 300 °C, and completely disappears over 300-400 °C (Pereira et al., 2018; Varela et al., 2010; Zema, 2021). More specifically, the highest reductions in K (85-95%, fire severities of 3 at the surface layer of the reforested soils, and of 5 in the deeper layer of the natural stand of pine, respectively) compared to the unburnt soils were observed when fire induced extreme water repellency of soils (class 4). Moreover, a severe water repellency (class 3) was detected in the lower soil depth of the reforested area burned by the wildfire with the highest severity (level 5), which strongly decreased the K (-70%). It is interesting to highlight that, in the reforested areas, also a low fire severity (level 1 or 2) can noticeably reduce the surface K (-80%), in spite of the limited SWR.

This result shows that the reforested areas can be more prone to a worsening of the hydrological conditions of the burned soils at limited fire severities compared to the natural forests, which are less exposed to hydrophobicity in their surface soil layer. Presumably, the soil disturbance due to the reforestation (for instance, the soil compaction, harvesting and the effects of other machinery) has reduced the K of reforested (Lucas-Borja et al., 2018), and this may be dangerous for the hydrological response after rainstorms. (Manuel Esteban Lucas-Borja et al., 2020) demonstrated in the same forest area that the management operations generate higher soil compaction and lower plant cover in plots affected by skidding, which could reduce water infiltration capacity. Correlations between K and SWR was found in this study only at the lower soil depth. The close linkage between K and SWR detected in this study is in contrast with the results of (Zema et al., 2021a), which did not find significant correlations between K and SWR (except in unmanaged and old pine stands), and this result was confirmed by low and non-significant linear regressions. A negative correlation between K and SWR was instead found in (Olorunfemi and Fasinmirin, 2017).

The changes in SWR should be found in other factors than organic matter content of soils (which is a very influential variable on SWR (de Jonge et al., 1999; DeBano, 1981)), which were similar among the investigated land conditions and fire severities. However, this assumption requires more investigation with specific measures of an important driver of SWR as organic matter is. On this regard, increases in organic matter content in burnt areas compared to the unburnt sites have been observed by many authors also for fires with low severity, such as the prescribed fires (Alcañiz et al., 2018b). In contrast, medium- or high-intensity fire causes a decrease in soil organic carbon content (Mataix-Solera et al., 2011), which may be due to combustion of organic matter of soil, and mineralization, volatilization, and solubilisation (Agbeshie et al., 2022; Rodriguez-Cardona et al., 2020).

The practical implications of the changes in K and SWR detected in this study among the different land conditions and fire severities may be a differentiated soil hydrologic response in terms of overland flow and soil erosion. Much eminent literature has shown that decreases or increases in soil infiltration (due to SWR or other factors, such as post-fire treatments) may lead to decreased or increased runoff rates (e.g., (Agbeshie et al., 2022; Alcañiz et al., 2018b; Bodí et al., 2012; Cawson et al., 2012; Certini, 2005; Moody et al., 2013). Infiltration and runoff rates may noticeably change after fires with the same severity. For instance, (Carrà et al., 2022, 2021) have reported significant differences in water infiltration and surface runoff after prescribed fires (with or without post-fire soil mulching), while (Zema et al., 2022) demonstrated a clear correlation between these two variables in the same experimental conditions. In soils burned by wildfires, (Pierson et al., 2002) reported noticeably changes in infiltration rates and soil erodibility. These examples combined to the results of our investigation, showing decreased infiltration with increasing fire severity, suggest the need of targeted measurements of runoff rates in burned areas, in order to verify the sensitivity of this hydrological variables to the infiltration variability. These measurements are essential to decide whether post-fire management actions must be adopted or not in areas burned by fire or prone to the wildfire risk.

5. CONCLUSIONS

The changes in the K and SWR with fire severity and soil depth have been evaluated in two forest ecosystems (natural stand of pine and reforested areas) of Castilla La Mancha (Central Eastern Spain).

In reply to the first and second research question about the variability of K and SWR with the fire severity and soil depth, the study has revealed a significant influence of both the fire severity on the infiltration rates, and this influence was different between the natural stand of pine and the reforested areas. At the soil surface, all fire severities severely reduced the K, but the highest reduction (80-90% compared to the unburnt soils) were found for the fires with low and intermediate severities. At the lower soil depth, the reduction of K due to fire were proportional to its severity. Moreover, the K and SWR of the soil surface layer was often higher compared to the water infiltration in the deeper layer.

The reductions of water infiltration were mainly due to the SWR induced by fire, and also for this hydrological property the variability with the fire severity was different between the two soil layers. While at the soil surface the highest SWR was found for the soils burned by fires with moderate severity (inducing the maximum reduction of K), in the deeper layer the hydrophobic effects increased with the fire severity.

About the second research question on the differences in K and SWR between natural forests of pine and reforested ecosystems, it has been demonstrated that the highest SWR and reductions in K occurred at intermediate fire severities in the reforested soils, and at the maximum severity in the natural stand of pine. In the reforested areas, also low fire severities can noticeably reduce the

surface K, despite the limited SWR, while the natural forests are less exposed to hydrophobicity in their surface soil layer.
Overall, it must be advised the need of primary and most urgent actions of post-fire management in reforested areas subjected to intermediate fire severities, in order to reduce the risk of flooding and erosion linked to a reduction in water infiltration and increase of soil repellency.

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DATA AVAILABILITY

Data is availabile upon request to the corresponding author.

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