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Research article

Soil response in a Mediterranean forest ecosystem of Southeast Spain following early prescribed burning

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ABSTRACT

The escalation of global warming, high temperatures, and wildfire frequency in dry ecosystems, including semi-arid landscapes, has resulted in increased wildfire regimes, compromising ecosystem resistance and resilience. To mitigate these risks, prescribed burning (PB) is being employed as a preventive measure to modify fuel loads in forest ecosystems. However, fire can also impact soil structure and microbiota, which play critical roles in nutrient cycling, biodiversity conservation, and overall ecosystem functioning. Therefore, understanding post-fire processes is essential for sustainable forest management. However, while previous studies have explored the effects of prescribed fire management on semi-arid soil properties in Mediterranean forest ecosystems, gaps remain in our understanding of its specific impact on the physical structure, chemical composition, and biological activities of soils.

In this study, we conducted early spring PB in SE Spain in 2021 and assessed the ecological and temporal effects of PB on semi-arid soils. Soil respiration (SR) measurements using automatic CO_2 flow chambers were employed to evaluate microbiota recovery. To examine impacts on soil structure we evaluated physicochemical characteristics, soil hydraulic conductivity (SHC), and soil water repellency (SWR). No significant differences were observed in any of the variables studied after one year. However, immediate effects were detected shortly after the PB. Our research specifically targeted soil structure and microbiota in a semi-arid landscape with poor soils, characterized by slower recovery and potentially fragile ecosystems. These results provide valuable insights for forest management practices, indicating that prescribed fire management strategies in similar ecosystems are unlikely to cause adverse effects on soil health. However, further research is warranted to explore the potential effects of prescribed fire intensity and seasonality. Future studies can focus on investigating these factors to provide more targeted recommendations for effective forest management strategies and wildfire prevention efforts.

1. Introduction

The escalating risk of wildfires in arid and semi-arid climates with extremely hot and dry summers has become a pressing concern

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[1]. Ecosystem vulnerability has intensified due to these factors, leading to slow vegetation regeneration, water stress, and degraded soil properties such as low organic matter and nutrient content [2,3]. Wildfires have significant impacts on water, air, vegetation, and fauna, shaping landscapes and prolonging dry seasons [4]. Effective forest fuel management, particularly through prescribed burning (PB), is crucial for fire prevention [5]. Preventive treatments, such as prescribed burning (PB), aim to modify vegetation strata in high-fire-risk areas, minimizing the extent and intensity of wildfires [6]. PB is increasingly used as a preventive tool, creating discontinuities in vegetation strata both horizontally and vertically [7]. Understanding the impacts of PB on soil microbial communities in semi-arid regions with poor soils, where water availability is limited, solar exposure becomes a critical factor affecting various ecological processes [8]. Further investigation is needed to unravel the intricate relationships between fire, microbial diversity, and ecosystem functioning, providing valuable insights for sustainable conservation and restoration practices [9]. Filling this knowledge gap can enhance our understanding of the potential impacts of PB, especially in areas where other tools, like mechanical cutting, have limited accessibility.

Fire exerts a significant influence on soil health and microbial communities, impacting crucial processes such as nutrient cycling, biodiversity maintenance, and ecosystem functioning [10]. The edaphic microbiota directly influences OM decomposition, fuel load, and the nutrient cycling of elements like carbon (C), nitrogen (N), and phosphorus (P) [11]. Assessing the sensitivity of these communities to heat is crucial, as some bacterial communities produce nitrate derivatives (from NO_3 in ashes) that become scarce after fires [12]. These derivatives can include various nitrogen-containing compounds such as nitrite (NO^{2-}), nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen gas (N_2), among others. The production of these derivatives is a vital part of the nitrogen cycle in forest ecosystems, influencing nutrient availability, greenhouse gas emissions, and overall soil fertility. However, micro-edaphic communities are extremely vulnerable to slight temperature variations [13], as well as other factors such as weather parameters, season of the year, and types of burning or fire [14]. They are one of the most useful bioindicators for measuring fire impact on soil [15]. Therefore, understanding the impacts on these microbial communities is vital for sustainable land management practices [16].

Forest fires result in numerous short- and long-term hydrological and geomorphological changes, affecting soil and water [17]. Post-fire, vegetation and organic matter depletion leave the soil surface exposed to increased runoff and erosion risks [18]. These alterations substantially modify the hydrological response of burned areas, affecting infiltration, surface flow, and erosion patterns [19]. Studies indicate that even low-severity fires or PB can influence runoff and soil erosion rates [20–22]. However, specific investigations are warranted to elucidate the mechanisms underlying these effects, such as the role of microbial communities in soil recovery processes and the long-term implications for ecosystem resilience. By conducting targeted studies on vegetation dynamics, soil microbial ecology, and hydrological processes, we aim to provide actionable insights for ecosystem management and post-fire rehabilitation strategies in dry and hot environments characterized by slowed vegetation regeneration.

PB is one of the strategies commonly used to reduce fuel loads by creating intensity bands, along with other fuels management techniques [23]. PB has been shown to promote the growth and germination of native species in some forest areas, although it is important to acknowledge that its effects can vary depending on the ecosystem and specific management practices [24,25]. PB timing is critical for ensuring its effectiveness and preventing disruption of biotic and abiotic processes [26]. Depending on climatic conditions, low-severity fires can significantly influence soil properties and bacterial communities [27,28]. Therefore, it is imperative to determine the optimal timing for PB application across diverse soil and ecosystem types. While PB has proven to mitigate fire severity in the southern and western USA, its ecological effects in the Mediterranean Basin remain understudied [29]. Ongoing research is investigating the impact of fire on soil in this region, crucial for understanding ecosystem responses and facilitating recovery [30].

In this study, we aim to investigate the effects of an early, low-severity PB on soil properties and ecosystem processes in a semi-arid Mediterranean landscape. Our research is grounded in previous findings that suggest prescribed burning can have significant implications for soil physicochemical properties and biological activity. As other studies [31,32] have indicated, recovery of different soil parameters recovered in the short term (one year), due to the low soil temperatures recorded and the heat residence time of PB. Enhancing our understanding of PB in the Mediterranean Basin is crucial given the increased risk of wildfires in these regions exacerbated by global warming [33,34]. This consideration is crucial due to the high fire risk and recurrent fires in these ecosystems [35]. Specifically, we hypothesize that: i) Microbiota activity, as measured by SR, will be initially impacted by the fire, with a rapid recovery anticipated within the study period following a low-severity prescribed burn. This hypothesis is based on observations from similar ecosystems and previous research indicating the sensitivity of soil microbial communities to fire disturbance. ii) SWR is expected to increase, and SHC is expected to decrease initially due to ash generation. However, we anticipate a short-term recovery after the low-severity prescribed burn. Our hypothesis considers the influence of fire intensity on these soil properties and their subsequent recovery over time. iii) PB is anticipated to influence specific soil physicochemical parameters, including N and C. Even in the context of a low-severity burn, we expect alterations to these parameters between burned and unburned areas, potentially resulting in increased levels of both N and C in the soil throughout the study period [36,37]. By testing these hypotheses and comparing burned plots with control areas, we aim to provide insights into the immediate and subsequent impacts of low-severity prescribed burning on soil properties in a typically semi-arid Mediterranean landscape like in our study a *Pinus halepensis* Aiton forest with an understory predominantly composed of *Macrochloa tenacissima* (L.) Kunth. Our study seeks to bridge gaps in knowledge regarding the ecological effects of prescribed burning and inform management practices in fire-prone environments.

2. Materials and methods

2.1. Study area

The PB was carried out in May (spring) 2021 between the municipalities of Ayna and Molinicos (Albacete, SE Spain) by the forest technicians staff of "Junta de Castilla La-Mancha (JCCM)" and "Gestión Ambiental de Castilla-La Mancha (GEACAM)" according to a regional burning plan. The study area encompasses an open forest dominated by *Pinus halepensis* Aiton, with an understory predominantly composed of *Macrochloa tenacissima* (L.) Kunth, commonly known as alpha grass. Scattered patches of *Salvia rosmarinus* (L.) Schleid. and *Cistus clusii* Dunal are also present within the landscape. This forest type is typical of the semi-arid Mediterranean landscape of the region, characterized by its susceptibility to small-scale runoff due to the presence of the Sierra del Segura mountain range. Although the study area does not feature steep slopes, it is sufficient to generate runoff, particularly during rainfall events. The landscape predominantly consists of grassland, reflecting the dominance of alpha grass. The region is highly vulnerable to desertification, exacerbated by its location in the southeast of Spain, which is experiencing significant impacts from climate change [38]. The centroid in GPS coordinates (UTM zone 30N) of the burned area within the study area is 38.538, −2.105, with 38.537, −2.102 for the control (unburned) area (Fig. 1).

The research area is located at 781 m a.s.l. The climate there is Mediterranean with hot summers, according to the Csa Köppen-Geiger climate classification [39]. The mean annual temperature is 14.3 °C and the approximate rainfall is 406 mm per year [40], for the period 2001–2021. The smallest rainfalls are in July–August, with an average of 9.3 mm, and the highest are in March–April, with a precipitation of 55 mm.

The soils in the study area are from the Beti-Iberian limb of the "Cazorla Alcaraz-Hellín" and are predominantly linked with gaps of calcareous formations without advanced horizons, due to a semi-arid climate [41]. In addition, these soils are eutrophic cambisols (CMe), with a limited age, which show a non-significant pedogenesis deriving from some rocks of aeolian, colluvial, and alluvial origins. Horizon A has poor humus, while the cambic horizon (horizon B) is characterized by the formation of iron oxides and clay minerals [42].

2.2. Experimental design

2.2.1. Plots

We set up six square plots (30 m^2) with similar conditions (ANNEX; S1) and a SE aspect. The orientation of a site is crucial for informed land management decisions [43]. It plays a pivotal role in determining the solar Three of them were installed where the PB was to be carried out (Burned = B), and the other three were outside the PB area (Control/Unburned = C). Each plot was separated by 10 m. While we aimed to minimize spatial pseudoreplication [44], we acknowledge that having one burned and one unburned area with multiple plots within each does not constitute true independent replication. This limitation is considered in our analysis and discussion. Periodically in all the plots, four sampling times were scheduled for the physico-chemical soil parameters (29/04/21, 12/05/21, 05/12/21, and 06/05/22) to collect data about annual variability, which is most important immediately after applying PB, in the first autumn, and 1 year after burning. These multiple time points allow us to explore the nuanced impact of prescribed burning on soil dynamics, including nutrient cycling, which exhibits notable seasonal variations [45]. SR, SHC, and SWR were measured every month until the 1-year period had ended. Furthermore, a pre-burning (pre-PB) sampling was conducted seven days before PB to characterize the pre-PB state.

For the preliminary soil characterization, soil physico-chemical properties were recorded before the PB (Table 1) in each plot.

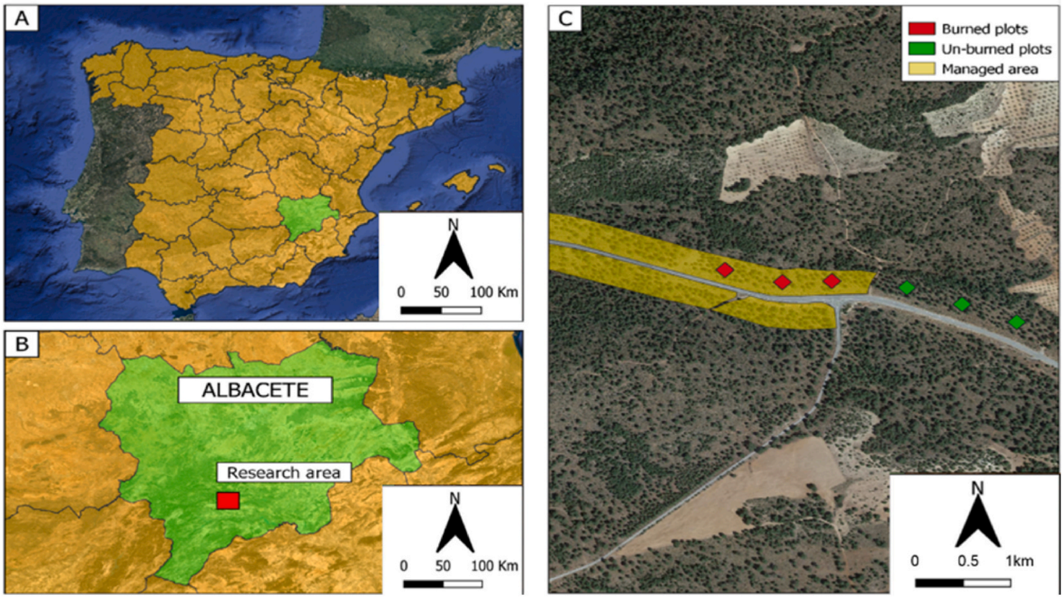


Fig. 1. A) Province of Albacete, Spain. B) Research area, Ayna Municipality in the Province of Albacete, Spain (in the 2021 spring). C) Area where was applicated PB (yellow). Plots on the burned area (burned = red), plots in the control area (un-burned = green).

Checks were made to see if the main variables (SR, SWR, and SHC) did not differ between plots (ANNEX; S1).

We employed a random sampling approach within each zone to select spatially distinct sampling units [46] in each plot. In addition, we considered the temporal aspect by collecting data at a single time point, thereby avoiding the potential confounding effects of temporal variations [47].

Our research aimed to mitigate concerns regarding pseudoreplication by implementing a carefully considered study design that accounted for spatial and temporal dependencies within our data [48]. However, conducting in-situ analyses presents inherent challenges due to variations in geomorphological, environmental, and temporal conditions, which may impact the robustness of the data analysis. This challenge is consistent with findings from other studies [49,50].

2.2.2. *Prescribed burn (PB)*

The PB was carried out in May 2021 in the municipality of Ayna (Albacete) by GEACAM and JCCM staff members.

The PB was executed using horizontal fire lines, each separated by 1 m and arranged perpendicularly to one another. Our PB strategy involves initiating back-fires or tail-burns, meaning it moved against the wind direction, a method recommended by forest technicians in Castilla-La Mancha and supported by relevant studies [51,52]. This approach aims to advance the fire front while minimizing the duration of ground contact and mitigates the risk of high temperatures belowground [53].

The PB began in the study area at 1:30 p.m. CET with the following meteorological conditions: temperature (T°): 24 °C; relative humidity (RH): 37 %; Wind speed (W): 0.83 m s^{-1} SE.

The fuel model was 5 (height less 1.5 m flammable shrub) according to Rothermel [54] and Albini [55] which is analyzed prior to treatment. The main shrub layers were *Macrochloa tenacissima*, *Cistus clusii*, *Salvia rosmarinus*, *Juniperus oxycedrus,* and *Genista scorpius* under an open forest of *Pinus halepensis*. Fire spreads fundamentally through scrubland, according to the technical notebooks of the combustible model taken from the digital terrain model and the phytoclimatic atlas of Spain (MAPAMA, 2022).

To assess burning intensity, we installed six thermocouples (HOBO UX120 4-Channel Analog Logger dataloggers), which is a device that records data over time, typically provided by a thermal sensor. These thermocouples were strategically placed at four different levels: 2 cm below the ground surface, at the mineral soil surface, above the litterfall, and 30 cm above the ground. This setup allowed us to record the temperatures reached during the prescribed burns and to characterize the duration of heat residence in the soil.

During PB, temperatures ranged from 9.1 ± 2.3 °C to average temperature (T°) and 32.1 ± 3.3 °C to maximum T° as -2 cm under mineral soil (overground); 17.1 ± 4.7 °C average T° and 38.5 ± 6.2 °C maximum T° on mineral soil (0 cm); 25.2 ± 3.7 °C average T° and 204.8 ± 11.5 °C maximum T° in the organic layer (litter); 28.8 ± 5.9 °C average T° and 247.5 ± 15.4 °C was the maximum T° above 30 cm of surface soil. Heat residence time on the ground did not exceed 100 °C and it was only above litter for 60 ± 0.6 s. The litter on the soil before the PB was minimal.

To characterize the fuel load burned, we set up 7 iron spikes of 1m per plot (21 in total) and measured the reduction of the canopy layer in depth after PB [56]. The canopy layer had been burned at 68.2 %.

2.2.3. *Soil sampling and analysis*

Each sample was made up of six subsamples; previously, we removed any element on the surface soil, like stones and litter. The subsamples were collected in the first 3–5 cm of soil on a 15 × $15cm^2$ (±1 cm of precision); at this depth, there is a maximum of microbiological activity [57]. In the laboratory, soil samples were passed through a 2 mm sieve and placed at 4 °C until the parameters were analyzed [58]. The composite sample values obtained were representative of each plot.

In May 2021, soil samples were collected to analyze soil physico-chemical properties. Three composite soil samples per plot were obtained from both the burned and control areas, ensuring comparable vegetation cover and soil type before PB (ANNEX 1). Each composite sample, considered representative of the entire plot for statistical analyses, was created by combining six randomly subsamples from different locations within the plot. The subsamples were collected using a defined 15 × 15 cm square, removing surface elements such as litter and stones. The top 2–3 cm of soil, where biological activity is highest, were then carefully excavated using a trowel with markings (1 cm precision) [59]. According to our experimental design, 72 soil samples (3 per plot x 3 plots x 2 treatments x 4 dates) were collected. Eighteen samples were obtained seven days before PB, another 18 were collected 7 days after PB, followed by 18 samples after 224 days of PB, and finally, 18 samples 1 year after burning. The selection of spring and autumn collection periods was crucial as it coincided with significant changes in vegetation and the seasonal dynamics of the plant-soil interface, when is a greater movement in soil nutrient cycling [60].

Our sampling approach aimed to capture variations in soil properties associated with prescribed burning over different time intervals. By collecting samples before burning and at three distinct post-burning time points (7 days, 224 days, and 1 year), our study primarily focuses on the immediate and short-term effects of prescribed burning on soil physico-chemical properties. The careful selection of sampling locations and timing enhances the robustness and reliability of our findings, providing valuable insights into the

Table 1

Result of the two-way ANOVA (Treatment and Date) for SR CO_2 flux.

	Sum Sq	Mean Sq	F Value	P-value
Treatment	0.08	0,08	0.16	0.69
Date	2.66	2.66	4.78	**0.03***
Treatment: Date	0.02	0.02	0.03	0.84

* Significance at a significance level of $p < 0.05$

dynamic changes in soil properties in the aftermath of prescribed burning events.

The soil was characterized by an analysis of the physico-chemical properties with the most relevant parameters according to other studies [61,62]. The analyzed parameters were: texture (clay, silt, and sand contents, % wt. wt^{-1}.) [63]; total nitrogen (N, %) [64]; available phosphorus (P, ppm) [65]; calcium (Ca^{2+}, meq. 100 g^{-1}); potassium (K^{+}, meq. 100 g^{-1}); magnesium (Mg^{2+}, meq. 100 g^{-1}); pH; electrical conductivity (EC, mhos cm^{-1}) by deionized water [66]; total soil organic matter (SOM, %); total soil organic carbon (Corg, %) [67].

2.2.4. Soil respiration (SR) by CO_2 flux, soil hydraulic conductivity (SHC) by infiltrate rates and soil water repellency (SWR) by water drop penetration time (WDPT)

We established 18 respiration points, three in each plot: nine B plots (SRburn) and nine others in the C plots (SRcontrol). In consideration of the irregular terrain at each sampling point, a PVC tube (20.7 cm diameter and 10 cm height) was employed to establish each measurement station. The collar height was measured post-burial, consistently targeted at a depth of 3–5 cm, to mitigate measurement errors in CO_2 flux. This approach aimed to enhance the precision of our flux measurements and correct for topographical variations in the study area. The SR variable was monitored using a portable analyzer in a closed system composed of a CO_2 analyzer. This method uses continuous measurements (every second) from the Infrared Gas Analyzer (IRGA) unit to measure the CO_2 concentration of a gas sample with a large hemispherical chamber: CFLUX-1 Automated Soil CO_2 Flux System (CFLUX-1). The chamber measured ambient temperature at the same time as respiration. Measurements were taken immediately before and after the PB and every month until the 1-year period ended. To reduce influences on diurnal SR fluctuations, all measurements were made between 09:00 and 15:00. We monitored the ambient temperature evolution using a CO_2 flow chamber, recording the mean temperature in both B and C plots. Notably, one measurement was taken on a rainy day (ANNEX; S2).

In total, 168 measurements were conducted (two per plot), one day each month until the year of study, with the same dates as SR, for SHC using a mini-disk infiltrometer, with each measurement lasting for 300 s, and SWR by WDPT. For the statistical analysis, we differentiated B and C plots as a factor for each variable, SHC, in the B (SHCburn) and C (SHCcontrol) plots.

With the infiltration rate, the runoff coefficient (k) was considered, which deals with the relation between the sheet of water that precipitates on a surface and the sheet of water that runs off the surface. The infiltration rate was expressed as m hr^{-1} comparing B and C plots. The value of parameter k vastly varies depending on the land-use type [68]. At the same time, we analyzed SWR, which was measured by WDPT. In addition, it is one of the most commonly used techniques to analyze the SWR degree [69]. SWR is quantitatively classified when one drop takes longer than 5 s to penetrate it [70]. Repellency classes were based exclusively on the time it took one drop to completely penetrate soil: class 0 is not water-repellent (infiltration of a drop at $t < 5$ s); class 1 is slightly water-repellent (5–60 s); class 2 is strongly water-repellent (60–600 s); class 3 is severely water-repellent (600s -1hr); classes 4–6 are extremely water-repellent as follows: class 4 (1–3 h); class 5 (3–6 h); and class 6 (>6 h).

2.3. Statistical analysis

Statistical analyses were conducted to assess the distribution and homogeneity of our data. Shapiro-Wilk tests were performed to assess normality, and Bartlett tests were used to verify homoscedasticity. For the SHC values, logarithmic transformations were applied to improve normality, and Anderson-Darling tests were conducted. A one-way repeated measures ANOVA was performed for soil analysis, and two-way ANOVAs were applied to evaluate changes in each variable after PB treatment, with time and treatment as factors. Statistical significance was set at $p < 0.05$. Post-hoc analyses of physico-chemical soil parameters were conducted using Fisher's independent least significant difference (LSD) test. Pearson's correlation test was used to analyze the relationships between SWR and SHC. To address the issue of pseudoreplication and data dependency, mixed-effects models were employed to rigorously assess treatment effects over time. This approach accounted for the lack of independence among plots within the burned and unburned areas. Correlation analysis was utilized to elucidate relationships between selected variables, while principal component analysis (PCA) was used to uncover underlying patterns. The mixed-effects models provided a robust framework for assessing the temporal effects of the treatment. Statistical analyses were conducted using Rstudio Desktop 2022.07.2 + 576 and IBM SPSS Statistics 24.

3. Results

3.1. Soil physico-chemical analysis

Burning at either time after the PB did not exert significant effects on soil pH, EC, K, Ca, Na, Mg, or soil texture (ANNEX, S3). However, significant differences were observed in SOM, N, P, and Corg. Notably, within the immediate post-burn period of 7 days, all aforementioned parameters exhibited significant changes, yet subsequently returned to non-significant differences between treatments, both temporally (days post-burn) and following a one-year observational period (ANNEX; S4).

3.2. Soil respiration (SR) in a CO_2 flux chamber

On a specific rainy day, measurements were taken from plots, revealing a significant disparity in SR compared to other sampling occasions (denoted by bars with 'c' or 'C'). Consequently, this outlier was excluded from further analysis to ensure robust assessment of significant differences. Notably, SR exhibited no statistically significant variance between control (SRcontrol) and B plots, as indicated by an F-statistic of 0.16 and a p-value of 0.69 over the study period. However, significant disparities were observed across different measurement dates (seasons), with a p-value <0.05 (Table 1 and Fig. 2). Maximum SR levels were notably recorded during spring, while a discernible decline in SR was observed during periods of extreme temperatures, particularly in colder seasons. Subsequently, Pearson's correlation test revealed a statistically significant positive correlation between SR and T°, with a p-value <0.05.

3.3. *SWR and SHC responses*

No statistically significant variances were detected for SHC (F-statistic = 0.06, p-value = 0.80) and SWR (F-statistic = 0.17, p-value = 0.68) between B and C plots, nor across different seasons throughout the study year. Over the course of the one-year study period, SHC exhibited lower values during summer and early winter but demonstrated an increase during autumn and late winter, reaching its peak 148 days post-prescribed burn (PB) (Fig. 3). Conversely, SWR attained its maximum during winter, specifically 224 days post-PB, and exhibited a subsequent increase in spring following the one-year study period (Fig. 4). Additionally, a negative correlation was observed between SHC and SWR based on Pearson's correlation test (corr. = −0.43; p-value = 0.69). In ANNEX, S5, the monthly evolution of mean precipitation throughout the study duration is depicted. Particularly noteworthy is the substantial increase in maximum precipitation observed during the second spring, occurring one year after the prescribed burning event, with levels ranging from 80 to 100 mm. This contrasts markedly with the comparatively lower values recorded during the first spring, where precipitation levels hovered around 40 mm. These discernible variations in precipitation between the two springs offer valuable contextual insights that may help elucidate observed differences in soil water repellency, as discussed in subsequent sections.

Fig. 5 illustrates the cumulative frequency of SWR by contrasting treatments (B vs. C) across different repellency classes. Notably, class 3 exhibited higher occurrence in B plots compared to C plots, although the disparity was not statistically significant (p-value = 0.68).

3.4. *Interaction and correlation between treatment and time*

The correlation matrix reveals significant correlations among the variables. Notably, there are strong positive correlations between N and P ($r = 0.88$) and between SOM and Corg ($r = 0.95$). Conversely, there is a negative correlation between SHC and SR ($r = -0.89$) (Fig. 6).

The PCA results demonstrate the variance explained by each principal component. The first principal component (PC1) accounts for 85.7 % of the total variance, followed by PC2 15.1 %). PC1 primarily reflects the variability in WDPT, while PC2 capture variations in SR and SHC. The PCA biplot, shown in Fig. 7, illustrates the loadings of each variable on the principal components.

The linear mixed-effects models provide insights into the effects of treatment and time on the response variables. For example, the model for SOM indicates a significant interaction between treatment and date ($t = -0.62$, $p > 0.05$). Similarly, the models for N, C, P, SHC, WDPT, and SR show significant fixed effects for treatment, date, or their interaction. These findings are illustrated in ANNEX; S6, which displays the observed data points and fitted lines for each variable across different treatment levels and dates.

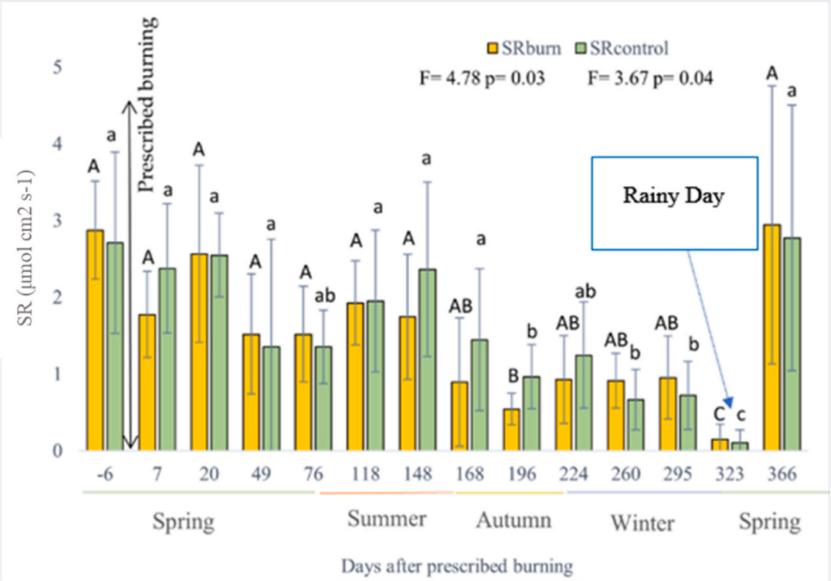


Fig. 2. Temporal evolution of the SR rates in the C and B plots (µmol CO_2 cm $^{-2}$ s-^{1}). The SRcontrol (green bars) corresponds to the C plots and the SRburn (yellow bars) to the B plots. There are mean values and standard deviations for the hanging bars. Lowercase letters (a, b, or c) indicate significant differences between temporal measurements (taken at each time) in the C plots. Capital letters (A, B, or C) denote significant differences among sampling dates (temporal measures) between plots. One measure was taken on a rainy day. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

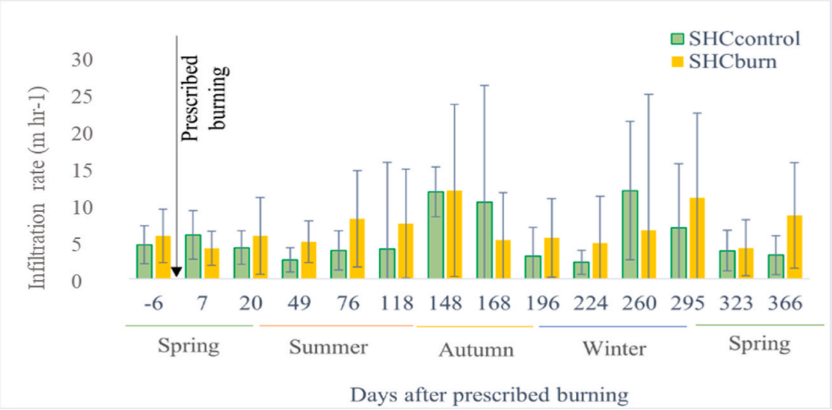


Fig. 3. Temporal SHC evolution by infiltration rates in the C and B plots (m hr^{-1}). SHCcontrol (green bars) corresponds to the unburned/C plots and SHCburn (yellow bars) to the B plots. Mean values and standard deviations (hanging bars). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

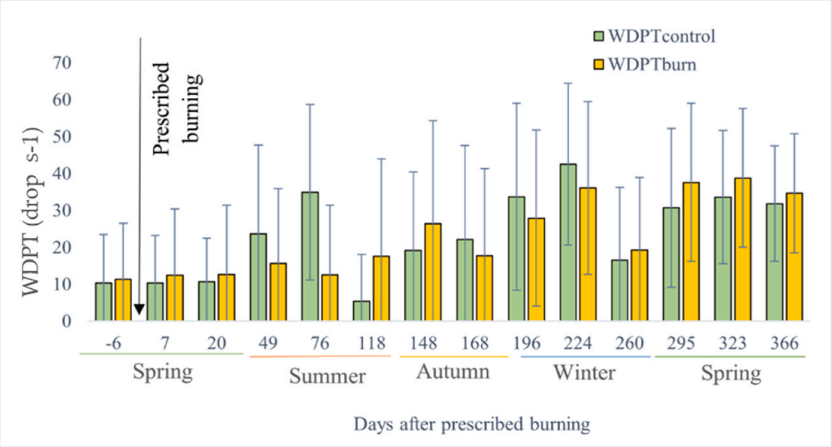


Fig. 4. Temporal SWR evolution by WDPT in the C and B plots (drop s^{-1}). WDPTcontrol (green bars) corresponds to the unburned/C plots and WDPTburn (yellow bars) to the B plots. Mean values and standard deviations (hanging bars). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

Our study aimed to investigate the impacts of low-severity PB on soil properties and ecosystem processes in a semiarid Spanish forest ecosystem. The findings reveal nuanced dynamics influenced by both the prescribed burn treatment and broader environmental factors.

The low-severity PB conducted adhered to established guidelines, ensuring temperatures remained below 400 °C with minimal soil heat residence time [71–73]. Despite the absence of significant changes in soil pH, EC, K, Ca, Na, Mg, or soil texture following the PB, notable alterations were observed in several key parameters [74,75]. Similar results were reported in a review by Certini (2005), who found that low-intensity fires often result in minimal changes to soil pH and texture due to limited heat penetration into the soil profile [76,77].

The prescribed burn led to a partial combustion of the OM layer, depositing charred residues on the soil surface. This process significantly increased SOM, Corg, N, and P levels immediately post-burn, with significant differences observed between B and C plots [78–80]. These findings are consistent with those of Raison (1979), who noted that low-severity fires often enhance nutrient availability by releasing nutrients from burned vegetation and converting organic forms to inorganic ones [81].

Over time, soil P levels tend to normalize due to plant uptake and leaching, while microbial community shifts further influence P availability [82,83]. Similarly, increased N levels post-fire result from NH4-N-rich ash deposits and favorable mineralization conditions. However, the absence of significant differences in N levels between B and C plots after one year suggests that short-term processes like plant uptake and microbial immobilization may have contributed to nitrogen reduction [84]. This aligns with findings by Pereira et al. (2018), who observed similar transient increases in soil nutrients following fire disturbances [85].

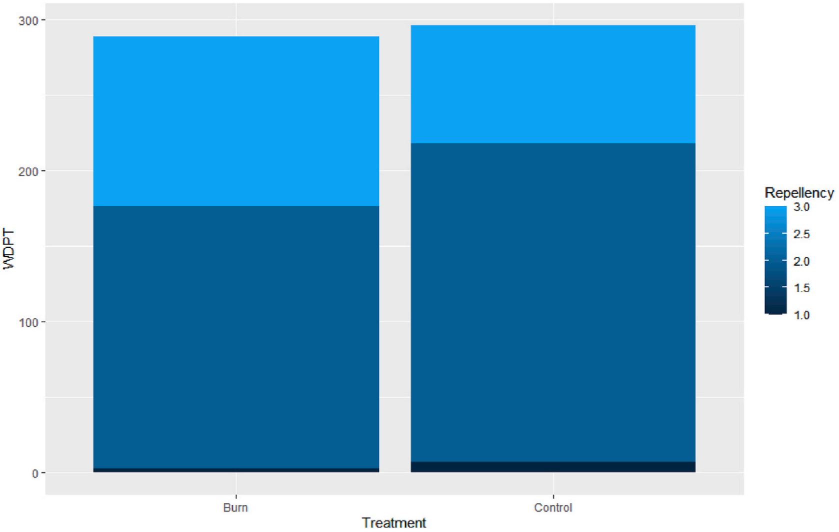
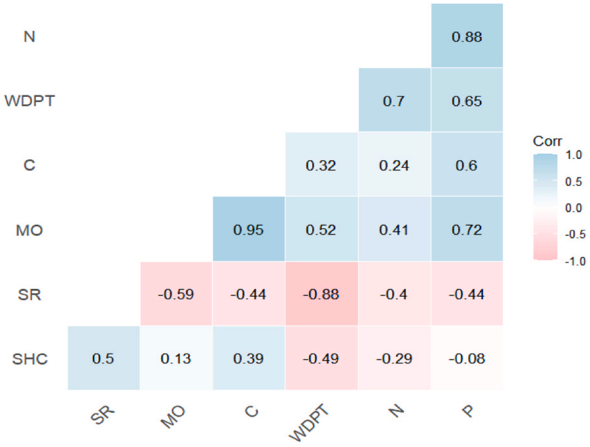


Fig. 5. Accumulative SWR frequency by WDPT (drop s^{-1}) in the C and B plots. Repellency classes 1–3.



	SR	MO	C	WDPT	N	P
N						0.88
WDPT					0.7	0.65
C				0.32	0.24	0.6
MO			0.95	0.52	0.41	0.72
SR		-0.59	-0.44	-0.88	-0.4	-0.44
SHC	0.5	0.13	0.39	-0.49	-0.29	-0.08

Fig. 6. Correlation matrix between variables with significant differences between treatments. Higher numbers and more intense blue a direct positive relationship, lower numbers (and negative) with more intense red colors. (MO =) SOM: The total soil organic matter; Corg: The total soil organic carbon; N: The total nitrogen; P: The available phosphorus. Soil respiration (SR); soil hydraulic conductivity (SHC) Water drop penetration time (WDPT). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

SR exhibited complex seasonal variations influenced by microclimatic factors beyond temperature alone. While a positive correlation with temperature aligns with expectations [86], observed reductions in SR during hot summer periods suggest additional factors at play. Long-term UV exposure and temperatures above 25 °C can suppress SR due to microbial inhibition [87]. Conversely, frost events in winter could further depress bacterial activity, resulting in minimum SR values [88]. These patterns are comparable to those reported by Conant et al. (2011), who demonstrated that extreme temperatures and moisture conditions significantly modulate soil microbial activity and respiration rates [89].

Our study highlights the critical role of seasonal rainfall and intrinsic soil moisture in shaping SR dynamics. While detailed precipitation data were available, the lack of specific information on fuel and soil moisture hinders a comprehensive evaluation. Nonetheless, insights from previous studies underscore the significance of these factors in SR dynamics [90,91]. Even in arid regions, SR is influenced not only by temperature but also by soil moisture content, significantly affecting microbial activity and SR dynamics [92–95] Understanding these interplays is vital for accurate ecosystem assessments [91,92].

Contrary to expectations, no significant differences in SWR were found between B and C plots, with notable variations in the second-year spring coinciding with increased precipitation [96–98]. The observed SWR surge may be attributed to enhanced organic matter decomposition, microbial activity, and seasonal dynamics influenced by precipitation [99]. Conversely, SHC exhibited pronounced seasonal fluctuations, with higher values in colder, wetter seasons and lower values in hotter, drier periods. The negative correlation between SHC and SWR suggests complex interactions between soil physical properties and water infiltration capacity [100,

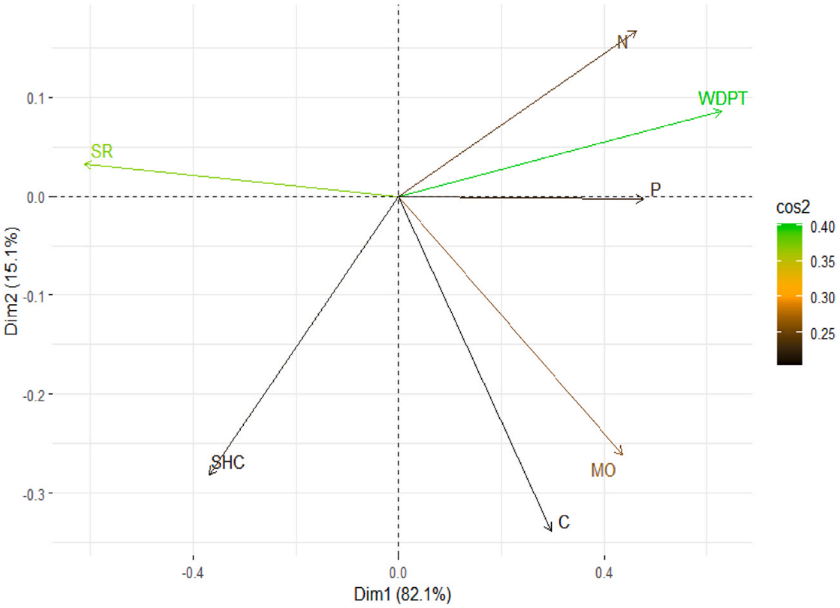


Fig. 7. The figure displays the principal component analysis (PCA) plot illustrating multivariate patterns in the dataset. Dim1 = PC1; Dim2 = PC2. The squared cosine (cos2) represents the contribution of each variable to the principal component (PC). It indicates how well each variable is represented by the PC. (MO =) SOM: The total soil organic matter; Corg: The total soil organic carbon; N: The total nitrogen; P: The available phosphorus. Soil respiration (SR); soil hydraulic conductivity (SHC) Water drop penetration time (WDPT).

101]. Minimal infiltration differences were noted between the B and C plots, although significant seasonal intra-annual variability was observed [102]. Our study provides valuable insights into the nuanced interplay of climatic and ecological factors on soil water repellency, emphasizing the need for comprehensive analyses that consider both prescribed burning effects and broader environmental influences [103,104]. Similar findings were noted by Doerr et al. (2006), who reported seasonal variability in soil hydraulic properties following fire events [105–107].

The correlation matrix revealed significant relationships among various soil properties and ecosystem processes. For instance, a positive correlation was observed between SOM and nutrient content (N, P, and Corg), indicating potential synergistic effects on soil fertility and ecosystem productivity [108]. Conversely, SHC negatively correlated with soil texture, suggesting a complex interplay between soil physical properties and water infiltration capacity [109,110]. These correlations underscore the interconnected nature of soil variables and highlight the importance of considering multiple factors in ecosystem assessments. PCA identified distinct patterns of variance in the dataset, with principal components capturing underlying gradients in soil properties and environmental conditions. Component loadings indicated that PC1 primarily represented variation in nutrient content and organic matter levels, while PC2 reflected variability in soil texture and moisture regimes [111–113]. These findings align with prior research, highlighting the utility of PCA in elucidating complex ecological patterns [114,115]. Mixed-effects models revealed significant treatment effects on variables such as SOM, N, P, and Corg, indicating the impact of fire on soil nutrient dynamics and carbon cycling [116]. Temporal trends showed transient treatment effects, underscoring the dynamic nature of ecosystem responses to fire disturbance [117]. These results emphasize the importance of long-term monitoring to assess recovery trajectories and inform management strategies, as recommended by Shakerby R.A (2011) and Alcañiz et al. (2018) [118,119].

In summary, our study elucidates the complex interplay between prescribed burning, environmental factors, and soil properties in semiarid forest ecosystems. The observed dynamics underscore the need for holistic approaches integrating multiple factors to accurately assess ecosystem responses to fire disturbance. Future research should focus on long-term effects of PB recurrence and its implications for ecosystem functioning and management strategies.

Our research aimed to address concerns regarding pseudoreplication; however, we recognize that our design, with one burned and one unburned area and multiple plots within each, still presents a limitation. Although we attempted to reduce pseudoreplication through plot separation, the lack of true independent replication is acknowledged. We utilized mixed-effects models to account for the lack of independence among plots and performed checks for normality and homogeneity of variance to justify the use of ANOVA. Despite these measures, future studies should incorporate multiple independent treatment areas to ensure true replication and enhance statistical robustness.

5. Conclusions

Our study demonstrates the resilience of semiarid forest ecosystems to low-severity prescribed burns, with most soil properties exhibiting no significant changes one-year post-burn. Initial variations in specific physicochemical properties were primarily due to organic matter deposition and ash percolation. Nutrient dynamics analysis revealed increased phosphorus availability and heightened microbial activity. Interestingly, there were no significant differences in SWR and SHC between burned and control plots, although an inverse correlation between SHC and SWR over time suggests complex seasonal and microbial interactions. Soil respiration showed no significant short-term differences, with variations largely linked to temperature fluctuations.

Effective prescribed burn implementation necessitates meticulous planning, considering factors such as recent rainfall, vegetation, and soil type. Our findings highlight the importance of informed decision-making in forest management and wildfire prevention. Prescribed burning proves to be a valuable tool for wildfire prevention and sustainable forest management in semiarid landscapes. Continued research is essential to refine management strategies and enhance ecosystem resilience.

Data availability

Sharing research data helps other researchers evaluate your findings, build on your work and to increase trust in your article. We encourage all our authors to make as much of their data publicly available as reasonably possible. Please note that your response to the following questions regarding the public data availability and the reasons for potentially not making data available will be available alongside your article upon publication.

Has data associated with your study been deposited into a publicly available repository?

No

Please select why. Please note that this statement will be available alongside your article upon publication. as follow-up to "Data Availability Sharing research data helps other researchers evaluate your findings, build on your work and to increase trust in your article. We encourage all our authors to make as much of their data publicly available as reasonably possible. Please note that your response to the following questions regarding the public data availability and the reasons for potentially not making data available will be available alongside your article upon publication.

Has data associated with your study been deposited into a publicly available repository?"

Data will be made available on request.

CRediT authorship contribution statement

Á. Fajardo-Cantos: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Jorge, Antonio. **E. Peña:** Validation, Data curation. **P. Plaza-Álvarez:** Validation. **J. González-Romero:** Validation. **D. Moya:** Validation, Supervision, Methodology, Conceptualization. **H. González-Camuñas:** as, Validation, Data curation. **A. Díaz:** Validation. **R. Botella:** Validation. **M.E. Lucas-Borja:** Validation. **J. De Las Heras:** ez, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e37948.

References

[1] I. Stavi, Wildfires in grasslands and shrublands: a review of impacts on vegetation, soil, hydrology, and geomorphology, Water 11 (2019) 1042, https://doi.org/10.3390/w11051042.

[2] Y. Cantón, A. Solé-Benet, J. de Vente, C. Boix-Fayos, A. Calvo-Cases, C. Asensio, J. Puigdefábregas, A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain, J. Arid Environ. 75 (2011) 1254–1261, https://doi.org/10.1016/j.jaridenv.2011.03.004.

[3] M. Collins, R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A. J. Weaver, M. Wehner, Long-term Climate Change: Projections, Commitments and Irreversibility, Long-Term Climate Change: Projections, Commitments and Irreversibility, 2013, pp. 1029–1136.

[4] T.A. Ontl, M.K. Janowiak, C.W. Swanston, J. Daley, S. Handler, M. Cornett, S. Hagenbuch, C. Handrick, L. Mccarthy, N. Patch, Forest management for carbon sequestration and climate adaptation, J. For. 118 (2020) 86–101, https://doi.org/10.1093/jofore/fvz062.

[5] M. Francos, X. Úbeda, Prescribed fire management, Current Opinion in Environmental Science & Health 21 (2021) 100250, https://doi.org/10.1016/j.coesh.2021.100250.

[6] J. Espinosa, Ó. Rodríguez De Rivera, J. Madrigal, M. Guijarro, C. Hernando, Use of bayesian modeling to determine the effects of meteorological conditions, prescribed burn season, and tree characteristics on litterfall of Pinus nigra and Pinus pinaster stands, Forests 11 (2020) 1006, https://doi.org/10.3390/f11091006.

[7] P.M. Fernandes, Fire-smart management of forest landscapes in the Mediterranean basin under global change, Landsc. Urban Plann. 110 (2013) 175–182, https://doi.org/10.1016/j.landurbplan.2012.10.014.

[8] B. Wolfslehner, R. Seidl, Harnessing ecosystem models and multi-criteria decision analysis for the support of forest management, Environ. Manag. 46 (2010) 850–861, https://doi.org/10.1007/s00267-009-9414-5.

[9] M.E. Lucas-Borja, P.A. Plaza-Àlvarez, S.M.M. Uddin, M. Parhizkar, D.A. Zema, Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by Macrochloa tenacissima (L.) Kunth, J. Arid Environ. 198 (2022) 104702, https://doi.org/10.1016/j.jaridenv.2021.104702.

[10] K. Ivashchenko, S. Sushko, A. Selezneva, N. Ananyeva, A. Zhuravleva, V. Kudeyarov, M. Makarov, S. Blagodatsky, Soil microbial activity along an altitudinal gradient: vegetation as a main driver beyond topographic and edaphic factors, Appl. Soil Ecol. 168 (2021) 104197, https://doi.org/10.1016/j.apsoil.2021.104197.

[11] J.K. Jansson, K.S. Hofmockel, Soil microbiomes and climate change, Nat. Rev. Microbiol. 18 (2020) 35–46, https://doi.org/10.1038/s41579-019-0265-7.

[12] A. Barreiro, M. Díaz-Raviña, Fire impacts on soil microorganisms: mass, activity, and diversity, Current Opinion in Environmental Science & Health 22 (2021) 100264, https://doi.org/10.1016/j.coesh.2021.100264.

[13] J.E. Knelman, S.K. Schmidt, V. Garayburu-Caruso, S. Kumar, E.B. Graham, Multiple, compounding disturbances in a forest ecosystem: fire increases susceptibility of soil edaphic properties, bacterial community structure, and function to change with extreme precipitation event, Soil Systems 3 (2019) 40, https://doi.org/10.3390/soilsystems3020040.

[14] M. Alcañiz, L. Outeiro, M. Francos, X. Úbeda, Effects of prescribed fires on soil properties: a review, Sci. Total Environ. 613–614 (2018) 944–957, https://doi.org/10.1016/j.scitotenv.2017.09.144.

[15] F. Borgogni, A. Lavecchia, G. Mastrolonardo, G. Certini, M.T. Ceccherini, G. Pietramellara, Immediate- and short-term wildfire impact on soil microbial diversity and activity in a mediterranean forest soil, Soil Sci. 184 (2019) 35, https://doi.org/10.1097/SS.0000000000000250.

[16] C. Wang, G. Wang, Y. Wang, R. Rafique, L. Ma, L. Hu, Y. Luo, Fire alters vegetation and soil microbial community in alpine meadow, Land Degrad. Dev. 27 (2016) 1379–1390, https://doi.org/10.1002/ldr.2367.

[17] B.G. Carrà, G. Bombino, P. Denisi, P.A. Plaza-Àlvarez, M.E. Lucas-Borja, D.A. Zema, Water infiltration after prescribed fire and soil mulching with fern in mediterranean forests, Hydrology 8 (2021) 95, https://doi.org/10.3390/hydrology8030095.

[18] J.M. Fernández-Guisuraga, S. Suárez-Seoane, P. García-Llamas, L. Calvo, Vegetation structure parameters determine high burn severity likelihood in different ecosystem types: a case study in a burned Mediterranean landscape, J. Environ. Manag. 288 (2021) 112462, https://doi.org/10.1016/j.jenvman.2021.112462.

[19] J. Chen, K.J. McGuire, R.D. Stewart, Effect of soil water-repellent layer depth on post-wildfire hydrological processes, Hydrol. Process. 34 (2020) 270–283, https://doi.org/10.1002/hyp.13583.

[20] D.A. Zema, J.P. Nunes, M.E. Lucas-Borja, Improvement of seasonal runoff and soil loss predictions by the MMF (Morgan-Morgan-Finney) model after wildfire and soil treatment in Mediterranean forest ecosystems, Catena 188 (2020) 104415, https://doi.org/10.1016/j.catena.2019.104415.

[21] J.R. Kurzweil, K. Metlen, R. Abdi, R. Strahan, T.S. Hogue, Surface water runoff response to forest management: low-intensity forest restoration does not increase surface water yields, For. Ecol. Manag. 496 (2021) 119387, https://doi.org/10.1016/j.foreco.2021.119387.

[22] M. Parlak, Effects of low-intensity fire on soil organic carbon stocks and physicochemical properties in the Mediterranean ecosystem, Eur. J. Sport Sci. 11 (2022) 167–173, https://doi.org/10.18393/ejss.1056847.

[23] P.M. Fernandes, Empirical support for the use of prescribed burning as a fuel treatment, Curr Forestry Rep 1 (2015) 118–127, https://doi.org/10.1007/s40725-015-0010-z.

[24] A. Duane, N. Aquilué, Q. Canelles, A. Morán-Ordoñez, M. De Cáceres, L. Brotons, Adapting prescribed burns to future climate change in Mediterranean landscapes, Sci. Total Environ. 677 (2019) 68–83, https://doi.org/10.1016/j.scitotenv.2019.04.348.

[25] O. Valkó, B. Deák, Increasing the potential of prescribed burning for the biodiversity conservation of European grasslands, Current Opinion in Environmental Science & Health 22 (2021) 100268, https://doi.org/10.1016/j.coesh.2021.100268.

[26] Q. Qin, Y. Zhang, Q. Zhu, Y. Bai, X. Sun, Y. Liu, Wildfire decouples soil multi-element cycles: contributions of legacy effects and temporal variations, Geoderma 424 (2022) 116012, https://doi.org/10.1016/j.geoderma.2022.116012.

[27] A.E. Catalanotti, E. Giuditta, R. Marzaioli, D. Ascoli, A. Esposito, S. Strumia, S. Mazzoleni, F.A. Rutigliano, Effects of single and repeated prescribed burns on soil organic C and microbial activity in a Pinus halepensis plantation of Southern Italy, Appl. Soil Ecol. 125 (2018) 108–116, https://doi.org/10.1016/j.apsoil.2017.12.015.

[28] R. Soria, A. Tortosa, N. Rodríguez-Berbel, M.E. Lucas-Borja, R. Ortega, I. Miralles, Short-term response of soil bacterial communities after prescribed fires in semi-arid mediterranean forests, Fire 6 (2023) 145, https://doi.org/10.3390/fire6040145.

[29] O. Joshi, N.C. Poudyal, J.R. Weir, S.D. Fuhlendorf, T.O. Ochuodho, Determinants of perceived risk and liability concerns associated with prescribed burning in the United States, J. Environ. Manag. 230 (2019) 379–385, https://doi.org/10.1016/j.jenvman.2018.09.089.

[30] A. Girona-García, D.C.S. Vieira, J. Silva, C. Fernández, P.R. Robichaud, J.J. Keizer, Effectiveness of post-fire soil erosion mitigation treatments: a systematic review and meta-analysis, Earth Sci. Rev. 217 (2021) 103611, https://doi.org/10.1016/j.earscirev.2021.103611.

[31] F. Fonseca, T. de Figueiredo, C. Nogueira, A. Queirós, Effect of prescribed fire on soil properties and soil erosion in a Mediterranean mountain area, Geoderma 307 (2017) 172–180, https://doi.org/10.1016/j.geoderma.2017.06.018.

[32] P. Hueso-González, J.F. Martínez-Murillo, J.D. Ruiz-Sinoga, Prescribed fire impacts on soil properties, overland flow and sediment transport in a Mediterranean forest: a 5 year study, Sci. Total Environ. 636 (2018) 1480–1489, https://doi.org/10.1016/j.scitotenv.2018.05.004.

[33] A.-M. Ciobotaru, N. Patel, R.-D. Pintilii, Tree cover loss in the mediterranean region—an increasingly serious environmental issue, Forests 12 (2021) 1341, https://doi.org/10.3390/f12101341.

[34] Z.-R. Wang, D.-C. Niu, Y.-G. Hu, Y.-S. Wang, L. Huang, Y.-B. Liu, Changes in soil phosphorus fractions associated with altered vegetation and edaphic conditions across a chronosequence of revegetated dunes in a desert area, Geoderma 424 (2022) 115995, https://doi.org/10.1016/j.geoderma.2022.115995.

[35] L.J.R. Nunes, M.A.M. Raposo, C.I.R. Meireles, C.J. Pinto Gomes, N.M.C.A. Ribeiro, Fire as a selection agent for the dissemination of invasive species: case study on the evolution of forest coverage, Environments 7 (2020) 57, https://doi.org/10.3390/environments7080057.

[36] G. Certini, Effects of fire on properties of forest soils: a review, Oecologia 143 (2005) 1–10, https://doi.org/10.1007/s00442-004-1788-8.

[37] D.F. Rossetti, The role of tectonics in the late Quaternary evolution of Brazil's Amazonian landscape, Earth Sci. Rev. 139 (2014) 362–389, https://doi.org/10.1016/j.earscirev.2014.08.009.

[38] S.C. Pereira, D. Carvalho, A. Rocha, Temperature and precipitation extremes over the iberian peninsula under climate change scenarios: a review, Climate 9 (2021) 139, https://doi.org/10.3390/cli9090139.

[39] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World Map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (2006) 259–263, https://doi.org/10.1127/0941-2948/2006/0130.

[40] AEMET, "Spanish Meteorological and Weather Agency"), AEMET: Weather Data from Hellín Station (Albacete-Spain) 2000–2020, Madrid, Spain, 2022. URL: http://www.aemet.es/. (Accessed 25 January 2022).

[41] IGN, Mapa de suelos de España, Escala 1:1.000.000, Instituto Geográfico Nacional, 2006. http://www.ign.es. (Accessed 14 December 2021).

[42] Working Group WRB IUSS, Base referencial mundial del recurso suelo 2014, Actualización 2015. Informes sobre recursos mundiales de suelos 106, FAO, Roma, 2015. ISBN 978-92-5-308369 5. Available online: https://www.fao.org/home/en/. (Accessed 24 January 2022).

[43] A.B. Frank, L. Hofmann, Relationship among grazing management, growing degree-days, and morphological development for native grasses on the northern great plains, J. Range Manag. 42 (1989) 199–202, https://doi.org/10.2307/3899472.

[44] S. Rudolph, J.G. Maciá-Vicente, H. Lotz-Winter, M. Schleuning, M. Piepenbring, Temporal variation of fungal diversity in a mosaic landscape in Germany, Stud. Mycol. 89 (2018) 95–104, https://doi.org/10.1016/j.simyco.2018.01.001.

[45] J.S. Kominoski, M. Fernandez, P. Breault, V. Sclater, B.B. Rothermel, Fire severity and post-fire hydrology drive nutrient cycling and plant community recovery in intermittent wetlands, Ecosystems 25 (2022) 265–278, https://doi.org/10.1007/s10021-021-00653-5.

[46] A.J. Underwood, Experiments in Ecology: Their Logical Design and Interpretation Using Analysis of Variance, Cambridge University Press, Cambridge, 1996, https://doi.org/10.1017/CBO9780511806407.

[47] J.H. Zar, Biostatistical Analysis, Prentice Hall, 1999.

[48] S.H. Hurlbert, Pseudoreplication and the design of ecological field experiments, Ecol. Monogr. 54 (1984) 187–211, https://doi.org/10.2307/1942661.

[49] E.D. Ford, A primer of ecological statistics, Am. Statistician 59 (2005), https://doi.org/10.1198/tas.2005.s32, 350–350.

[50] A.M.M. Ahmed, F.M.A. Hamarai, Using Analysis of Variance in the Academic Achievement to Compare Three Learning Patterns for University Students, CE 13 (2022) 2104–2118, https://doi.org/10.4236/ce.2022.136131.

[51] P.M. Fernandes, E. Rigolot, 13. Prescribed burning in the European Mediterranean Basin. https://hal.inrae.fr/hal-03549228, 2022. (Accessed 29 February 2024).

[52] Z. Dong, R.A. Williams, Effects of wildland fuel composition on fire intensity, Fire 6 (2023) 312, https://doi.org/10.3390/fire6080312.

[53] J.A. Vega, J. Landsberg, S. Bará, T. Paysen, M.T. Fontúrbel, M. Alonso, Efectos del fuego prescrito bajo arbolado de P. Pinaster en suelos forestales de Galicia y Andalucía. Cuadernos de la Sociedad Española de Ciencias Forestales, 2000, https://doi.org/10.31167/csef.v0i9.9190.

[54] R.C. Rothermel, A Mathematical Model for Predicting Fire Spread in Wildland Fuels, Res. Pap. INT-115, U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station, Ogden, UT, 1972, p. 115, 40, http://www.fs.usda.gov/treesearch/pubs/32533. (Accessed 9 August 2022).

[55] F.A. Albini, Estimating Wildfire Behavior and Effects, Gen. Tech. Rep. INT-GTR-30, vol. 92, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 1976, p. 30. http://www.fs.usda.gov/treesearch/pubs/29574. (Accessed 10 August 2022).

[56] S.N. Little, F.R. Ward, D. Sandberg, P.N. Forest, Or.) range experiment station (portland, duff reduction caused by prescribed fire on areas logged to different management intensities, U.S. Department of agriculture, forest Service, Pacific Northwest Forest and Range Experiment Station (1982). https://books.google.es/books?id=JI-y9cyPnwUC.

[57] D. Moya, S. González-De Vega, F. García-Orenes, A. Morugán-Coronado, V. Arcenegui, J. Mataix-Solera, M.E. Lucas-Borja, J. De las Heras, Temporal characterisation of soil-plant natural recovery related to fire severity in burned Pinus halepensis Mill. forests, Sci. Total Environ. 640–641 (2018) 42–51, https://doi.org/10.1016/j.scitotenv.2018.05.212.

[58] G. Bárcenas-Moreno, F. García-Orenes, J. Mataix-Solera, J. Mataix-Beneyto, Plant community influence on soil microbial response after a wildfire in Sierra Nevada National Park (Spain), Sci. Total Environ. 573 (2016) 1265–1274, https://doi.org/10.1016/j.scitotenv.2016.05.013.

[59] M. Lange, N. Eisenhauer, C.A. Sierra, H. Bessler, C. Engels, R.I. Griffiths, P.G. Mellado-Vázquez, A.A. Malik, J. Roy, S. Scheu, S. Steinbeiss, B.C. Thomson, S. E. Trumbore, G. Gleixner, Plant diversity increases soil microbial activity and soil carbon storage, Nat. Commun. 6 (2015), https://doi.org/10.1038/ncomms7707.

[60] D. Moya, S. González-De Vega, F. García-Orenes, A. Morugán-Coronado, V. Arcenegui, J. Mataix-Solera, M.E. Lucas-Borja, J. De las Heras, Temporal characterisation of soil-plant natural recovery related to fire severity in burned Pinus halepensis Mill. forests, Sci. Total Environ. 640–641 (2018) 42–51, https://doi.org/10.1016/j.scitotenv.2018.05.212.

[61] S. Huerta, V. Fernández-García, L. Calvo, E. Marcos, Soil resistance to burn severity in different forest ecosystems in the framework of a wildfire, Forests 11 (2020) 773, https://doi.org/10.3390/f11070773.

[62] V. Carrión-Paladines, M.B. Hinojosa, L. Jiménez Álvarez, F. Reyes-Bueno, L. Correa Quezada, R. García-Ruiz, Effects of the severity of wildfires on some physical-chemical soil properties in a humid montane scrublands ecosystem in southern Ecuador, Fire 5 (2022) 66, https://doi.org/10.3390/fire5030066.

[63] G.W. Gee, D. Or, 2.4 particle-size analysis, in: Methods of Soil Analysis, John Wiley & Sons, Ltd, 2002, pp. 255–293, https://doi.org/10.2136/sssabookser5.4.c12.

[64] J.m. Bremner, C.s. Mulvaney, Nitrógeno-Toal. Métodos de análisis de suelos. Parte 2. Propiedades químicas y microbiológicas, in: Methods of Soil Analysis, John Wiley & Sons, Ltd, 1983, pp. 595–624, https://doi.org/10.2134/agronmonogr9.2.2ed.c31.

[65] S.r. Olsen, L.e. Sommers, Phosphorus, in: Methods of Soil Analysis, John Wiley & Sons, Ltd, 1983, pp. 403–430, https://doi.org/10.2134/agronmonogr9.2.2ed.c24.

[66] A. Roig, M. Romero, A. Lax, F.G. Fernández, Comparative study of methods of determination of the cation exchange capacity in calcareous soils, An. Edafol. Agrobiol. 39 (1980) 2021–2032.

[67] D.w. Nelson, L.e. Sommers, Total carbon, organic carbon, and organic matter, in: Methods of Soil Analysis, John Wiley & Sons, Ltd, 1983, pp. 539–579, https://doi.org/10.2134/agronmonogr9.2.2ed.c29.

[68] P. Kiprotich, X. Wei, Z. Zhang, T. Ngigi, F. Qiu, L. Wang, Assessing the impact of land use and climate change on surface runoff response using gridded observations and SWAT+, Hydrology 8 (2021) 48, https://doi.org/10.3390/hydrology8010048.

[69] L.W. Dekker, C.J. Ritsema, K. Oostindie, D. Moore, J.G. Wesseling, Methods for determining soil water repellency on field-moist samples, Water Resour. Res. 45 (2009), https://doi.org/10.1029/2008WR007070.

[70] L.W. Dekker, P.D. Jungerius, Water repellency in the dunes with special reference to The Netherlands, Catena Suppl. (1990) 173–183.

[71] P.G. Monsanto, J.K. Agee, Long-term post-wildfire dynamics of coarse woody debris after salvage logging and implications for soil heating in dry forests of the eastern Cascades, Washington, For. Ecol. Manag. 255 (2008) 3952–3961, https://doi.org/10.1016/j.foreco.2008.03.048.

[72] G.A.C.L.-M.S.A. Geacam, Manejo del fuego nivel I, Junta de Castilla-La Mancha (JCCM), 2013. Castilla-La Mancha, Spain, UF2364. 5-73. https://www.geacam.es/. (Accessed 23 February 2022).

[73] M.R.A. Pingree, L.N. Kobziar, The myth of the biological threshold: a review of biological responses to soil heating associated with wildland fire, For. Ecol. Manag. 432 (2019) 1022–1029, https://doi.org/10.1016/j.foreco.2018.10.032.

[74] R. Guénon, R. Gros, Frequent-wildfires with shortened time-since-fire affect soil microbial functional stability to drying and rewetting events, Soil Biol. Biochem. 57 (2013) 663–674, https://doi.org/10.1016/j.soilbio.2012.07.006.

[75] E. Gómez-Sánchez, M.E. Lucas-Borja, P.A. Plaza-Álvarez, J. González-Romero, J. Sagra, D. Moya, J. De Las Heras, Effects of post-fire hillslope stabilisation techniques on chemical, physico-chemical and microbiological soil properties in mediterranean forest ecosystems, J. Environ. Manag. 246 (2019) 229–238, https://doi.org/10.1016/j.jenvman.2019.05.150.

[76] S. Montoya, G. Marín, E. Ortega, Impact of prescribed burning on soil properties in a Mediterranean area (Granada, SW Spain), Spanish Journal of Soil Science: Serbian J. Sports Sci. (SJSS) 4 (2014) 88–98.

[77] S.N. Araya, M. Meding, A.A. Berhe, Thermal alteration of soil physico-chemical properties: a systematic study to infer response of Sierra Nevada climosequence soils to forest fires, SOIL 2 (2016) 351–366, https://doi.org/10.5194/soil-2-351-2016.

[78] P.R. Robichaud, Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA, J. Hydrol. 231–232 (1–4) (2000) 220–229. http://www.fs.usda.gov/treesearch/pubs/23562. (Accessed 20 July 2022).

[79] T. Vadilonga, X. Úbeda, P.F. Germann, M. Lorca, Effects of prescribed burnings on soil hydrological parameters, Hydrol. Process. 22 (2008) 4249–4256, https://doi.org/10.1002/hyp.7032.

[80] S. Verma, S. Jayakumar, Impact of forest fire on physical, chemical and biological properties of soil: a review, Proceedings of the International Academy of Ecology and Environmental Sciences 2 (2012) 168.

[81] A. Moghli, V.M. Santana, M.J. Baeza, E. Pastor, S. Soliveres, Fire recurrence and time since last fire interact to determine the supply of multiple ecosystem services by mediterranean forests, Ecosystems 25 (2022) 1358–1370, https://doi.org/10.1007/s10021-021-00720-x.

[82] A.R. Nelson, A.B. Narrowe, C.C. Rhoades, T.S. Fegel, R.A. Daly, H.K. Roth, R.K. Chu, K.K. Amundson, R.B. Young, A.S. Steindorff, S.J. Mondo, I.V. Grigoriev, A. Salamov, T. Borch, M.J. Wilkins, Wildfire-dependent changes in soil microbiome diversity and function, Nat Microbiol 7 (2022) 1419–1430, https://doi.org/10.1038/s41564-022-01203-y.

[83] R. Ortega, D.A. Zema, N. Valiente, R. Soria, I. Miralles, M.E. Lucas-Borja, The impacts of post-fire straw mulching and salvage logging on soil properties and plant diversity in a mediterranean burned pine forest, Forests 13 (2022) 1580, https://doi.org/10.3390/f13101580.

[84] J. Durán, A. Rodríguez, J.M. Fernández-Palacios, A. Gallardo, Changes in soil N and P availability in a Pinus canariensis fire chronosequence, For. Ecol. Manag. 256 (2008) 384–387, https://doi.org/10.1016/j.foreco.2008.04.033.

[85] P. Pereira, M. Francos, E.C. Brevik, X. Ubeda, I. Bogunovic, Post-fire soil management, Current Opinion in Environmental Science & Health 5 (2018) 26–32, https://doi.org/10.1016/j.coesh.2018.04.002.

[86] P. Plaza-Álvarez, M. Lucas-Borja, J. Sagra, D. Moya, T. Fontúrbel, J. de las Heras, Soil respiration changes after prescribed fires in Spanish black pine (Pinus nigra arn. ssp. salzmannii) monospecific and mixed forest stands, Forests 8 (2017) 248, https://doi.org/10.3390/f8070248.

[87] D.R. Zak, W.E. Holmes, N.W. MacDonald, K.S. Pregitzer, Soil temperature, matric potential, and the kinetics of microbial respiration and nitrogen mineralization, Soil Sci. Soc. Am. J. 63 (1999) 575–584, https://doi.org/10.2136/sssaj1999.03615995006300030021x.

[88] V. Suseela, R.T. Conant, M.D. Wallenstein, J.S. Dukes, Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment, Global Change Biol. 18 (2012) 336–348, https://doi.org/10.1111/j.1365-2486.2011.02516.x.

[89] R.M. Cadenas, F. Castedo-Dorado, L. Valbuena, Medium-term comparative effects of prescribed burning and mechanical shredding on soil characteristics in heathland and shrubland habitats: insights from a protected natural area, Fire 7 (2024) 160, https://doi.org/10.3390/fire7050160.

[90] E.A. Davidson, I.A. Janssens, Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, Nature 440 (2006) 165–173, https://doi.org/10.1038/nature04514.

[91] J.-A. Subke, I. Inglima, M. Francesca Cotrufo, Trends and methodological impacts in soil CO2 efflux partitioning: a metaanalytical review, Global Change Biol. 12 (2006) 921–943, https://doi.org/10.1111/j.1365-2486.2006.01117.x.

[92] J. Curiel yuste, I.A. Janssens, A. Carrara, R. Ceulemans, Annual Q10 of soil respiration reflects plant phenological patterns as well as temperature sensitivity, Global Change Biol. 10 (2004) 161–169, https://doi.org/10.1111/j.1529-8817.2003.00727.x.

[93] A.J.P. Granged, L.M. Zavala, A. Jordán, G. Bárcenas-Moreno, Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: a 3-year study, Geoderma 164 (2011) 85–94, https://doi.org/10.1016/j.geoderma.2011.05.017.

[94] K. Parro, K. Köster, K. Jõgiste, K. Seglinš, A. Sims, J.A. Stanturf, M. Metslaid, Impact of post-fire management on soil respiration, carbon and nitrogen content in a managed hemiboreal forest, J. Environ. Manag. 233 (2019) 371–377, https://doi.org/10.1016/j.jenvman.2018.12.050.

[95] C. Ribeiro-Kumara, C. Santín, S.H. Doerr, J. Pumpanen, G. Baxter, K. Köster, Short- to medium-term effects of crown and surface fires on soil respiration in a Canadian boreal forest, Can, J. For. Res. 52 (2022) 591–604, https://doi.org/10.1139/cjfr-2021-0354.

[96] L.F. DeBano, The role of fire and soil heating on water repellency in wildland environments: a review, J. Hydrol. 231–232 (2000) 195–206, https://doi.org/10.1016/S0022-1694(00)00194-3.

[97] Q. Li, S. Ahn, T. Kim, S. Im, Post-fire impacts of vegetation burning on soil properties and water repellency in a pine forest, South Korea, Forests 12 (2021) 708, https://doi.org/10.3390/f12060708.

[98] G. Caltabellotta, M. Iovino, V. Bagarello, Intensity and persistence of water repellency at different soil moisture contents and depths after a forest wildfire, J. Hydrol. Hydromechanics 70 (2022) 410–420, https://doi.org/10.2478/johh-2022-0031.

[99] C.R. Stoof, D. Moore, C.J. Ritsema, L.W. Dekker, Natural and fire-induced soil water repellency in a Portuguese shrubland, Soil Sci. Soc. Am. J. 75 (2011) 2283–2295, https://doi.org/10.2136/sssaj2011.0046.

[100] G. Leighton-Boyce, S.H. Doerr, R.A. Shakesby, R.P.D. Walsh, A.J.D. Ferreira, A.-K. Boulet, C.O.A. Coelho, Temporal dynamics of water repellency and soil moisture in eucalypt plantations, Portugal, Soil Res. 43 (2005) 269–280, https://doi.org/10.1071/SR04082.

[101] P. Hallett, An Introduction to Soil Water Repellency, 2007, pp. 6–9.

[102] F.B. Pierson, P.R. Robichaud, C.A. Moffet, K.E. Spaeth, C.J. Williams, S.P. Hardegree, P.E. Clark, Soil water repellency and infiltration in coarse-textured soils of burned and unburned sagebrush ecosystems, Catena 74 (2008) 98–108, https://doi.org/10.1016/j.catena.2008.03.011.

[103] C. Fernández, J.A. Vega, T. Fonturbel, E. Jiménez, P. Pérez-Gorostiaga, Effects of wildfire, salvage logging and slash manipulation on Pinus pinaster Ait. recruitment in Orense (NW Spain), For. Ecol. Manag. 255 (2008) 1294–1304, https://doi.org/10.1016/j.foreco.2007.10.034.

[104] M. Francos, X. Úbeda, P. Pereira, Impact of torrential rainfall and salvage logging on post-wildfire soil properties in NE Iberian Peninsula, Catena 177 (2019) 210–218, https://doi.org/10.1016/j.catena.2019.02.014.

[105] Ó. González-Pelayo, V. Andreu Pérez, E. Gimeno-García, J. Campo, J.L. Rubio, Rainfall influence on plot-scale runoff and soil loss from repeated burning in a Mediterranean-shrub ecosystem, Valencia, Spain. https://doi.org/10.13039/501100003359, 2010.

[106] J.G. Cawson, G.J. Sheridan, H.G. Smith, P.N.J. Lane, Surface runoff and erosion after prescribed burning and the effect of different fire regimes in forests and shrublands: a review, Int. J. Wildland Fire 21 (2012) 857–872, https://doi.org/10.1071/WF11160.

[107] D. Badía-Villas, J. Esteban-Piñeiro, A. Girona-García, O. Ortiz-Perpiñá, R.M. Poch, Topsoil microstructure changes after a shrubland prescribed burn (Central Pyrenees, NE Spain), Sci. Total Environ. 748 (2020) 141253, https://doi.org/10.1016/j.scitotenv.2020.141253.

[108] J.D. Murphy, D.W. Johnson, W.W. Miller, R.F. Walker, E.F. Carroll, R.R. Blank, Wildfire effects on soil nutrients and leaching in a tahoe basin watershed, J. Environ. Qual. 35 (2006) 479–489, https://doi.org/10.2134/jeq2005.0144.

[109] M. Muñoz-Rojas, W. Lewandrowski, T.E. Erickson, K.W. Dixon, D.J. Merritt, Soil respiration dynamics in fire affected semi-arid ecosystems: effects of vegetation type and environmental factors, Sci. Total Environ. 572 (2016) 1385–1394, https://doi.org/10.1016/j.scitotenv.2016.02.086.

[110] J. Liu, L. Qiu, X. Wang, X. Wei, H. Gao, Y. Zhang, J. Cheng, Effects of wildfire and topography on soil nutrients in a semiarid restored grassland, Plant Soil 428 (2018) 123–136, https://doi.org/10.1007/s11104-018-3659-9.

[111] V.M. Ngole-Jeme, Fire-induced changes in soil and implications on soil sorption capacity and remediation methods, Appl. Sci. 9 (2019) 3447, https://doi.org/10.3390/app9173447.

[112] E. Kurbanov, O. Vorobev, S. Lezhnin, J. Sha, J. Wang, X. Li, J. Cole, D. Dergunov, Y. Wang, Remote sensing of forest burnt area, burn severity, and post-fire recovery: a review, Rem. Sens. 14 (2022) 4714, https://doi.org/10.3390/rs14194714.

[113] H. Gui, J. Wang, M. Hu, Z. Zhou, S. Wan, Impacts of fire on soil respiration and its components: a global meta-analysis, Agric. For. Meteorol. 336 (2023) 109496, https://doi.org/10.1016/j.agrformet.2023.109496.

[114] A. Merino, M.T. Fonturbel, C. Fernández, B. Chávez-Vergara, F. García-Oliva, J.A. Vega, Inferring changes in soil organic matter in post-wildfire soil burn severity levels in a temperate climate, Sci. Total Environ. 627 (2018) 622–632, https://doi.org/10.1016/j.scitotenv.2018.01.189.

[115] A.A. Agbeshie, S. Abugre, T. Atta-Darkwa, R. Awuah, A review of the effects of forest fire on soil properties, J. For. Res. 33 (2022) 1419–1441, https://doi.org/10.1007/s11676-022-01475-4.

[116] Y. Cheng, P. Luo, H. Yang, H. Li, C. Luo, H. Jia, Y. Huang, Fire effects on soil carbon cycling pools in forest ecosystems: a global meta-analysis, Sci. Total Environ. 895 (2023) 165001, https://doi.org/10.1016/j.scitotenv.2023.165001.

[117] J.A. González-Pérez, F.J. González-Vila, G. Almendros, H. Knicker, The effect of fire on soil organic matter—a review, Environ. Int. 30 (2004) 855–870, https://doi.org/10.1016/j.envint.2004.02.003.

[118] R.A. Shakesby, Post-wildfire soil erosion in the Mediterranean: review and future research directions, Earth Sci. Rev. 105 (2011) 71–100, https://doi.org/10.1016/j.earscirev.2011.01.001.

[119] M. Alcañiz, L. Outeiro, M. Francos, X. Úbeda, Effects of prescribed fires on soil properties: a review, Sci. Total Environ. 613–614 (2018) 944–957, https://doi.org/10.1016/j.scitotenv.2017.09.144.