OPEN ACCESS

RESEARCH ARTICLE

Forest Systems 34 (2)
May-August, 2025, 20956
ISSN-L: 2171-5068, eISSN: 2171-9845
https://doi.org/10.5424/fs/2025342-20956

Surface runoff and soil loss after fire and post-fire treatments in forests of Castilla-La Mancha: a meta-analysis on a 10-year database

Manuel E. Lucas-Borja[1] and Demetrio A. Zema[2*]

[1]*Castilla La Mancha University, School of Agronomy, Forestry Engineering and Biotechnology. Department of Agroforestry Technology and Science and Genetics, Campus Universitario. E-02071 Albacete, Spain.*
[2]*AGRARIA Department, Mediterranean University of Reggio Calabria, Loc. Feo di Vito. I-89122 Reggio Calabria, Italy.*

***Correspondence** should be addressed to Demetrio Antonio Zema: dzema@unirc.it

Abstract

Aim of the study: A meta-analysis was applied to evaluate surface runoff and soil loss after fires of different severity and post-fire treatments in semi-arid forests of Central Eastern Spain.

Area of study: Four sites (Lezuza, Agramón, Liétor and Ayna) were identified in Castilla-La Mancha and were monitored throughout 10 years at the plot and event scale.

Material and methods: Rainfall simulations and observations after natural rainfalls were carried out, to measure surface runoff and soil loss in unburned sites, burned and untreated sites, and burned sites treated with post-fire management techniques. The log response ratio of runoff and soil loss was calculated at the same site in order to evaluate the hydrological response to fire and post-fire management.

Main results: The meta-analysis has shown: (i) prescribed fires do not noticeably increase runoff, while wildfires at every severity is able to trigger erosion, except in the case of low-severity fires and less intense rainfall; (ii) runoff generation capacity of burned soils is higher after moderate rainfalls; (iii) fire changed soil erodibility according to rainfall intensity between unburned and burned soils; (iv) in general, the evaluated treatments were not effective at reducing surface runoff (except for mulching using wood chips and manual logging); (v) in contrast, soil erosion under burned conditions decreased after almost all techniques, especially with mulching using *Loranthus europaeus* J. and wheat straw; (vi) the mulch made of the latter substrate (combined with manual logging or not) seems to be the most feasible post-fire anti-erosive action.

Research highlights: Forest managers should prioritise areas potentially affected by high-severity wildfires for fire prevention. The most effective post-fire management technique is mulching, using wheat straw and wood chips to mitigate soil erosion and surface runoff, respectively.

Keywords: post-fire management; rainstorms; semi-arid environment; soil hydrology; wildfire effects.

Escorrentía y erosión del suelo después del fuego y tratamientos post-fuego en ecosistemas forestales de Castilla La Mancha: Análisis de una base de datos de 10 años

Resumen

Objetivo del estudio: Se aplicó un meta-análisis para evaluar la escorrentía superficial y la pérdida de suelo tras incendios de diferente severidad y tratamientos post-incendio en ecosistemas forestales semiáridos del centro-este de España.

Área de estudio: Se identificaron cuatro lugares (Lezuza, Agramón, Liétor y Ayna) en Castilla-La Mancha, y se monitorizaron la escorrentía y erosión a lo largo de 10 años a escala de parcela y de evento.

Materiales y métodos: Se realizaron simulaciones de precipitación y observaciones directas tras precipitaciones

naturales, midiendo la escorrentía superficial y la pérdida de suelo en sitios no quemados, quemados y no tratados, y quemados tratados con técnicas de gestión post-incendio. Se calculó la relación de respuesta logarítmica de la escorrentía y la pérdida de suelo en el mismo sitio con el fin de evaluar la respuesta hidrológica al fuego y a la gestión post-incendio.

Principales resultados: El meta-análisis ha mostrado los siguientes resultados: (i) Las quemas prescritas no aumentan notablemente la escorrentía, mientras que los incendios forestales de cualquier severidad son capaces de desencadenar procesos de erosión, excepto en el caso de incendios de baja severidad y precipitaciones menos intensas; (ii) la capacidad de generación de escorrentía de los suelos quemados es mayor tras precipitaciones moderadas; (iii) el fuego y la intensidad de precipitación cambian la erodibilidad del suelo cuando se comparan zonas no quemadas y los quemadas; (iv) en general, los tratamientos evaluados no fueron eficaces para reducir la escorrentía superficial (excepto el acolchado con astillas de madera y la corta de madera de manera manual); (v) por el contrario, la erosión del suelo quemado disminuyó tras casi todas las técnicas, especialmente con el mulching con *Loranthus europaeus* J. y paja de trigo; (vi) el mulching realizado con este último sustrato (combinado o no con la corta de arbolado manual) parece ser la acción antierosiva post-incendio más factible.

Aspectos destacados de la investigación: Los gestores forestales deben priorizar las actuaciones en zonas potencialmente afectadas por incendios con alta severidad. Dentro de las técnicas de gestión postincendio, el mulching es el más eficaz, ya sea con paja de cultivos agrícolas o astillas para controlar respectivamente la erosiòn del suelo y la escorrentía superficial.

Palabras clave: ambiente semiárido; efectos de los incendios; gestión post-fuego; hidrología del suelo; tormenta.

Citation: Lucas-Borja, ME; Zema, DA (2025). Surface runoff and soil loss after fire and post-fire treatments in forests of Castilla-La Mancha: a meta-analysis on a 10-year database. Forest Systems, Volume 34, Issue 2, 20956. https://doi.org/10.5424/fs/2025342-20956

Received: 25/09/2024. **Accepted:** 09/12/2024. **Published:** 06/10/2025.

Copyright © 2025 CSIC. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

Introduction

Surface runoff and soil erosion rates can noticeably increase after forest fires, regardless of their characteristics (intensity, severity, frequency, etc.). In Mediterranean semi-arid environments, the specific climatic (e.g., high-intensity rainstorms, long drought periods) and soil (shallow profiles and low content of organic matter) characteristics make these increases generally severe (Shakesby, 2011; Bodí et al., 2012; Almendros and González-Vila, 2014). Due to these peculiar characteristics, the effects of fire are generally site-specific, requiring targeted investigation in a given area to understand the soil's response to fire (Moody et al., 2013). In other words, it is essential to identify the characteristics of the rainfall events that mostly increase this hydrological response as well as the maximum expected runoff and erosion rates on one hand. On the other hand, there is a need to identify the most effective post-fire management technique to restore, if, when and where possible, the original soil hydrological response that is typical of sites not affected by fire.

Direct measurements of surface runoff and soil loss in forest areas are commonly expensive and time-consuming. Therefore, the relevant databases are generally scarce and often carried out by scholarly institutions on the occasion of targeted research projects (Girona-García et al., 2021; Zema and Lucas-Borja, 2023). However, when available, these databases are useful to draw indications about the magnitude and frequency of non-tolerable runoff and erosion rates (that is, the rates that exceed the suggested guidelines reported in the scientific and technical literature) as well as the beneficial effects of a given post-fire management techniques. Several universities and other research institutions have published a large body of research in the Iberian Peninsula, especially in Portugal, Galicia, Catalonia and Castilla-La Mancha (e.g., Francos et al., 2018; Lopes et al., 2020; de Pagter et al., 2023). About the latter region, the University of Castilla-La Mancha (*Campus de Albacete*) has carried out several investigations (mainly at the plot and event scales) in burned sites with variable morphological (e.g., slope and aspect) and soil (texture and chemical properties) characteristics and under different post-fire management techniques (e.g., mulching, salvage logging). A meta-analysis applied to this database can quantitatively reveal the magnitude of runoff and erosion rates, the characteristics of the driving rainfall events as well as the feasibility of a set of post-fire management techniques implemented in regional sites.

This study evaluates surface runoff and soil loss after fires of different severity and post-fire treatments in forests of Castilla-La Mancha, applying a meta-analysis on a 10-year database of records collected in experiments at the plot and event scale. The specific objectives are: (i) to identify the rainfall and intensity thresholds that generate runoff and erosion in burned sites significantly more than in unburned conditions; (ii) to estimate the maximum unit runoff and erosion rates per given rainfall characteristics (depth and intensity) in unburned and burned conditions; and (iii) to disentangle the most effective post-fire treatment to reduce runoff and erosion in burned conditions. These results are useful for forest managers to identify the areas to be prioritised for fire prevention and post-fire restoration.

Material and methods

Study areas and experimental sites

Castilla-La Mancha is a region of Central Spain, known for its diverse landscapes and agriculture. The climate is typically Mediterranean, Bsk according to Koppen's classification (Kottek et al., 2006) with continental influences. Summers are hot and dry (with temperatures often exceeding 35 °C), while winters are cold (on average from 0 °C to 10 °C) and occasional frost, and temperature noticeably varies among seasons. Rainfall is generally low, averaging between 300 to 500 mm/year, with most precipitation occurring in spring and autumn. The region often experiences droughts, especially in the summer.

Natural vegetation is primarily the Mediterranean scrubland, with oak, juniper, and pine trees on the higher elevations. Plains are characterized by low shrubs and grassland, while cultivated areas feature vineyards, olive groves, and cereal fields.

Soils are predominantly clayey and calcareous, with areas of sandy or loamy textures. In some sites, soils are fertile and thus suitable for agriculture, especially for growing cereals, olives, and grapes, while other areas are more arid and rockier.

The investigations (Table 1 and Figure 1) were carried out in four experimental sites (Liétor, Agramón, Ayna and Lezuza), where devices for collecting surface runoff and sediments produced by simulated or natural rainfalls were installed after wildfires of different burn severity from July 2012. Burn severity was classified according to (Parson et al., 2010), based on some visual indicators.

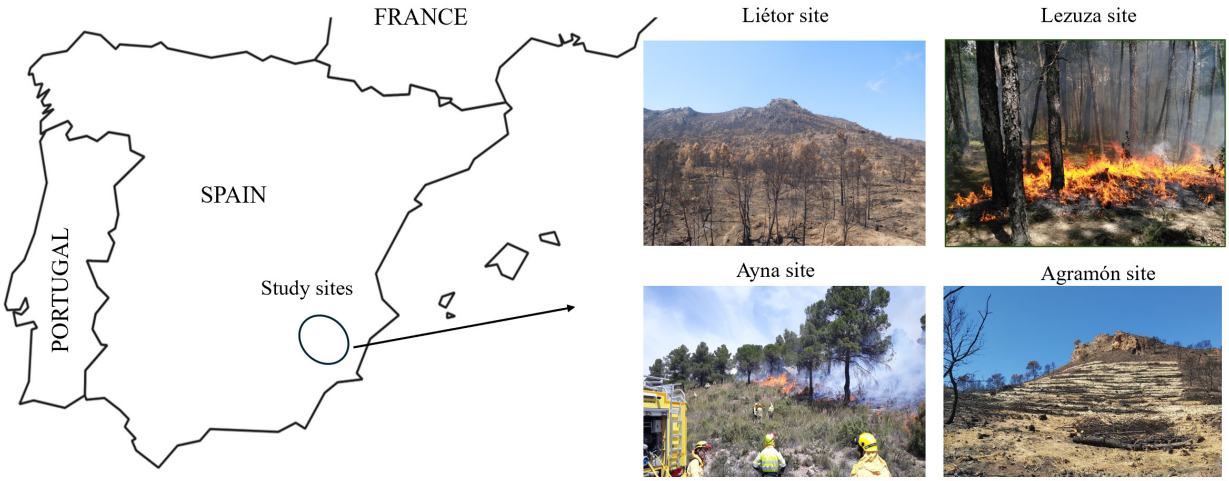
In these areas, the following post-fire management techniques were implemented: mulching (with wheat straw, wood chips, *Loranthus europaeus* J. + wheat straw, *L. europaeus* + wheat straw + clay particles), mulching with hand logging, mechanical logging (with heavy machinery), hand logging (with slight machinery). More details about site characteristics, measurement devices and hydrological characteristics can be found in the papers reported in Table 1 and Supplementary material Table S1.

Table 1. Main characteristics of the experimental sites identified in the study area (Castilla-La Mancha, Spain). Complete information on these characteristics is provided in Supplementary Material, Table S1

#	Paper	Site	Soil condition and site characteristics	Fire characteristics			Monitoring device				Rainfall
	First author, year			Type	Severity	Date	Spatial scale	Time scale	Plot number	Plot size (m^2)	
1	Lucas-Borja et al., 2022b	Agramón	Unburned + bare - low slope	Wildfire	High	July 2020	Microplots	Event	8	0.06	Simulated
			Unburned + bare - medium slope						10	0.06	
			Unburned + bare - high slope						22	0.06	
			Burned + M. tenacissima - low slope						4	0.06	
			Burned + M. tenacissima - medium slope						12	0.06	
			Burned + M. tenacissima - high slope						24	0.06	
			Unburned + M. tenacissima - low slope						4	0.06	
			Unburned + M. tenacissima - medium slope						18	0.06	
			Unburned + M. tenacissima - high slope						18	0.06	
2	Díaz et al., 2022	Liétor	Burned + high slope	Wildfire	High	July 2020	Microplots	Event	3	0.06	Simulated
			Burned + low slope								
			Burned + mulched with wheat straw + high slope								
			Burned + mulched with wheat straw + low slope								
			Burned + mulched with wood chips + high slope								
			Burned + mulched with wood chips + low slope								

3	Lucas-Borja et al., 2019a	Liétor	Mulching+logging	Wildfire	High	July 2016	Plots	Event	12	200	Natural
			Mulching+no-logging								
			No-mulching+logging								
			No-mulching+no-logging								
4	Navidi et al., 2023	Liétor	Burned and not treated	Wildfire	High	July 2021	Microplots	Event	5	0.06	Simulated
			Burned and mulched with *Loranthus europaeus* J. and wheat straw								
			Burned and mulched with *L. europaeus*, wheat straw and clay particles								
5	Lucas-Borja and Zema, 2024	Liétor + Agramón	Site 1 - burned (Agramón)	Wildfire	High	July 2020	Hillslope	Event	4	24	Natural
			Site 2 - burned (Lietor)								
			Site 1 - burned (Agramón)								
			Site 1 - burned and mulched (Agramón)								
			Site 2 - burned and mulched (Lietor)								
			Site 1 - burned and mulched (Agramón)								
6	de Pagter et al., 2023	Liétor	Mechanical logging	Wildfire	High	July 2021	Microplots	Event	22	0.01	Simulated
			Hand logging								
			No logging								
			Unburned								
7	Lucas-Borja et al., 2022	Ayna	High-severity prescribed fire	Prescribed fire	Moderate to high	October 2019	Plots	Event	5	2	Natural
			Unburned								
8	Lucas-Borja et al., 2019b	Lezuza	Burned	Prescribed fire	Low	March 2016	Plots	Event	6	8	Natural
			Unburned								
9	Lucas-Borja et al., 2021	Liétor	Mulched	Wildfire	High	July 2016	Plots	Event	6	20	Natural
			Non-mulched								
10	Plaza-Álvarez et al., 2024	Liétor	Burned + high slope	Wildfire	High	July 2021	Plots	Event	4	24	Natural
			Burned + low slope								
			Burned + mulched with wheat straw + high slope								
			Burned + mulched with wheat straw + low slope								
			Burned + mulched with wheat straw + high slope								
			Burned + mulched with wheat straw + low slope								
11	Gonzalez-Romero et al., 2023	Agramón	Unburned	Wildfire	High	July 2020	Micro-catchments	Event	3	5000	Natural
			Burned and not treated								
			Burned and mulched								

Figure 1. Geographical location of the experimental sites identified in the study area (Castilla-La Mancha, Spain). Geographical coordinates: Agramón 38.4222258, -1.6374748, Ayna 38.5511088218764, -2.1486548007, Liétor 38.5113313739949, -1.9430555163, Lezuza 38.9605098203747, -2.3240753160.



Experimental design

The sampling design in each site was replicated in plots (at least three per soil condition). The soil conditions reported in Table 1 were set up (namely, unburned soil, burned soil, and soil burned and then treated with a post-fire management technique).

The specific post-fire response is considered regarding surface runoff and soil loss, the two major processes of soil hydrology in addition to precipitation governing flooding and erosion downstream of the fire-affected areas (Moody et al., 2013). Surface runoff and soil loss were measured using two strategies: under natural rainfalls, to follow the actual weather patterns in the study area, and under simulated rainfalls, to simulate extreme rainfall events with very high erosivity.

In more detail, hydrological observations under simulated rainfalls were carried out at micro-plots with replications in Agramón and Liétor. Each micro-plot had an area of 0.25 × 0.25 m and covered 0.0625 m^2. Observations under natural rainfalls were carried out in Agramón, Liétor, Lezuza, and Ayna at replicated plots with different sizes. All plots were randomly distributed inside the monitored area, at a reciprocal distance always greater than 300 m, in order to avoid pseudo-replication.

Measurements of surface runoff and soil loss

About simulations at each plot, an artificial rainfall was produced using an Eijelkamp® rainfall simulator (Hlavčová et al., 2019; Iserloh et al., 2013). For these simulations and the following measurements of surface runoff and soil loss, the methods by Bombino et al. (2019) and Carrà et al. (2021) were adopted. The height and intensity of the simulated rainfall with a duration of 300 s was set up to the desired values (Table 1). The drop diameter and the falling height of the precipitation were 5.9 mm and 40 cm, respectively. Following the operating manual, the precipitation volume in the simulator tank (about 2.2 litres) was set by varying the pressure head, and the rainfall to be simulated was calibrated in the laboratory before the field experiment. Throughout the rainfall simulation, the runoff water and sediments were collected in a small bucket and oven-dried at 104 °C for 24 h.

The natural rainfalls were continuously measured at a time step of 5 minutes at the closest weather stations compared to the experimental site. Runoff/erosion and erosion plots with different sizes were installed (Table 1). Boundaries were made of a 0.5 m strip of geotextile inserted up to 0.4 m below the ground surface to prevent the surface water flow using 20 mm iron rods. For runoff/erosion plots, the geotextile narrowed at the bottom to convey the runoff and sediment through a pipe into storage tanks. For erosion plots, the sediment accumulated in plastic sediment traps was collected after the rainfall and transported to the laboratory, where the volume was oven-dried (24 h at 105 °C) and weighed.

In order to consider the variability of precipitation from one experimental site to another and from a soil condition to another, the coefficient of runoff and the unit soil loss were calculated per each event as the ratios between the runoff volume and the generating rainfall depth (in mm of runoff per mm of rainfall) as well as soil loss and the corresponding max 30 min rainfall intensity (in tons/ha per mm/h of rainfall intensity) in the period adopted by each study. The normalized indicators of runoff and soil erosion that consider the rainfall amounts allow the standardised comparison among the experimental data (Girona-García et al., 2021).

Meta-analysis

The variability of soil hydrology was studied between burned and unburned soils as well as burned and untreated, and burned and treated soils. The unburned, and burned and untreated soils were assumed to be the "reference" or "baseline" values for each of the two investigated hydrological variables.

For each case study, the so-called "effect size" (e.g., Vieira *et al.*, 2015; Girona-García *et al.*, 2021) for the changes in the burned vs. unburned sites or treated vs. untreated sites was calculated for both the short-term and medium-term. This effect size was calculated as "log response ratio (Ln(RR)), (Curtis and Wang, 1998; Hedges et al., 1999) as follows:

$$\ln\left(\mathrm{RR}\right) = \ln\left(\frac{x\prime}{x}\right) \qquad (1)$$

where *x'* is the mean value of the response variable (runoff volume and soil loss) measured in burned (or treated site) and *x* is the corresponding value measured in the unburned (or burned without any treatments) conditions at the same site. The value of the Ln(RR)s measures the impact of fire (or post-fire treatment) on runoff or soil loss in a given soil using a logarithmic scale (e.g., Kalies *et al.*, 2010). If Ln(RR) is < 0, the runoff or soil loss in the burned (or treated) condition is lower compared to the unburned (or untreated) site (Lucas-Borja et al., 2022c), the Ln(RR) being the order of magnitude of this increase. Following Vieira et al. (2015) and Girona-García et al. (2021), the standard deviations of runoff and soil loss, as calculated among the plots of each soil condition, were the weighting factors of the individual observations ("moderator variables"), in order to estimate the weighted least squares relationship between the moderator variables and the true effects (Viechtbauer, 2010).

The different conditions where the experimental observations were collected do not hinder the results of this meta-analysis, because the calculation of the size effect has been made in each site under the same conditions and monitoring period in each study (Vieira et al., 2015; Girona-García et al., 2021). In other words, the standardisation of the studied variables (x'/x) allows the analysis of data from different sites and under variable experimental and environmental conditions (Lajeunesse, 2015).

Statistical analyses

A one-way ANOVA was applied to Ln(RR) runoff and Ln(RR) soil loss as response variables to identify the significant differences between (i) burned and untreated, and unburned soils as well as (ii) burned and treated, and burned and untreated soils (adopting each soil condition as factor levels). To satisfy the assumptions of the statistical tests (equality of variance and normal distribution), the data was subjected to a normality test or was square root-transformed whenever necessary. 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 variables.

Moreover, according to Vieira et al. (2015) and Girona-García et al. (2021), Cochran's QE-test (Cochran, 1954) was adopted to test the significance of residual heterogeneity of the moderator variables, in order to assess whether the variability in each effect size, that is not accounted for by the moderator variables, is larger than expected.

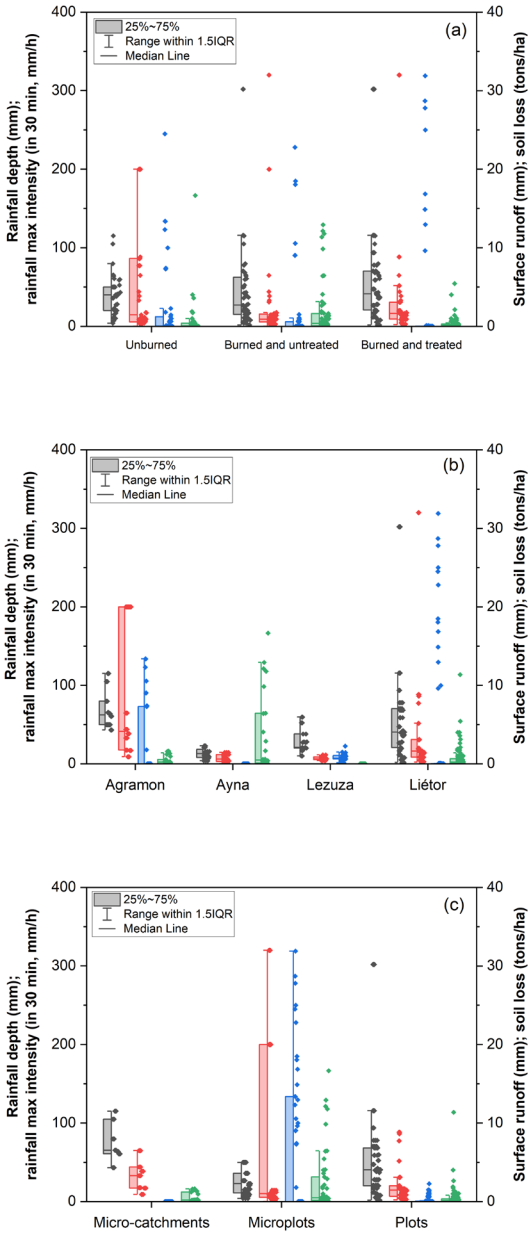
All the statistical tests were carried out with the OriginPro software, release 2024, except Cochran's QE-tests, which were performed using the "R" statistical package.

Results

Variability of rainfall, runoff and soil loss in experimental sites

The hydrological input in the experimental sites was rainfall with depth between 1.8 and 302 mm and maximum intensity (in 30 minutes) in the range of 0.2 to 320 mm/h. Surface runoff volume was up to a maximum of 31.9 mm, while the highest soil loss was 16.7 tons/ha (Figure 2).

Figure 2. Variability of rainfall (depth and 30-min maximum intensity), runoff volume and soil loss according to soil condition (a), site (b) and spatial scale (c) measured in the experimental sites identified in the study area (Castilla-La Mancha, Spain). Legend: rainfall depth (grey); rainfall maximum intensity (30-min) (red); surface runoff (blue); soil loss (green).

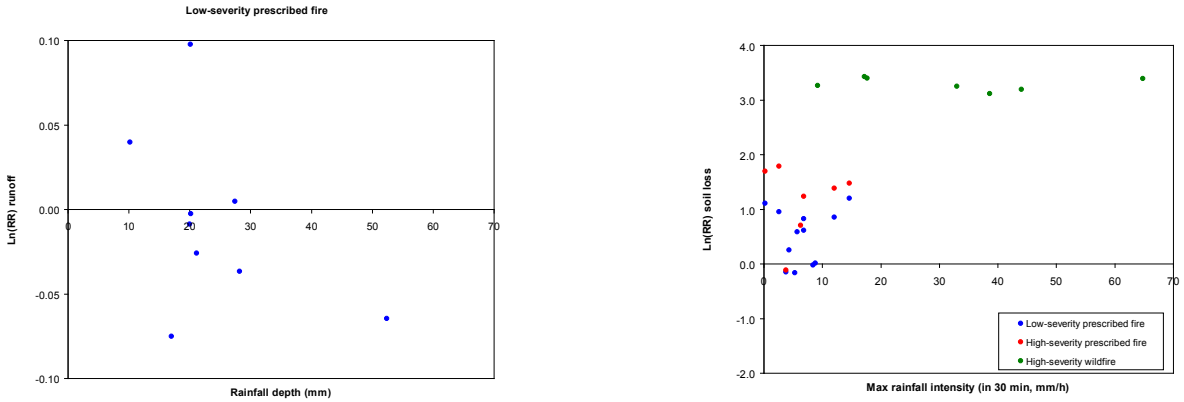


Identification of rainfall depth and intensity thresholds that generate runoff and erosion in burned sites

Ln(RR) runoff, measured in unburned soils as well as in corresponding sites burned by low severity prescribed fire, was in the range -0.07 (corresponding to a rainfall of 17 mm) to 0.10 (20.1 mm). Increases (Ln(RR) runoff > 0) were detected only in three cases after rainfall lower than 30 mm (Figure 3a).

Ln(RR) soil loss was positive for almost all observations at sites burned by prescribed fires (with low and high severity) and high-severity wildfires. In more detail, no erosion increases (Ln(RR) soil loss < 0) were measured only after prescribed fires at very low rainfall intensity (max I_{30} < 8.4 mm/h). In contrast, positive Ln(RR) soil loss (with peaks of 1.78) was observed in most cases also at generally low intensities (< 15 mm/h). After high-severity wildfires, Ln(RR) soil loss increased up to 3.4 regardless of the max I_{30}. It is worth noticing that increasing fire severity may increase Ln(RR) soil loss by a factor of two compared to prescribed fires also at the lowest rainfall intensities, and the difference is always significant ($F = 145$, $p < 0.001$). In contrast, the difference in Ln(RR) soil loss between fires of different severity was non-significant (Figure 3b).

Figure 3. Log Response Ratios of runoff (Ln(RR) runoff, a) and soil loss (Ln(RR) soil loss, b) between burned and unburned soils in the experimental sites identified in the study area (Castilla-La Mancha, Spain).

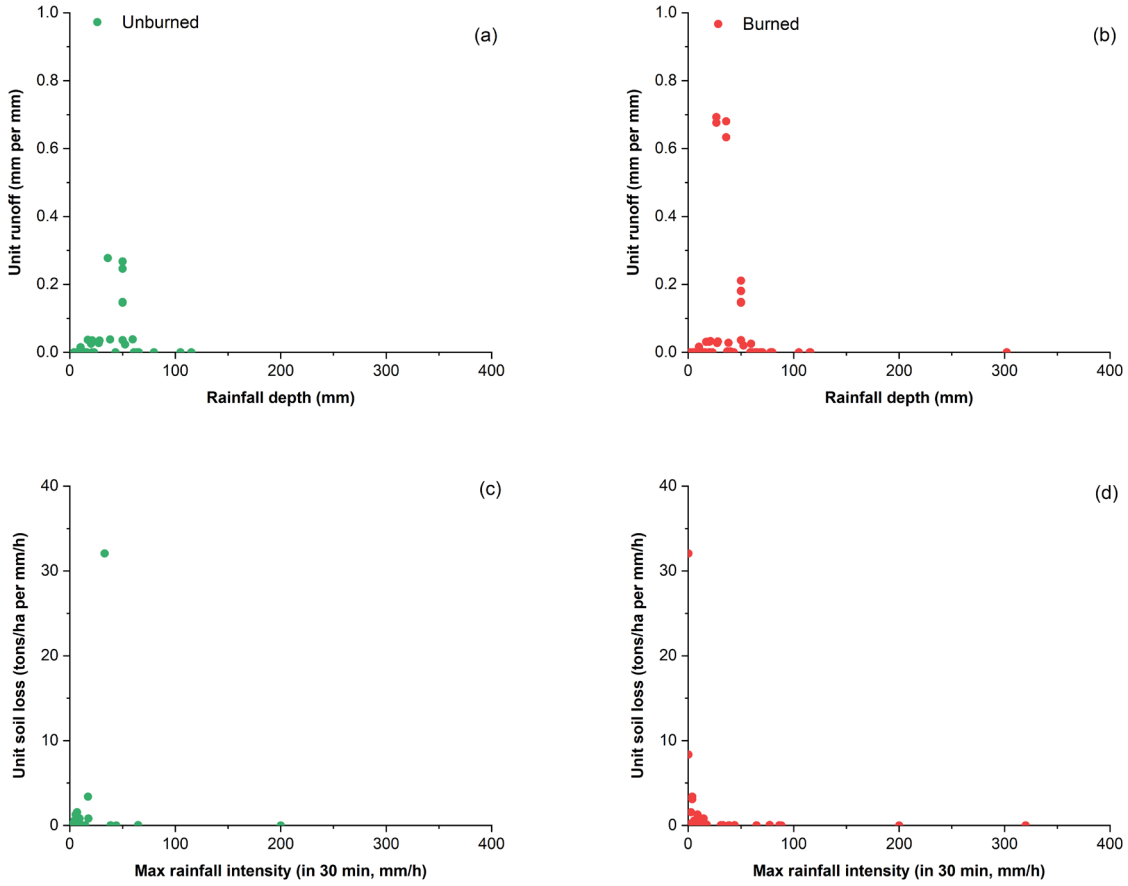


(a) (b)

Maximum unit runoff and erosion rates per given rainfall characteristics (depth and intensity) in unburned and burned conditions

The measurements at the burned and unburned sites showed that the highest unit runoff response of burned soils was recorded after rainfall in the range of 10 to 100 mm, and this was up to 0.69 mm/mm, while, in unburned soils, a maximum of 0.28 mm/mm occurred. It is worth noting that high rainfalls can generate relatively moderate unit runoff in unburned soils (e.g., less than 1 mm after rainfalls of over 100-120 mm) (Figure 4).

Figure 4. Maximum surface runoff per unit rainfall depth (a and b) and soil loss per unit 30-min rainfall intensity, c and d) measured in unburned and burned (without any post-fire treatments) soils in the experimental sites identified in the study area (Castilla-La Mancha, Spain).

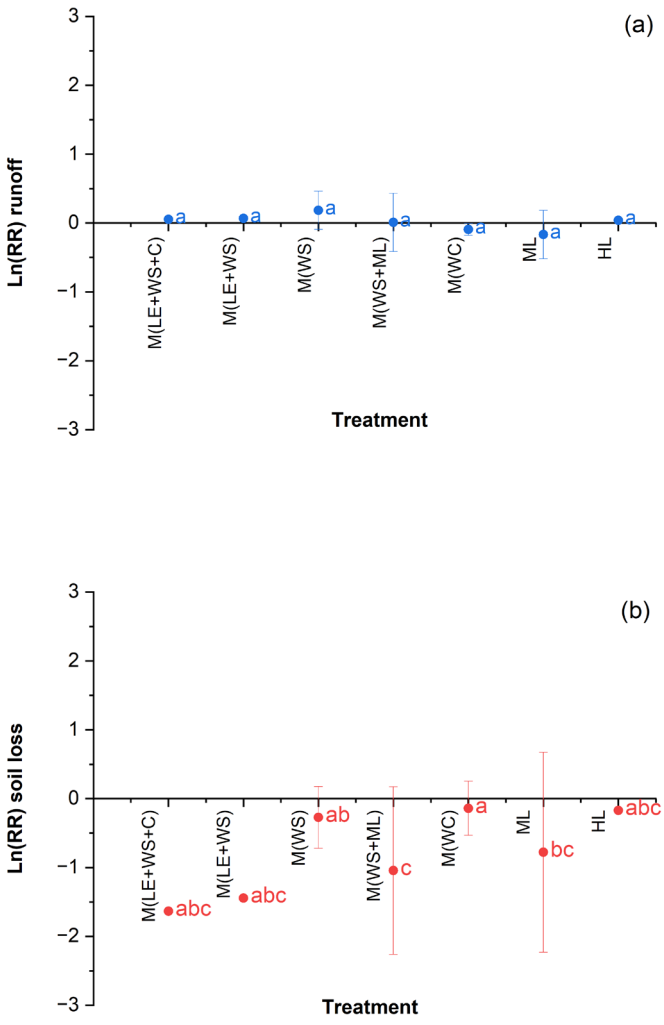


Concerning soil erosion, the observations clearly show that, in the unburned soils, the unit soil loss was the highest at moderate to high intensity. Under this condition, the unit erosion is affected by high variability, occurring with high soil loss (4.38 tons/ha per mm/h of rainfall intensity) after rainfalls with a max I_{30} of only 3.80 mm/h and very low unit erosion (less than 1.8 x 10^{-3} tons/ha per mm/h) after extremely intense rainfalls (200 mm/h). In contrast, in burned soils, the unit soil loss decreases with rainfall intensity, the highest values (32.1 tons/ha per mm/h) being measured after rainfall with max I_{30} of only 0.2 mm/h (following an event of 9 mm) and very low unit soil loss (6 x 10^{-3} tons/ha per mm/h) after an extreme rainfall intensity (320 mm/h). It is also evident how unit runoff and erosion in burned soils were always higher compared to unburned sites (Figure 4)

Disentangling the most effective post-fire treatment to reduce runoff and erosion in burned conditions

The calculation of Ln(RR) runoff under burned conditions between treated and untreated sites shows a generally low effectiveness of all investigated post-fire treatments at reducing the flooding risk. The Ln(RR) runoff differences among the treatments were not statistically significant (F = 0.912, p = 0.503). For some treatments (namely, mulching using wheat straw, mean Ln(RR) runoff equal to 0.19 ± 0.28) surface runoff may slightly increase in the treated sites. The use of woodchips as mulch (Ln(RR) runoff of -0.09 ± 0.09) and manual logging (-0.17 ± 0.35) can slightly reduce the soil's hydrological response, although never significantly (Figure 5).

Figure 5. Log Response Ratios of runoff (Ln(RR) runoff, a) and soil loss (Ln(RR) soil loss, b) in soils treated with post-fire management techniques in the experimental sites identified in the study area (Castilla-La Mancha, Spain). Legend: Ln(RR) = log response ratio; M(LE+WS+C) = Mulching (L. europaeus J. + wheat straw + clay particles); M(LE+WS) = Mulching (Loranthus europaeus J. + wheat straw); M(WS) = Mulching (wheat straw); M(WS+ML) = Mulching (wheat straw) + mechanical logging; M(WC) = Mulching (wood chips); ML = Mechanical logging; HL = Hand logging. Different letters indicate significant differences ($p < 0.05$).



Differently from what was recorded for surface runoff, all post-fire treatments reduced the soil loss from burned soils compared to untreated sites. In this case, the pair-wise comparisons gave significant differences among some pairs of studied treatments (ANOVA $F = 2.775$, $p = 0.02$). In more detail, the lowest Ln(RR) soil loss was observed for mulching using *L. europaeus*, wheat straw and clay particles (-1.63 ± 0.01) and the highest (-0.14 ± 0.39) for mulching with wood chips. In soils under the latter treatment, the Ln(RR) soil loss was significantly different only compared to mulching with straw (-0.27 ± 0.45) and mechanical logging (-0.78 ± 1.45) (Figure 5).

Discussion

The soil capacity to generate runoff and erosion is widely variable in space and many factors, such as anthropogenic disturbances, can drive its response to rainstorms (Shakesby, 2011; Girona-García et al., 2021). This suggests targeted investigations to understand how fire and management may alter this capacity and response typical of the unburned soils, and this meta-analysis goes in this direction.

The hydrological measurements showed that the soils of Castilla-La Mancha may produce relatively high runoff volumes and important soil losses after a single rainstorm. If rainfall events over 13 mm and soil loss over 10 tons/ha are considered erosive storms and non-tolerable erosion at the annual scale according to Wischmeier and Smith (1978) and Bazzoffi (2009), nearly 100 erosive events produced four non-tolerable soil losses, of which one recorded under low-severity fires. Only in one case, this huge erosion was measured in unburned soil, while the other four occurrences were detected in burned and untreated soils. This is alarming, since in four cases erosion produced by one event can exceed the total annual soil loss. This confirms that fire, especially at high severity, can greatly increase the background erosion that is typical of unburned sites, and this requires targeted actions from forest managers. Other studies in semi-arid forests have revealed: (i) annual erosion of up to 600 tons/ha per year in the first year after the fire (Fernández-Raga et al., 2021); (ii) total erosion in the entire monitoring period (10 years after the fire) of about 1100 tons/ha (González-Pelayo et al., 2023) with mean soil loss exceeding 70 tons/ha per year and a total amount of 260 tons/ha.

A more detailed analysis of runoff and erosion rates in association with the triggering rainfall characteristics shows that prescribed fires are not able to noticeably increase surface runoff, which confirms that controlled fires applied for wildfire prevention rarely increase the flooding hazards in line with relevant literature (e.g., Cawson et al., 2012; Carrà et al., 2022;) regardless of the rainfall input. In contrast, fire at every severity can trigger erosion, and also low-severity fires may result in increased soil loss. For instance, Stoof et al. (2015) reported increased runoff and erosion risk also in areas with limited soil physical changes due to fire, and Zema et al. (2022) found that prescribed fires at low intensity resulted in increases in sediment concentration in post-fire runoff. In this regard, this meta-analysis indicates that, compared to unburned conditions, soil loss does not increase only in the case of low-severity fires and less intense rainfall intensity. This is an expected result, which may ascribed both to the low erodibility of rainstorms with low intensity as well as the low disturbance of low-severity fires, which are not able to remove the canopy trees (intercepting part of rainfall) and severely alter the physico-chemical properties of the burned soils (Alcañiz et al., 2018; Zema and Lucas-Borja, 2023). In contrast, wildfires can raise soil erosion by a factor between 5 (rainfall with relatively low intensity) to even 30 (at the highest intensity). This clearly suggests that, after a fire of high severity, post-fire management actions are essential to mitigate the erosion risk with consequent damage to valley areas surrounding burned forests.

This study has also indicated that the runoff generation capacity of burned soils is higher after moderate rainfalls of medium depth, and this capacity is on average more than two-fold the response recorded for unburned sites. At first sight, this contrasts with what can be expected (increasing runoff generation with increasing rainfalls), but the presence of hydrophobic ash in burned soils may justify the lower response of burned soils after high rainstorms (Pereira et al., 2018).

An important indication given by this study is the shift in soil erodibility with rainfall intensity between unburned and burned soils. In other words, while the unit soil loss is the highest after rainfalls with moderate to high intensity in the unburned soils, lower-intensity precipitation shows higher erosivity in burned sites compared to the extreme events. This means that also less intense but very frequent rainfalls can mobilise high amounts of sediments, leading to the need for post-management actions in sites characterised by low hydrological input. In any case, the large variability in soil erosion in both burned and unburned conditions suggests careful monitoring of soil hydrology in forest sites, especially after deforestation, and prompt implementation of post-fire management actions, where needed.

In this regard, this study highlighted that the post-fire management techniques investigated in this study are not particularly suitable to mitigate the flooding risk, their effectiveness being quite low at reducing surface runoff from burned and treated areas. This is somewhat expected, since, in the specific case of mulching, also other studies have shown that mulches are not fully able to intercept rainwater, but mainly reduce the flow velocity (Cawson et al., 2012; Girona-García et al., 2021; Carrà et al., 2022) without a significant decrease in the total amount of runoff. Overall, mulching using wood chips and manual logging showed the highest effectiveness for this purpose, presumably because chips are more resistant to the drag forces exerted by flowing water compared to straw sticks, and manual logging does not compact too much soil, thus not decreasing porosity and water infiltration as for mechanical logging (Francos et al., 2019; Lucas-Borja et al., 2019b).

In contrast, the evaluated techniques resulted in generalised reductions (sometimes significant) in soil erosion, although with differentiated effects among sites and types of post-fire management. Undoubtedly, mulching with *L. europaeus* and

wheat straw appeared the most effective anti-erosive practice, but the availability of this herbaceous species limits its practical applicability in the region. We identified mulching using wheat straw (preferably with manual logging) as a feasible post-fire management action to control and mitigate erosion in the area, considering its good effectiveness (shown by a mean reduction of 60-70% of soil loss compared to untreated areas) and the possibility to combine this restoration action with salvage logging as forest management practice. Mulching using wheat straw alone leads to reductions in soil loss of 20-25%, which becomes lower in the case of the use of wood chips. The literature shows generally good effectiveness of wheat straw at reducing soil erosion in semi-arid environments, and this statement could be considered in agreement with our findings.

A possible limitation of the study relies on the different spatial scales of hydrological measurements (micro-plots, plots and micro-catchments), which may alter the comparisons among the sites, and, more specifically, underestimations at the micro-catchment scale (where sedimentation processes may have reduced soil loss) and over-estimations at the smaller scales (measuring mainly splash erosion).

Conclusions

The meta-analysis applied to hydrological observations at five study areas affected by fires of different intensity and treated with post-fire management techniques in forests of Castilla-La Mancha (Central Eastern Spain) has shown:

- the soils typical of this region produce relatively high runoff volumes and important soil losses after a single rainstorm,
- sometimes, erosion after even one event in burned soils can exceed the annual value of tolerable soil loss in the literature,
- prescribed fires do not noticeably increase runoff, while wildfires at every severity can trigger erosion, except in the case of low-severity fires and less intense rainfall,
- specifically, wildfires can result in 5- to 30-fold erosion measured in unburned conditions,
- runoff generation capacity of burned soils - on average more than two-fold the response recorded for unburned sites - is higher after moderate rainfalls,
- fire shifts soil erodibility with rainfall intensity between unburned and burned soils.

These results indicate the need for post-fire management actions after a fire of high severity to mitigate the erosion risk, which may be high also after low to moderate rainfalls. In general, the evaluated treatments were not effective at reducing surface runoff (except for mulching using wood chips and manual logging). In contrast, soil erosion under burned conditions decreased after almost all techniques, especially with mulching using *L. europaeus*. and wheat straw. The mulch made of the latter substrate (combined with manual logging or not) seems to be the most feasible post-fire anti-erosive action.

Data availability: Data will be shared upon reasonable request made to the authors.

Acknowledgements: The authors would like to extend my deepest gratitude to all those who have supported and contributed to all research included in this work. The authors also thanks to all colleagues and peers for all their thought-provoking discussions and willingness to collaborate.

Supplementary material (Table S1): accompanies the paper on the Forest Systems website.

Competing interests: The authors have declared that no competing interests exist.

Statement about use of generative AI: The authors did not employ any generative AI and AI-assisted technologies while preparing this work.

Authors' contributions: Manuel E. Lucas-Borja: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Demetrio A. Zema:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding:

Funding agencies/institutions	Project / Grant
MCIN/AEI/10.13039/501100011033 and European Union Next Generation EU/PRTR	"Effects of short- and long-term post-fire management on the multifunctionality of Iberian forests after forest fires TED2021-12945B-41"
MCIN/AEI/10.13039/501100011033/ and FEDER A way for Europe	Evaluation of post-fire management strategies to improve the multifunctionality of Mediterranean forest ecosystems affected by fire PID2021-126946OB-100"

References

Alcañiz M, Outeiro L, Francos M, Úbeda X, 2018. Effects of prescribed fires on soil properties: A review. Sci Tot Environ 613: 944–957.https://doi.org/10.1016/j.scitotenv.2017.09.022

Almendros G, González-Vila FJ, 2014. Wildfires, soil carbon balance and resilient organic matter in Mediterranean ecosystems. A review. Span J Soil Sci 2: 153.https://doi.org/10.3232/SJSS.2012.V2.N2.01

Bazzoffi P, 2009. Soil erosion tolerance and water runoff control: minimum environmental standards. Reg Environ Change 9: 169–179.https://doi.org/10.1007/s10113-008-0072-2

Bodí MB, Cerdà A, Mataix-Solera J, Doerr SH, 2012. A review of fire effects on vegetation and soil in the Mediterranean Basin. Bol Asoc Geógrafos Esp 58: 291-310.https://doi.org/10.21138/bage.1704

Bombino G, Denisi P, Gómez JA, Zema DA, 2019. Water infiltration and surface runoff in steep clayey soils of olive groves under different management practices. Water 11: 240.https://doi.org/10.3390/w11020240

Borja MEL, Zema DA, 2024. Delayed application of straw mulching increases soil erosion in Mediterranean pine forests burned by wildfires. Catena 236: 107714.https://doi.org/10.1016/j.catena.2023.107714

Carrà BG, Bombino G, Denisi P, Plaza-Àlvarez PA, Lucas-Borja ME, Zema DA, 2021. Water infiltration after prescribed fire and soil mulching with fern in Mediterranean forests. Hydrology 8: 95.https://doi.org/10.3390/hydrology8020095

Carrà BG, Bombino G, Lucas-Borja ME, Plaza-Alvarez PA, D'Agostino D, Zema DA, 2022. Prescribed fire and soil mulching with fern in Mediterranean forests: Effects on surface runoff and erosion. Ecol Eng 176: 106537.https://doi.org/10.1016/j.ecoleng.2022.106537

Cawson JG, Sheridan GJ, Smith HG, Lane PNJ, 2012. 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: 857–872.https://doi.org/10.1071/WF11116

Cochran WG, 1954. The combination of estimates from different experiments. Biometrics 10: 101–129.https://doi.org/10.2307/3001666

Curtis PS, Wang X, 1998. A meta-analysis of elevated CO2 effects on woody plant mass, form, and physiology. Oecologia 113: 299–313.https://doi.org/10.1007/s004420050381

de Pagter T, Lucas-Borja ME, Navidi M, Carra BG, Baartman J, Zema DA, 2023. Effects of wildfire and post-fire salvage logging on rainsplash erosion in a semi-arid pine forest of Central Eastern Spain. J Environ Manage 329: 117059.https://doi.org/10.1016/j.jenvman.2022.117059

Díaz MG, Lucas-Borja ME, Gonzalez-Romero J, Plaza-Alvarez PA, Navidi M, Liu YF, et al, 2022. Effects of post-fire mulching with straw and wood chips on soil hydrology in pine forests under Mediterranean conditions. Ecol Eng 182: 106720.https://doi.org/10.1016/j.ecoleng.2022.106720

Fernández-Raga M, Gutiérrez EG, Keesstra SD, Tárrega R, Nunes JP, Marcos E, et al, 2021. Determining the potential impacts of fire and different land uses on splash erosion in the margins of drylands. J Arid Environ 186: 104419.https://doi.org/10.1016/j.jaridenv.2020.104419

Francos M, Pereira P, Alcañiz M, Úbeda X, 2018. Post-wildfire management effects on short-term evolution of soil properties (Catalonia, Spain, SW-Europe). Sci Total Environ 633: 285–292.https://doi.org/10.1016/j.scitotenv.2018.03.195

Francos M, Úbeda X, Pereira P, 2019. Impact of torrential rainfall and salvage logging on post-wildfire soil properties in NE Iberian Peninsula. Catena 177: 210–218.https://doi.org/10.1016/j.catena.2019.02.016

Girona-García A, Vieira DCS, Silva J, Fernández C, Robichaud PR, Keizer JJ, 2021. Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis. Earth-Sci Rev 217: 103611.https://doi.org/10.1016/j.earscirev.2021.103611

González-Pelayo O, Prats SA, Vieira AMD, Vieira DCS, Maia P, Keizer JJ, 2023. Impacts of barley (Hordeum vulgare L.) straw mulch on post-fire soil erosion and ground vegetation recovery in a strawberry tree (Arbutus unedo L.) stand. Ecol Eng 195: 107074.https://doi.org/10.1016/j.ecoleng.2023.107074

Gonzalez-Romero J, Zema DA, Carrà BG, Neris J, Fajardo A, Plaza-Álvarez PA, et al, 2023. Soil erosion modelling of burned and mulched soils following a Mediterranean forest wildfire. Soil Use Manag 39: 881–899.https://doi.org/10.1111/sum.12884

Hedges LV, Gurevitch J, Curtis PS, 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80: 1150–1156.https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2

Hlavčová K, Danáčová M, Kohnová S, Szolgay J, Valent P, Výleta R, 2019. Estimating the effectiveness of crop management on reducing flood risk and sediment transport on hilly agricultural land – A Myjava case study, Slovakia. Catena 172: 678–690.https://doi.org/10.1016/j.catena.2018.09.027

Iserloh T, Ries JB, Arnáez J, Boix-Fayos C, Butzen V, Cerdà A, et al, 2013. European small portable rainfall simulators: A comparison of rainfall characteristics. Catena 110: 100–112.https://doi.org/10.1016/j.catena.2013.06.002

Kalies EL, Chambers CL, Covington WW, 2010. Wildlife responses to thinning and burning treatments in southwestern conifer forests: a meta-analysis. For Ecol Manage 259: 333–342.https://doi.org/10.1016/j.foreco.2009.10.021

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

Lajeunesse MJ, 2015. Bias and correction for the log response ratio in ecological meta-analysis. Ecology 96: 2056–2063.

https://doi.org/10.1890/14-2402.1
Lopes AR, Prats SA, Silva FC, Keizer JJ, 2020. Effects of ploughing and mulching on soil and organic matter losses after a wildfire in Central Portugal. Cuad Investig Geográfical Res Lett 303–318.https://doi.org/10.18172/cig.4623
Lucas-Borja ME, de las Heras J, Moya Navarro D, González-Romero J, Peña-Molina E, Navidi M, et al, 2022a. Short-term effects of prescribed fires with different severity on rainsplash erosion and physico-chemical properties of surface soil in Mediterranean forests. J Environ Manage 322: 116143.https://doi.org/10.1016/j.jenvman.2022.116143
Lucas-Borja ME, González-Romero J, Plaza-Álvarez PA, Sagra J, Gómez ME, Moya D, et al, 2019a. The impact of straw mulching and salvage logging on post-fire runoff and soil erosion generation under Mediterranean climate conditions. Sci Total Environ 654: 441–451.https://doi.org/10.1016/j.scitotenv.2018.11.161
Lucas-Borja ME, Parhizkar M, Zema DA, 2021. Short-Term Changes in Erosion Dynamics and Quality of Soils Affected by a Wildfire and Mulched with Straw in a Mediterranean Forest. Soil Syst 5: 40.https://doi.org/10.3390/soilsystems5030040
Lucas-Borja ME, Plaza-Álvarez PA, Gonzalez-Romero J, Sagra J, Alfaro-Sánchez R, Zema DA, et al, 2019b. Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, soil erosion and water quality of runoff. Sci Total Environ 674: 615–622.https://doi.org/10.1016/j.scitotenv.2019.04.144
Lucas-Borja ME, Plaza-Àlvarez PA, Uddin SM, Parhizkar M, Zema DA, 2022b. Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by Macrochloa tenacissima (L.) Kunth. J Arid Environ 198: 104702.https://doi.org/10.1016/j.jaridenv.2021.104702
Lucas-Borja ME, Zema DA, Fernández C, Soria R, Miralles I, Santana VM, et al, 2022c. Limited contribution of post-fire eco-engineering techniques to support post-fire plant diversity. Sci Total Environ 815: 152894.https://doi.org/10.1016/j.scitotenv.2022.152894
Moody JA, Shakesby RA, Robichaud PR, Cannon SH, Martin DA, 2013. Current research issues related to post-wildfire runoff and erosion processes. Earth-Sci Rev 122: 10–37.https://doi.org/10.1016/j.earscirev.2013.04.004
Navidi M, Shafiei AB, Alijanpour A, Pirsa S, Ahmady-Birgani H, Lucas-Borja ME, et al, 2023. Effects of Post-Fire Mulching with Loranthus europaeus Jacq. on Surface Runoff and Rainsplash Erosion in a Semi-Arid Pine Forest. Resources 12: 31.https://doi.org/10.3390/resources12030031
Parson A, Robichaud PR, Lewis SA, Napper C, Clark JT, 2010. Field guide for mapping post-fire soil burn severity. US Dept Agric For Serv, Rocky Mountain Research Station, Ft. Collins, CO. RMRS-GTR-243.https://doi.org/10.2737/RMRS-GTR-243
Pereira P, Francos M, Brevik EC, Ubeda X, Bogunovic I, 2018. Post-fire soil management. Curr Opin Environ Sci Health 5: 26–32.https://doi.org/10.1016/j.coesh.2018.04.002
Plaza-Álvarez PA, Lucas-Borja ME, Carmona-Yáñez MD, Candel-Pérez D, Zema DA, 2024. Mid-term effects of postfire mulching with straw or wood chips on soil erosion in semi-arid forests. Land Degrad Dev 35: e2953.https://doi.org/10.1002/ldr.2953
Shakesby RA, 2011. Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth-Sci Rev 105: 71–100.https://doi.org/10.1016/j.earscirev.2011.01.001
Stoof CR, Ferreira AJ, Mol W, Van den Berg J, De Kort A, Drooger S, et al, 2015. Soil surface changes increase runoff and erosion risk after a low–moderate severity fire. Geoderma 239: 58–67.https://doi.org/10.1016/j.geoderma.2014.10.007
Viechtbauer W, 2010. Conducting meta-analyses in R with the metafor package. J Stat Softw 36: 1–48. https://doi.org/10.18637/jss.v036.i03
Vieira DCS, Fernández C, Vega JA, Keizer JJ, 2015. Does soil burn severity affect the post-fire runoff and interrill erosion response? A review based on meta-analysis of field rainfall simulation data. J Hydrol 523: 452–464.https://doi.org/10.1016/j.jhydrol.2015.01.071
Wischmeier WH, Smith DD, 1978. Predicting rainfall erosion losses: a guide to conservation planning. Department of Agriculture, Science and Education Administration. Agric Handb 537.
Zema DA, Carrà BG, Lucas-Borja ME, 2022. Exploring and Modeling the Short-Term Influence of Soil Properties and Covers on Hydrology of Mediterranean Forests after Prescribed Fire and Mulching. Hydrology 9: 21.https://doi.org/10.3390/hydrology9020021
Zema DA, Lucas-Borja ME, 2023. Effects of prescribed fire on the post-fire hydrological processes in agro-forest ecosystems: A systematic review and a meta-analysis. Hydrol Process 37: e14957.https://doi.org/10.1002/hyp.14957