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Mid-Term Effects of Postfire Mulching With Straw or Wood Chips on Soil Erosion in Semi-Arid Forests

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ABSTRACT

Soil mulching has been studied as a postfire management action to reduce soil erosion in several forest environments. Less research exists about the effectiveness of mulching with straw and wood chips beyond the first year after a wildfire on sites with different slopes. To fill this gap, this study has measured soil erosion in three burned sites (untreated soils, and soils mulched using wheat straw or pine wood chips) throughout a 2.5-year observation period in a forest of Castilla-La Mancha (Central Eastern Spain). Soil condition and slope (gentle, < 32%, gentle vs. steep, > 38%, slopes) significantly influenced erosion, which, however, was of low entity due to the relatively low rainfall erosivity. Mulching was generally effective after the most intense events (maximum 30-min rainfall intensity over 15 mm/h). On the gentle hillslopes, mulch application did not reduce postfire soil loss compared with the untreated sites. In contrast, on the steep slopes, the effectiveness of soil mulching was significant for the two most intense rainfall events (−30% of soil loss in plots treated with wheat straw compared with the burned and untreated sites). The cumulated soil loss significantly decreased on the treated sites (−40%) only when wheat straw was used. On steep slopes, the anti-erosive effects of mulching were almost durable, since the mulch covered more than one-third of the plot areas until the end of the monitoring period. These results help land managers adopt the most effective measures of postfire management in semi-arid forests affected by severe wildfires.

1 | Introduction

The impacts of high-severity fires on the forest ecosystem greatly alter the soil's hydrological and erosive response to precipitation. Fire generally reduces soil water infiltration and induces water repellency (Zema et al. 2021). These effects sum up to severe changes in other physicochemical properties of soil due to heating (Agbeshie et al. 2022) as well as to the partial or even total removal of vegetation cover due to burning, generally resulting in increases in surface runoff and erosion (Moody et al. 2013; Shakesby and Doerr 2006). Commonly, these increases may be very high (Shakesby 2011; Wagenbrenner et al. 2021), and can cause floods and burial of infrastructures downstream of wildfire-affected areas (Prosser, Lu, and Moran 2003; Robinne et al. 2021).

Forest managers often adopt postfire management actions as soil conservation measures to prevent or reduce the hydrological impacts of wildfires (Girona-García et al. 2021). Mulching is one of the most common techniques to protect the soil from rainfall impacts and support postfire restoration of vegetation (Zituni, Wittenberg, and Malkinson 2019). Much research has confirmed the positive effects of this technique on the soil's erosive response (e.g., Carrà et al. 2022; Fernández and Vega 2014; Keizer et al. 2018; Kim et al. 2008; Lucas-Borja et al. 2019; Robichaud, Jordan, et al. 2013; Wagenbrenner, MacDonald, and Rough 2006). However, the hydrological effectiveness of mulching is variable site by site, depending on the specific climatic, geomorphological, and ecological conditions of the area of application, on the wildfire characteristics as well as on the type of mulch applied to the soil (Girona-García et al. 2021; Vieira et al. 2015; Wittenberg and Pereira 2021). As a consequence of this variability, some cases of low effectiveness of postfire mulching have been reported in the literature. For instance, after simulated rainfalls in a shrubland area of Northern Spain, Fernández et al. (2012) reported nonsignificant differences in erosion between soils treated with straw mulching and seeding, and untreated sites. According to Lucas-Borja et al. (2018), water infiltration can be reduced by soil mulching with straw, especially in the dry season. Therefore, more research is needed to explore whether and to what extent a specific mulch material is suitable as a postfire management action to limit erosion in a specific site burned by fire. This issue is essential in the Mediterranean semi-arid environments, where the alteration of soil erosion rates due to severe burning may be extreme (McGuire et al. 2021; Moody et al. 2013), due to the specific weather conditions (heavy rainfalls that generate flash floods and extreme erosion) (Gaume et al. 2016; Morán-Ordóñez et al. 2020), and fragility of soils, which generally show high erodibility (Cawson et al. 2012; Shakesby 2011). Therefore, flood and hydromorphological hazards may be amplified by fire compared with unburned environments (Moody et al. 2013; Wagenbrenner et al. 2021).

Moreover, studies comparing the soil's hydrological response after wildfires and mulching using different vegetal residues (such as agricultural straw or wood chips) may give scientific evidence of how much these mulches are effective at reducing postfire erosion in the same burned environment. In this regard, comparisons of the effectiveness of straw and wood mulches have been previously conducted by Fernández et al. (2011), Fernández and Vega (2014), Robichaud, Wagenbrenner, et al. (2013), Robichaud, Jordan, et al. (2013), Robichaud, Lewis, et al. (2013), and Vieira et al. (2018), but only the study by Robichaud, Wagenbrenner, et al. (2013) was carried out in semi-arid climates. Recently, Garcia-Diaz et al. (2022) measured soil erosion under extremely high rainfall intensity in a pine forest of Central Eastern Spain (and, therefore, under typically Mediterranean conditions) burned by a large wildfire and mulched with wheat straw or wood chips. However, this investigation was carried out using a portable rainfall simulator, which does not consider the variability of natural precipitation, and did not evaluate the anti-erosive action of mulch, which may be variable depending on rainfall characteristics as well as substrate dispersion or degradation over time throughout a significant monitoring period.

This study aims to fill the aforementioned literature gaps and follows up the previous investigation by Garcia-Diaz et al. (2022) in the same burned sites. To these ends, soil erosion was measured on burned and untreated, and burned and mulched soils (using straw or wood chips, as never carried out in previous studies) throughout a 2.5-year observation period on steep and mild hillslopes in a forest of Castilla-La Mancha (Central Eastern Spain) after a severe wildfire. Moreover, to understand better the observed erosion rates, they were correlated with the ground cover and rainfall characteristics. Assuming these experimental conditions (mid-term observations and natural precipitation), the specific research questions supporting this study are the following: (i) Is soil loss influenced by treatment and slope under the studied conditions (no treatment, mulching with wheat straw and mulching with wood chips) during the first 2 years and half after the wildfire and postfire actions? (ii) Is mulching able to reduce soil erosion (at the event scale and for longer periods) compared with the untreated sites, and, in this case, which of the two mulches is more effective in reducing erosion on the treated hillslopes? (iii) Is the variability of soil loss associated with soil texture and ground cover in untreated or mulched sites? The replies to these research questions may help land managers adopt measures of postfire management in semi-arid forests affected by severe wildfires.

2 | Materials and Methods

2.1 | Study Area

The study area was in Liétor, Castilla-La Mancha, Spain (38°30′41″ N; 1°56′35″ W) at an elevation between 520 and 770 m above the mean sea level (Figure 1). The area shows a semi-arid Mediterranean climate (BSk type, according to the Köppen classification) (Kottek et al. 2006). According to the historical records of the Spanish Meteorological Agency (AEMET, https://www.aemet.es/en/portada), the mean annual temperature and precipitation are equal to 16.6°C and 321 mm, respectively (weather data of the last 20 years recorded at the meteorological station of Liétor, about 5 km far from the study area). Following the characterization of soil type reported by Gómez-Miguel and Badía-Villas (2016), soils are Calcic Aridisols (Nachtergaele 2001; Soil Survey Staff 2014).

Field surveys in the area, based on a general characterization of vegetation of the Castilla-La Mancha region proposed by Peinado, Monje, and Martínez (2008), showed that the overstory vegetation mainly consists of a tree layer of natural and reforested (about 60–70 years ago) *Pinus halepensis* Mill., and a shrub layer of *Quercus coccifera* L. The prefire stand density and tree height were between 500 and 650 trees/ha, and 7 and 14 m, respectively. The understory vegetation includes *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal., *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus coccifera* L., and *Plantago albicans* L.

2.2 | Experimental Design

About 2500 ha of the study area was affected by a wildfire on July 24, 2021, which burned ground vegetation and tree

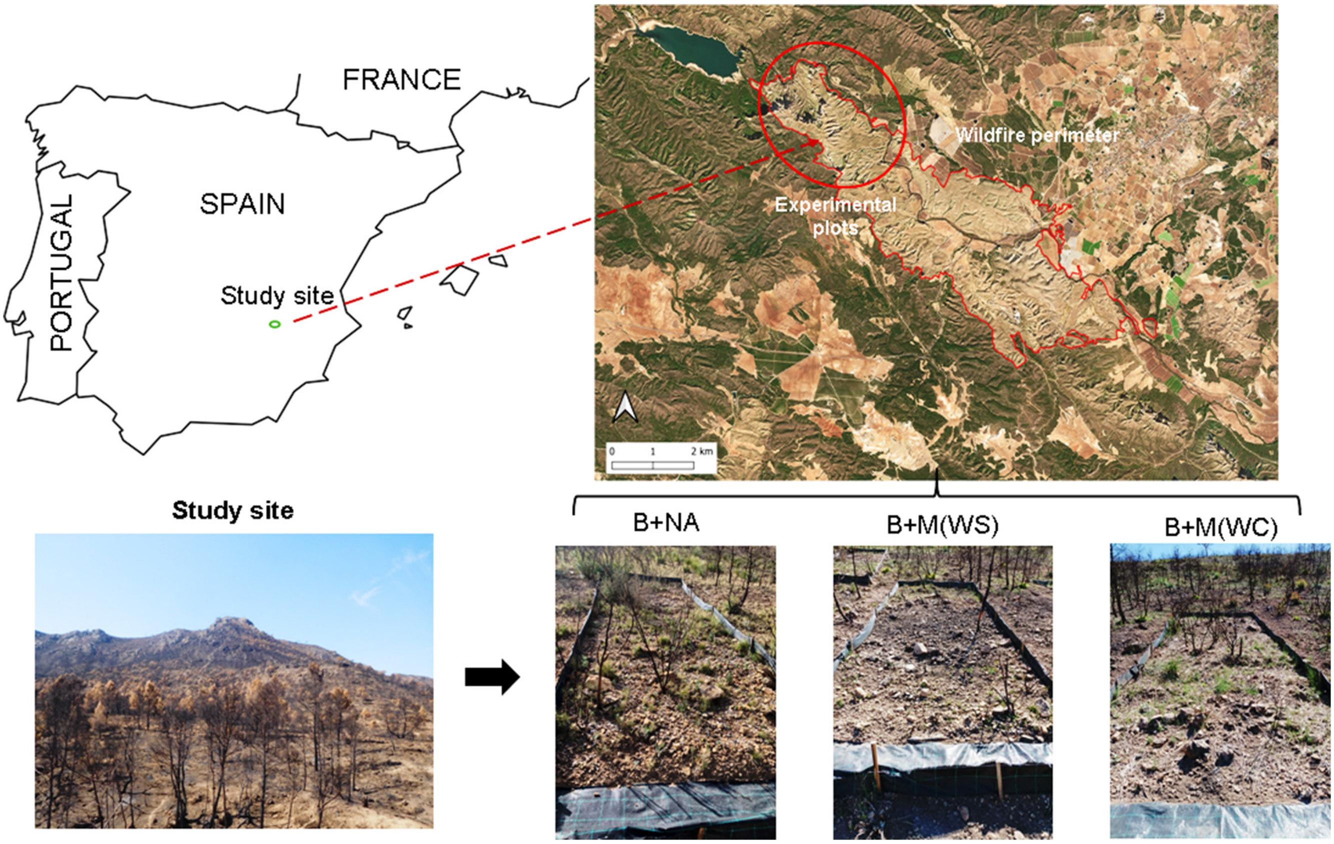

FIGURE 1 | Geographical location of the study area (lower left), orthophoto of the burned catchment (red perimeter) and location of the experimental plots (upper left), and pictures of the burned and treated sites (right) (Liétor, Castilla-La Mancha, Central Eastern Spain). B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw. [Colour figure can be viewed at wileyonlinelibrary.com]

crowns. A subarea of about 400 ha affected by 100%-crown consumption was identified. In this subarea, the soil burn severity was assessed using a modification of the classification proposed by Vega et al. (2013), based on the level of ground vegetation burning, crown consumption, and ash color. According to the aforementioned criterion, this soil burn severity, homogenous overall subarea, was classified as "high," since the forest floor and organic matter of the soil surface (about 1 cm) were completely consumed, its structure was altered, and its color was gray.

In the fire-affected subarea, 3 months after the wildfire event (late October–early November 2021) the Forest Service of the Castilla-La Mancha Region adopted two postfire management actions, namely mulching with wheat straw or wood chips, to limit erosion and other adverse hydrological impacts. In the period between the wildfire and postfire mulching, no rainfall events over 1–2 mm were recorded.

In the northern part of this subarea, 24 plots were randomly identified some days after the mulching operations and delimited with red and black ribbons. A visual analysis of soil texture slope and vegetation characteristics was carried out, progressively increasing the distance from each of the three sample plots (one per soil condition, see below). Evidence of changes in those characteristics was detected at a distance over 200–250 m, which was set as the minimum reciprocal distance among plots. This minimum distance was identified to avoid pseudoreplication, and therefore statistically dependent observations or correlations of measurements in time or space.

Of these 24 plots, eight were identified in the burned but not treated area, while 16 other plots were set in the mulched areas (8 plots for straw mulching and 8 plots for mulching using wood chips) (Figure 1). Chips were made of pine wood, logged in a close unburned forest, mechanically shredded in the application site, and manually applied at 0.3 kg/m^2 (length: 3–10 cm; width: 2–4 cm; thickness: 1–2 cm; density: 500–550 kg/m^3). Wheat straw was manually distributed at a rate of 0.2 kg/m^2 (length: 5–25 cm; width: 0.25–1.0 cm; thickness: 0.1–0.7 cm; density: 80–100 kg/m^3). These application rates were adopted according to literature data (e.g., Girona-García et al. 2021; Kim et al. 2008), and can be considered as "low to medium rates" in the common range between 80 and 1200 g/m^2 (Girona-García et al. 2021).

The soil slope, between 23.6% and 57.4% (Table 1), was split into two classes, namely steep hillslopes (slope > 38%) and gentle hillslopes (slope < 32%), to have the same number of plots for each class and a balanced statistical design between the burned sites. The soil texture was from sandy loam to clay loam.

Therefore, the experimental design consisted of three "soil conditions" and two "soil slope" classes. The soil conditions were (i) burned and untreated soil, that is, burned but without

TABLE 1 | Main soil characteristics of plots to measure soil loss under three soil conditions after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain).

Soil condition	Plot	Slope (%)[a]	Slope Class
B + NA	1	45.2	Steep
	2	44.5	
	3	40.7	
	4	39.6	
	5	30.4	Gentle
	6	29.6	
	7	29.1	
	8	28.8	
B + M(WC)	1	43.5	Steep
	2	39.4	
	3	44.1	
	4	45.3	
	5	28.6	Gentle
	6	27.5	
	7	29.2	
	8	23.6	
B + M(WS)	1	44	Steep
	2	40.1	
	3	48.7	
	4	57.4	
	5	28.9	Gentle
	6	28.5	
	7	29.7	
	8	27.4	

Note: B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw.
[a]Measured by a clinometer.

the application of any postfire management actions, hereafter indicated as "B + NA"; (ii) soil burned and then mulched with straw, "B + M(WS)"; and (iii) soil burned and mulched with wood chips, "B + M(WC)." The soil slope classes were "steep" and "gentle" slopes.

2.3 | Rainfall Characterization

During the monitoring campaign (October 2021–November 2023), rainfall (15-min time step) was continuously measured by a rain gauge at the meteorological station of Liétor. According to Wischmeier and Smith (1958), two consecutive events were considered separate in the rainfall series, if no rainfall was recorded for 6 h or more; a rainfall event was considered potentially erosive when its depth was over 13 mm. The occurrence of an individual event was detected by telemetry. Of the recorded rainfalls, only eight events produced soil loss in the plots.

From the recorded rainfall depths, the maximum intensity in 30 min (I_{30}), and the kinetic energy (EI_{30}) were calculated throughout the whole observation period. According to Wischmeier and Smith (1978), the latter parameter was estimated as the product of the kinetic energy, E, and I_{30} (Table 2).

2.4 | Soil Loss Measurements

Each plot (8 m × 3 m, each covering 24 m^2) was equipped to collect the eroded sediments. In more detail, sediment traps were installed at the bottom of the plot, and soil losses were measured during the monitoring period after the individual rainfall events. The accumulated sediment at each sediment trap was collected after the rainfall and transported to the laboratory, where the volume was oven-dried (24 h at 105°C) and weighed (Table 2). A texture analysis was carried out on the 2-mm sieved sediments according to the method of Guitian Ojea and Carballas (1976) to determine the three particle fractions (sand, silt, and clay).

2.5 | Ground Cover Measurements

The cover of vegetation, rock, mulch, dead wood, ash, and bare soil in percent over the total surveyed area was measured on July 1, 2023 and November 30, 2023 (about 23 and 27 months after the fire). The measurements were carried out in a middle horizontal strip (3 m × 3 m) of each plot. The grid method was applied (Vogel and Masters 2001) to measure the vegetation cover, using 0.50 × 0.50-m grid squares on the subplot. The photographic method, applied to the grid square, was used to measure the remaining variables.

2.6 | Statistical Analysis

First, a two-way analysis of variance (ANOVA) with interactions was applied to evaluate whether the soil condition—three levels: B + NA, B + M(WC), and B + M(WS)—and slope class—two levels: steep and gentle soils—considered as independent variables or explanatory factors, play a significant role in the total soil loss (dependent or response variable) measured throughout the whole monitoring period.

Then, a one-way ANOVA with repeated measures was applied to the soil loss (response variable) after each erosive event, and separately at each soil slope class (steep and gentle) to evaluate the statistical significance of the differences among the three soil conditions (explanatory factor). A one-way ANOVA was also used to evaluate the presence of statistical differences in the ground covers (response variables) among the soil conditions (explanatory factors) at two dates, July 1, 2023 and November 30, 2023.

TABLE 2 | Rainfall data and resulting soil loss (mean ± standard deviation, $n=8$ per soil condition) measured throughout a 2.5-year monitoring period under three soil conditions (B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw) after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain).

		Event rainfall							
Rainfall data	Date	May 7, 2022	July 2, 2022	October 12, 2022	January 28, 2023	April 4, 2023	June 6, 2023	July 7, 2023	November 30, 2023
	Depth	302.00	1.80	70.40	40.50	7.90	115.80	78.00	68.40
	Max I_{30}	16.40	2.20	14.60	8.60	2.80	14.80	31.00	13.71
	EI_{30}	17.49	0.23	27.57	5.43	0.76	18.76	68.47	9.26
		Soil loss (mean ± standard deviation)							
Soil condition	B + NA	1.08 ± 0.15	0.11 ± 0.02	0.45 ± 0.07	0.09 ± 0.01	0.27 ± 0.05	0.07 ± 0.01	0.63 ± 0.19	0.20 ± 0.10
	B + M(WC)	0.92 ± 0.18	0.09 ± 0.02	0.38 ± 0.07	0.11 ± 0.04	0.21 ± 0.03	0.13 ± 0.03	0.23 ± 0.06	0.07 ± 0.04
	B + M(WS)	0.77 ± 0.16	0.08 ± 0.02	0.35 ± 0.04	0.12 ± 0.03	0.27 ± 0.06	0.09 ± 0.02	0.36 ± 0.10	0.08 ± 0.04

In all cases, the equality of variance (by F test) and normal distribution (by Shapiro–Wilk test) underpinning ANOVA were evaluated, and, if needed to meet these assumptions, the data were square root-transformed. One-way ANOVAs with repeated measures also met Mauchly's test, and therefore the assumption of data sphericity was not violated. The differences in soil loss or ground covers among the ANOVA factors were evaluated using the pairwise comparison by Tukey's test ($p < 0.05$).

Finally, a correlation analysis between the total soil loss (dependent variable), and soil particle fractions and ground covers (independent variables, the latter measured at two survey dates) was carried out by calculating Pearson's coefficients (r).

The statistical analysis was carried out using the XLSTAT software (release 2019, Addinsoft, Paris, France).

3 | Results

3.1 | Influence of Treatment and Slope on Total Soil Loss

According to the two-way ANOVA, the soil condition ($F=4.42$, $p<0.03$) and its interaction with slope ($F=3.49$, $p<0.05$) had a significant effect on the total soil loss. In contrast, the soil slope alone was not significant in explaining the differences in soil loss ($F=3.60$, $p=0.07$) (Table 3).

In more detail, the cumulated soil loss measured throughout the observation period was statistically similar for the gentle slopes, ranging from 2.03 ± 0.31 tons/ha for B + M(WC) plots to 2.23 ± 0.13 tons/ha for B + NA plots. In contrast, for the steep slopes, the B + NA showed significantly higher erosion (3.59 ± 2.49 tons/ha) compared with the soil loss produced by the B + M(WS) plots (2.05 ± 0.59 tons/ha), but not by the B + M(WC) sites (2.24 ± 0.16 tons/ha) (Figure 2).

3.2 | Effects of Mulching on Soil Loss at the Event Scale

The one-way ANOVA with repeated measures revealed that throughout the 2.5-year observation period, soil loss was never significantly different among the three soil conditions on gentle hillslopes. On steep slopes, significant differences were found after the events recorded on May 7, 2022 (rainfall of 302 mm with an intensity of 16.4 mm/h) and July 7, 2023 (78 mm and 31 mm/h). For this slope class, the maximum soil loss was measured on May 7, 2022 in B + NA plots (1.23 ± 0.12 tons/ha), and this value was significantly higher compared with the erosion measured in B + M(WS) plots (0.85 ± 0.24 tons/ha), but not in B + M(WC) areas (1.04 ± 0.14 tons/ha). For the events recorded on July 7, 2023, the soil loss in B + NA soils (1.03 ± 0.19 tons/ha) was significantly higher compared with the erosion measured in burned and mulched soils—0.21 ± 0.01, B + M(WC) plots, and 0.27 ± 0.05 tons/ha, B + M(WS) plots—the latter soil losses being statistically similar (Figure 3).

TABLE 3 | Results of two-way ANOVA applied to observations of total soil loss measured under three soil conditions after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain).

Factor	Degrees of freedom	Sum of squares	Mean squares	*F*	Pr > *F*
Soil condition	2	3.13	1.56	4.42	**0.03**
Slope class	1	1.27	1.27	3.60	0.07
Soil condition × slope class	2	2.47	1.23	3.49	**0.05**

Note: Bold indicate significant values $p < 0.05$.

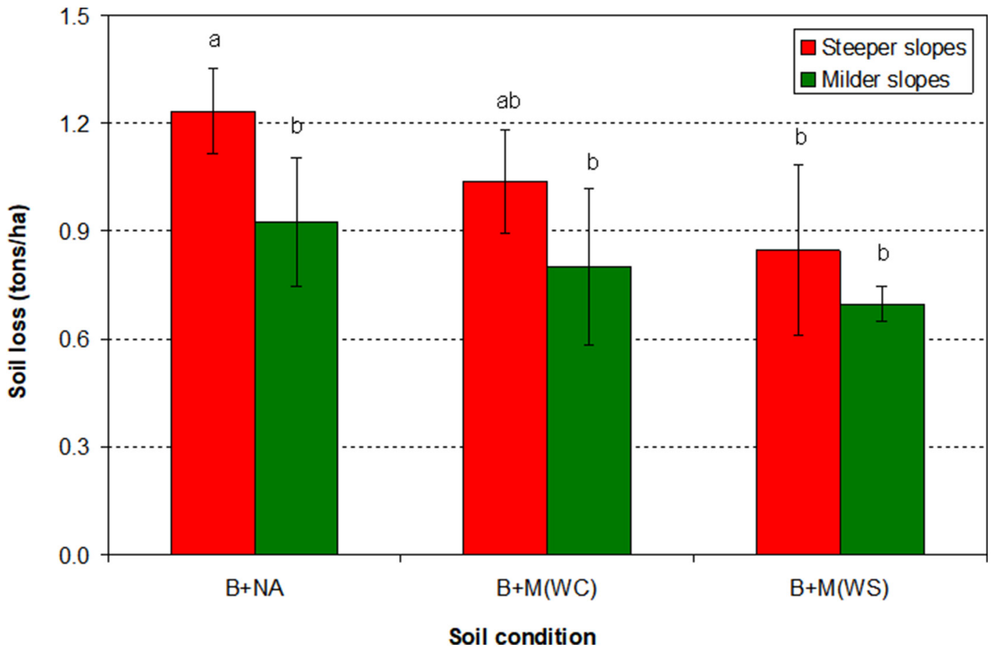

FIGURE 2 | Total soil loss (mean ± standard deviation) measured throughout a 2.5-year monitoring period under three soil conditions (B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw) and two slope classes after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain). [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Correlations Between Soil Loss, and Rainfall and Soil Characteristics Under the Three Soil Conditions

Regardless of the slope (gentle and steep), the soil loss was significantly and positively correlated with the rainfall depth under all soil conditions ($r > 0.47$, $p < 0.05$). Lower but again significant coefficients of correlation were found between the soil loss and maximum kinetic energy of rainfall ($r > 0.47$, $p < 0.05$), but only for B + NA soils. In contrast, the correlations "soil loss versus max I_{30}" were always poor and nonsignificant for all soil conditions ($r < 0.40$, $p > 0.05$) (Table 4).

Generally, soil erosion decreased in soils with increasing sand content ($|r| > 0.52$, $p < 0.05$), especially when treated ($r > -0.89$, $p < 0.05$). In contrast, the correlations between the silt ($r > 0.59$, $p < 0.05$) and clay ($r > 0.61$, $p < 0.05$, except for B + NA plots, in this case being nonsignificant at $p > 0.05$) fractions, on one hand, and the total soil loss, on the other hand, were positive (Table 4).

The one-way ANOVA applied to ground covers reveals that the dead wood—4.68 ± 1.09%, B + M(WC) plots on November 30, 2023, to 9.79 ± 1.93%, B + NA on July 7, 2023—and rock—9.28 ± 1.47%, B + M(WC) plots on November 30, 2023, to 15.3 ± 1.74%, B + M(WS) on July 7, 2023—covers were not statistically different. In contrast, the bare soil in B + NA sites (43.8 ± 4.68% on November 30, 2023 and 63.8 ± 3.22% on July 7, 2023) was significantly larger compared with the mulched plots, from 11.5 ± 1.41%, B + M(WS) on November 30, 2023, to 24.7 ± 3.91%, B + M(WC) on July 7, 2023. The vegetation cover was higher on November 30, 2023 (33%–36%) compared with July 7 (15%–16%) and not statistically different among the three soil conditions. The covers of mulch were 44.4 ± 4.15% (July 7, 2023) and 35 ± 1.61% (November 30, 2023) for wood chips, and 42.4 ± 2.21% (July 7, 2023) and 36 ± 2.9% (November 30, 2023) for wheat straw. It is worth mentioning the absence of ash on both survey dates (Figure 4).

The correlation analysis shows that the soil loss measured on the occasion of both events is significantly correlated with the bare soil ($r > 0.39$, $p < 0.05$) in B + NA plots recorded under all soil conditions. In contrast, the correlation between erosion and bare soil was low and nonsignificant in the mulched sites ($r < 0.18$, $p > 0.05$), except for the event recorded in the B + M(WC) plots on July 7, 2023 ($r = 0.76$, $p < 0.05$). The r coefficient between soil loss and vegetation cover was significant (nevertheless not high) only in B + NA sites ($|r| > 0.46$, $r < 0.05$), while no correlations were found between soil loss and mulch cover for the treated soils ($|r| < 0.30$, $p > 0.05$) (Table 5).

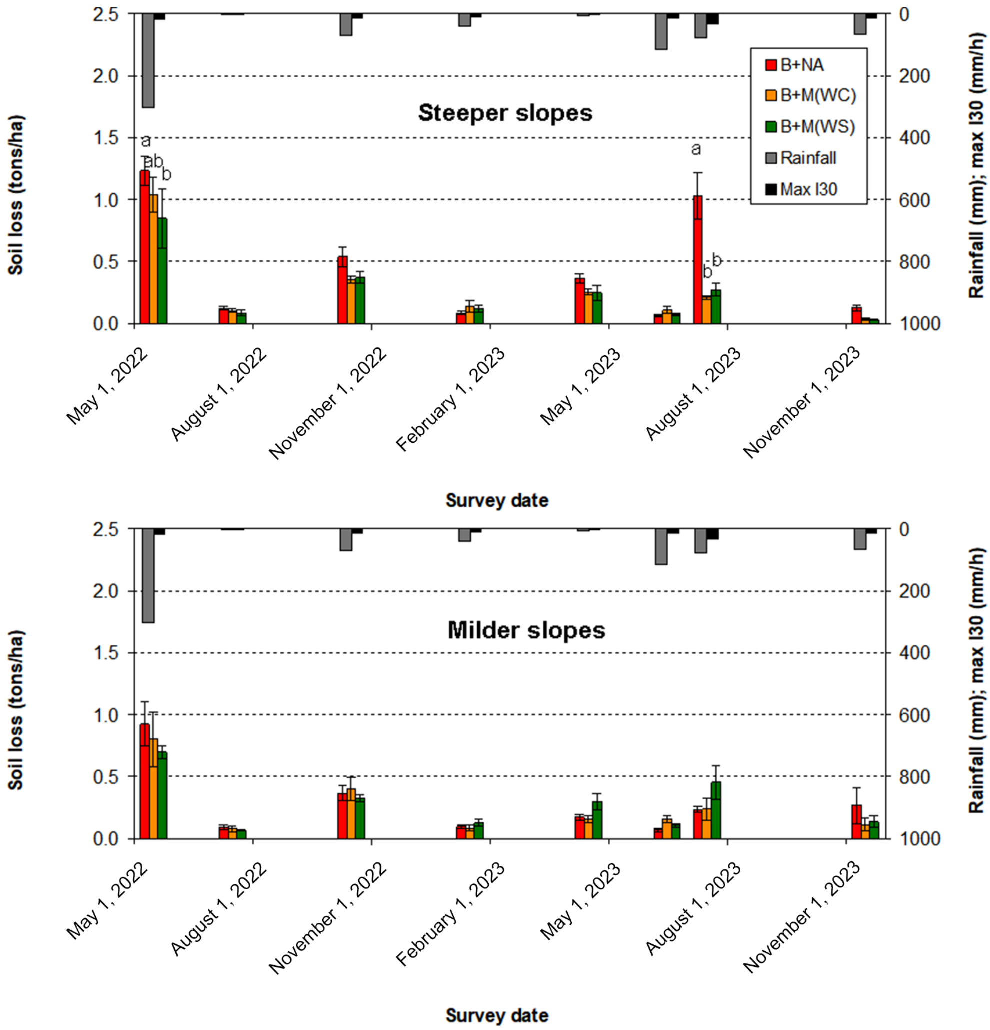

FIGURE 3 | Soil loss (mean ± standard deviation) and rainfall characteristics measured in eight surveys under three soil conditions (B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw) and two slope classes after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain). The differences in soil loss between pairs of soil conditions at each date were never significant after Tukey's test ($p < 0.05$), except when different letters were reported. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 | Pearson's correlation coefficients (r) between the soil loss and rainfall characteristics measured in eight surveysunder three soil conditions (B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw) after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain).

Soil condition	Correlation soil loss vs. rainfall characteristics					
	Steeper slopes			*Milder slopes*		
	Rainfall	Max I_{30}	EI_{30}	Rainfall	Max I_{30}	EI_{30}
B+NA	**0.47**	0.40	**0.47**	**0.78**	0.08	**0.78**
B+M(WC)	**0.75**	0.03	0.01	**0.80**	0.11	0.05
B+M(WS)	**0.67**	0.07	0.04	**0.57**	0.26	0.21

Note: The bar length is proportional to r value; significant values are highlighted in bold.

4 | Discussion

The investigation has shown that the soil condition and its interaction with the slope class play a significant role in the postfire variability of soil erosion rates. This led to carrying out a separate analysis of the effects of wildfire and soil treatments on the postfire erosive response for each slope class.

For both slopes, the study highlighted that the soil loss was significantly different among the three soil conditions for rainfalls with a 30-min maximum intensity of over 15–30 mm/h. This result indicates that postfire mulching shows effectiveness against soil erosion only for rainfall events over a certain threshold. As widely reported in the literature (e.g., Kinnell 2003, 2023; Wischmeier and Smith 1958), the max I_{30} can be therefore

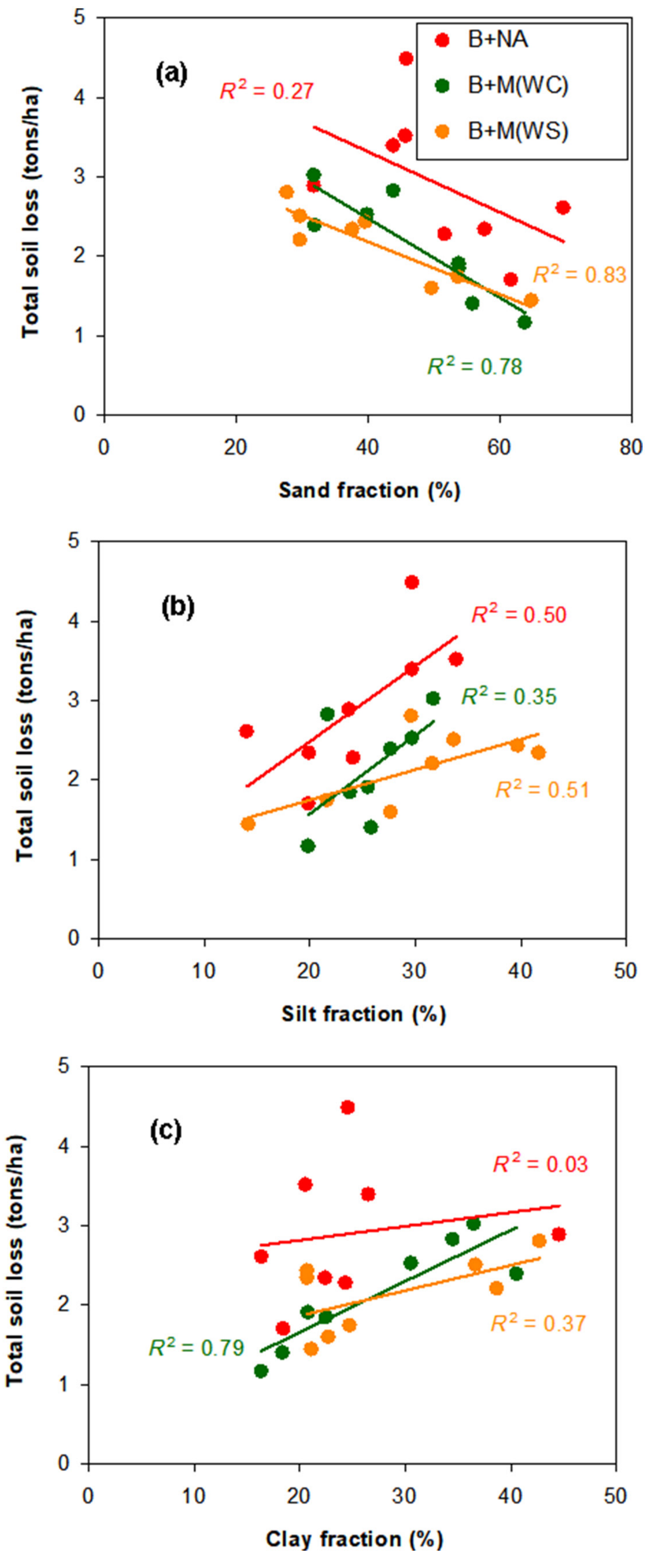

FIGURE 4 | Linear correlations between total soil loss and slope and particle fractions measured in 24 plots under three soil conditions (B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw) after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain). [Colour figure can be viewed at wileyonlinelibrary.com]

assumed as a meaningful indicator of the rainfall erosivity threshold, in order to identify a significant disturbance factor for soil hydrology (in our case fire or mulching). However, this is not true for rainfalls with a lower maximum intensity (as in the experimental conditions).

The correlation analysis shows that the soil loss was statistically influenced only by the rainfall depth for all soil conditions. This result is quite surprising, since the literature reports that erosion is more triggered by the intensity and kinetic energy of rainfall than by its amount (e.g., Fornis, Vermeulen, and Nieuwenhuis 2005; Van Dijk, Bruijnzeel, and Rosewell 2002). This may be explained by the fact that the rainfall erosivity measured throughout the observation period is quite low, and the soil loss collected at the experimental plots results from several peaks of the same rainfall event rather than a short precipitation with a high and constant peak. Under more intense rainfalls, erosion increases, and few events may produce soil loss that may be close or even higher to 10–12 tons/ha-year, which is a tolerable erosion for agricultural areas (Bazzoffi 2009; Wischmeier and Smith 1978), generally showing higher erosion compared with forests. Garcia-Diaz et al. (2022) demonstrated that, after the simulation of heavy rainfall, the peak soil loss may be up to 4 tons/ha in the burned sites with a high slope (over 40%). According to these authors, the Mediterranean forests burned by severe wildfires require effective soil conservation measures, and mulching theoretically may be able to noticeably reduce the postfire erosion rates, especially on steep soils, where the highest soil loss is expected.

In this study, the analysis of erosion rates on the gentle slopes shows that, compared with the untreated areas, the treatments produced a nonsignificant reduction in postfire soil loss (on average by only 9%–10% for mulching with wood chips) and even the same erosion (in the case of straw distribution). This presumably depends on the fact that the efficiency of the treatments got diluted into very low erosion rates, thus leading to nonsignificant differences in many cases. Moreover, in none of the monitored events, the application of the two mulches significantly reduced erosion in burned sites. On the occasion of the soil loss measurement after the first and highest rainfall (depth of about 300 mm, more or less one-third of the annual mean precipitation in the area), both wood chips and wheat straw reduced the soil loss by 13% and 25%, respectively, and in both cases never significantly compared with the absence of treatments. Even, for some events (e.g., January 28 and June 6, 2023), higher soil erosion was detected for both mulches (over 120% in the case of application of wood chips, and 28% after distribution of straw) compared with the untreated soils. It is worth noting that the erosion rates measured at these dates were very low and among the lowest across all surveys, which may justify the anti-erosive ineffectiveness of the soil treatments. These results agree with other studies, showing the low effectiveness of mulching in reducing soil erosion under low to moderate precipitations (Fernández-Fernández et al. 2016) as well as a nonsignificant increase in vegetation cover (Fernández et al. 2012).

In contrast to what was observed for gentle profiles, on the steep slopes, the effectiveness of soil mulching was significant for the two most intense rainfall events (May 7, 2022 and July 7, 2023, rainfall depths of 302 and 78 mm, and max I_{30} of 16.4 and

TABLE 5 | Pearson's correlation coefficients (*r*) between the soil loss and the main ground covers measured at two survey dates under three soil conditions (B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw) after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain).

Survey date	Soil condition	Correlation soil loss vs. ground covers			
		Bare soil	*Vegetation*	*Wood chips*	*Wheat straw*
7 July 2023	B+NA	**0.62**	**-0.61**	-	-
	B+M(WC)	**0.76**	0.28	-0.15	-
	B+M(WS)	0.18	0.06	-	0.05
30 November 2023	B+NA	0.39	-0.46	-	-
	B+M(WC)	0.11	0.02	0.30	-
	B+M(WS)	0.00	0.23	-	0.26

Note: Red and green colors indicate negative and positive values, respectively; the bar length is proportional to *r* value; the significant values are highlighted in bold.

31 mm/h, respectively) and, more in general, for the cumulated soil loss (but only in the case of application of wheat straw). To be more precise, in comparison with the burned and untreated soils, both mulches significantly reduced the soil loss produced by the second event (by about 70%–80%), while only the mulching with wheat straw produced an appreciable and significant reduction in soil loss after the first event (−70% of soil loss). In contrast, only wheat straw was effective at reducing the total erosion (−31%), the overall anti-erosive effect of wood chips being lower (16%) and not significant. The soil loss measured after the two treatments was comparable under the remaining rainfall events, but, also on steep slopes, some cases of mulching ineffectiveness were recorded after the events with the lowest erosivity (January 28 and June 6, 2023), when the erosion in treated sites was even higher compared with the areas without any treatments.

However, the effectiveness of mulching with the two substrates, although being significant at least in the steep hillslopes, should be considered quite limited, given the low rainfall erodibility throughout the monitoring period. In other words, compared with the untreated areas (where annual erosion, approx. 1.43 tons/ha year, was about one-third of the tolerable amount), the postfire management avoided mobilization of only 0.53 (in the case of wood chips) to 0.61 (for straw mulching) tons/ha year on the steep hillslopes and much less (0.8–0.9 tons/ha year) on gentle profiles.

The beneficial effects of mulching on soil hydrology are well known (Fernández and Vega 2014; Prats et al. 2014; Prosdocimi, Tarolli, and Cerdà 2016). The ground cover provided by mulch reduces the kinetic energy of rainfall, resulting in a limited displacement of soil particles due to rain splash (Ran et al. 2012; Te Chow 2010) and an obstacle to overland flow with a consequent decrease in water velocity (Lucas-Borja, Parhizkar, and Zema 2021; Robichaud, Jordan, et al. 2013; Robichaud, Lewis, et al. 2013; Robichaud, Wagenbrenner, et al. 2013). However, the effectiveness of mulching to reduce the cumulated soil loss measured in this study is noticeably lower compared with the erosion reductions (~85%–90%) measured in eucalypt forests of Portugal treated with straw mulching by Keizer et al. (2018) and Prats et al. (2016) under different climate and rainfall regimes. Compared with these studies, the use of wood residues for mulching resulted in an even higher reduction in soil loss (up to 95%) again in Portugal (Lopes et al. 2020). The mean erosion measured after soil mulching in this study (0.15–0.2 tons/ha) is comparable with the soil loss reported by Fernández et al. (2012) (0.2 tons/ha, measured under simulated rainfalls), but more than half of the value reported by Fernández and Vega (2014) (0.5 tons/ha), both these studies being carried out under humid climates. Moreover, the higher reduction in soil loss on the steep hillslopes found in this study is in close agreement with the findings of the previous findings of Garcia-Diaz et al. (2022) under the same environmental conditions. These authors, after extremely high rainfalls simulated immediately after the wildfire, found noticeably lower erosion (approx.−70%), especially when wheat straw was applied as mulch (approx.−90%) compared with untreated sites. The comparison between the two studies, in spite of the limitations of this study associated with the much lower rainfall input, indirectly indicates that mulching is effective on both the mechanisms of soil erosion (rain splash erosion and overland erosion) on the steep slopes. In other words, Garcia-Diaz et al. (2022) measured only rain splash erosion using a portable rainfall simulator, while this study, working in plots with a length of 20 m, was able to quantify also the soil loss due to the overland flow, which shows a limited erosive power on gentle profiles due to the lower water velocity compared with the steep soils (Lucas-Borja et al. 2022). Again Garcia-Diaz et al. (2022) demonstrated that the reduction of water velocity in mulched soils is more pronounced on the gentler slopes.

On the steep hillslopes, the effects of mulching were durable. Even 2 years and a half after the wildfire, the mulches were able to reduce soil erosion (although not always significantly). This may be due to the noticeable residual cover of mulch on more than one-third of the plot area (although the vegetation cover was similar) at the end of the monitoring period. High surface runoff and soil erosion rates are usually associated with low vegetation cover (e.g., Cawson et al. 2012; Moody et al. 2013). In mulched soils, the soil surface directly exposed to erosion is lower by 50% compared with the bare soil of the untreated plots, where soil loss increases due to the absence of mulch protection against rain splash erosion and surface water stream. This result contrasts with the study by Carrà et al. (2022), who found limited effectiveness of mulching on the hydrological response in three forests of Southern Italy 1 year after the fire. However, these authors measured the erosion after a prescribed fire and on hillslopes with a gentler profile.

The correlation analysis indicates that, in this study, erosion decreases in soils with higher sand content, while finer soils may produce higher soil loss, and this presumably is due to selective detachment due to rain splash erosion and transport capacity of the overland flow according to the different sizes of soil particles (Asadi et al. 2011; Li et al. 2023; Sirjani, Mahmoodabadi, and Cerdà 2022). The influence of ground cover against soil erodibility is demonstrated by the significant correlation between soil loss and bare soil (i.e., the ground area not subjected to the anti-erosive effects of vegetation and mulch covers). This suggests that the anti-erosive action of soil treatments is due to the increase in soil mechanical protection, thanks to vegetation and residues applied, while the separate effects of mulches and living plants are less influential on decreasing soil erosion.

A limitation of this study is the low erosivity of the monitored rainfalls, which did not result in noticeable erosion. This limited hydrological input was not expected when this study was planned, since the rainfall pattern in this semi-arid area is usually characterized by a low number of events with high erosivity (which, in contrast, theoretically justifies the need for postfire treatment for soil conservation). A dataset of more intense or heavy events may have better shown the effectiveness of postfire mulching in forest soils under experimental conditions. This implies the practical usefulness of this soil conservation technique at least to control erosion after several events of low to moderate intensity and on the steep hillslopes. More work is needed to evaluate the anti-erosive effects of mulching with the two residues after very intense rainstorms immediately after a wildfire (when the highest erosion is expected, Prosser and Williams 1998; Shakesby 2011) and a timely treatment (since delayed operations may reduce the beneficial actions of mulches) (Lucas-Borja and Zema 2024). These are both research gaps, since many studies are carried out under simulated in some cases unrealistic precipitations, and postfire management and/or the installation of measuring devices in the field are often delayed after forest burning (Girona-García et al. 2021).

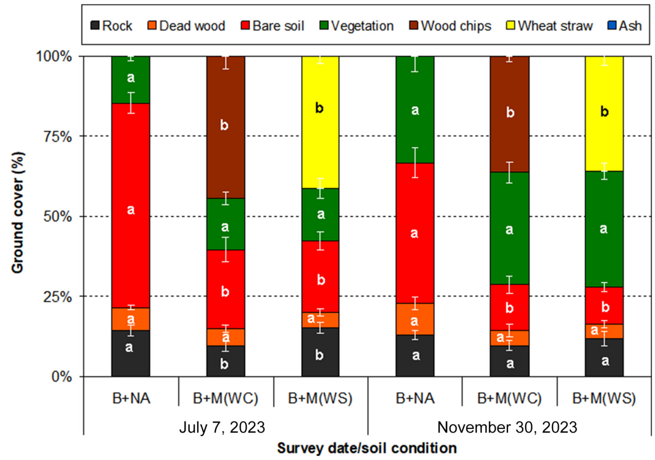

FIGURE 5 | Ground cover (mean ± standard deviation) measured in the experimental plots at two survey dates under three soil conditions (B + NA = burned soil without treatment; B + M(WC) = soil burned and mulched with wood chips; B + M(WS) = soil burned and mulched with wheat straw) after the wildfire of 2021 (Liétor, Castilla-La Mancha, Spain). Different letters indicate significant differences after Tukey's test ($p < 0.05$). [Colour figure can be viewed at wileyonlinelibrary.com]

5 | Conclusions

This study has measured soil erosion under three soil conditions (burned and untreated, and burned soils mulched using straw or wood chips) throughout a 2.5-year observation period under natural precipitation in a forest of Castilla-La Mancha (Central Eastern Spain).

In response to the first research question, the study has indicated that, under a low precipitation input, mulching generally results in a nonsignificant reduction in postfire soil loss on the gentle hillslopes compared with the untreated sites. In contrast, on the steep hillslopes, the effectiveness of soil mulching is significant for the two most intense rainfall events, and, more in general, for the cumulated soil loss. On this slope class, the anti-erosive effects of mulching have been durable, thanks to the appreciable residual mulch cover on the burned and treated areas. These results respond to the second research question, indicating that, compared with the burned and untreated sites, mulching can reduce postfire cumulated erosion (significantly with the application of wheat straw). In the experimental site, a maximum 30-min rainfall intensity over 15 mm/h is the threshold of soil treatment effectiveness on steep slopes. The correlation analysis has explained the variability of soil loss associated with soil texture and ground cover in untreated or mulched sites, which has inspired the last research question. The results of this analysis have shown that, in mulched sites, erosion significantly decreases in coarser soils, while soil erodibility increases with the content of finer fractions. The anti-erosive action of soil treatments is due to the increase in soil mechanical protection, thanks to living vegetation and mulch residues, as demonstrated by the significant correlation between soil loss and bare soil.

Overall, some useful indications for hydrologists and forest managers arise from this study: (i) mulching, regardless of the material applied to burned soils, is not cost-effective (or, better, its effectiveness is faded in the variability of postfire soil erosion) for low-intensity events, since the amount of soil retained on hillslopes is very low and erosion never exceeds the tolerable limits; (ii) when mulched is adopted as a postfire management measure in forests affected by severe wildfires, the more erodible soils (e.g., due to higher steepness, weaker structure, and finer texture) should be prioritized for conservation purposes. In these areas, mulching with straw or chips is more effective at stabilizing large amounts of soil and thus reducing the hydraulic and hydrogeological hazards (Figure 5).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be available upon request to the corresponding author.

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