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Delayed application of straw mulching increases soil erosion in Mediterranean pine forests burned by wildfires

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Abstract

Several studies have explored the effectiveness of straw mulching against soil erosion in wildfire-affected forests as post-fire management technique. In contrast, scarce literature exists about the application time of the mulch cover, although this factor - beside climate patterns of the application site - is essential to increase mulching effectiveness. To fill this gap, this study has evaluated the soil loss in two forest sites of Castilla La Mancha (Spain), in which straw mulching was applied in two burned forests immediately after the wildfire or four months after the fire event. These sites show similar characteristics (soil burn severity, soil type, and vegetation), and thus the difference in soil erosion can be attributed to the treatments. The mulching effectiveness has been measured as the difference between the soil loss per unit of erodibility comparing unburned and untreated, and burned and mulched plots. At a comparable rainfall erosivity (difference in EI_{30} between the two sites lower than 40%), soil loss decreased by 67% (in the case of timely distribution) and 33% (when the action is delayed) in mulched sites compared to the untreated areas. After a rainstorm with very high erosivity (+ 600% of EI_{30}), soil loss reduction was equal to 85% in the case of early mulching application. This higher effectiveness of early mulching compared to the delayed application was due to the quicker post-fire regrowth of vegetation, and the increased level of incorporation of vegetal residues into the soil. This result suggests to land managers that straw mulching should be applied immediately after a wildfire in burned forests, in order to achieve the highest anti-erosive effects. Further research is suggested to validate these results in other environments and after application of other mulches.

Keywords: post-fire management; soil loss; rainfall erosivity; soil erodibility; soil conservation.

1. Introduction

Soil mulching is the most common post-fire management strategy, in order to control the hydrological response of soil after wildfires (Lucas-Borja, 2021; Zema, 2021). Vegetal materials, such as straw and forest residues, are spread on the ground of the burned sites, in order to protect the soil from rainsplash erosion and increase the soil roughness (Prosdocimi et al., 2016). Several studies have shown the effectiveness of post-fire straw mulching at limiting the runoff and erosion rates in burned forests in several environments (e.g., Fernández and Vega, 2014; Girona-García et al., 2021; Robichaud et al., 2013). These authors have reported that straw mulching was generally successful in reducing erosion after a wildfire. In a period that may be variable from few months to several years depending on the fire severity (Shakesby, 2011), the soil is bare, due to vegetation burning, and many soil properties undergo severe changes, due to soil heating (Alcañiz et al., 2018; Certini, 2005). The mulch material acts as an artificial cover of soil, contrasting the particle detachment due to rainfall and overland flow. The effectiveness of mulching depends on several factors, and especially on climate and rainfall distribution of the area to be treated as well as on the application times (e.g., (Prosdocimi et al., 2016)). However, a rapid action to timely spread the mulch cover on ground after the wildfire is essential, in order to avoid the highest runoff and erosion rates in the so-called “window of disturbance” after fire (Prosser and Williams, 1998). However, if it is obvious that a delayed distribution of the mulch material may be ineffective against the first rainstorms after the fire, which result in the highest erosion rates, a late mulching operation may be more effective against the rainfalls occurring some months after the wildfire compared a timely distribution. While the literature has widely investigated why and to what extent soil erosion decreases in burned and mulched forest soils compared to untreated areas, less knowledge exists about the comparison of the effects of post-fire straw mulching in different times on soil erosion. Such information is essential for land managers, since the mulching treatments after a wildfire are often carried out too late (for difficulties in supplying mulch materials or unexpected and too vast wildfires) with consequent increase in the hydrogeological hazard due to off-site fire effects.

To fill this gap, this study has evaluated the soil loss in two forest sites of Castilla La Mancha (Spain) with similar characteristics (soil burn severity, soil type, and vegetation), in which straw mulching was carried out immediately after the wildfire or after four months. Previously, we checked that the soils in the two forest sites can undergo to high erosion rates under simulated rainfalls. The main objective of this investigation is to demonstrate that an application of the mulch material immediately after the fire may be more beneficial against soil erosion determined by rainfall events with normal or extreme erosivity compared to a delayed soil mulching.

2. Materials and methods

2.1. Study area

The study area is the forest landscape of Castilla La Mancha, Central Eastern Spain. The climate type is "BSk" according to the Köppen classification (Kottek et al., 2006). The mean annual temperature and precipitation are 16.6 °C and 321 mm, respectively (weather station of Hellín). In this area, two forest sites were identified (Agramón and Liétor, Figure 1, about 11 and 19 km far from Hellín, respectively), of which the main characteristics are reported in Table 1. The sites are at the same altitude (520 to 770 m a.s.l.), but differ for aspect (south-west in Agramón and north-west in Liétor) and soil texture (silty loamy in Agramón and sandy loamy in Liétor, according to the USDA classification). The soil type is the same (*Calcic Aridisols,* Nachtergaele, 2001).

In both forests, the dominant overstory vegetation consists of Aleppo pine (*Pinus halepensis* Mill.) (Peinado et al., 2008). Before the wildfire, the stand density and tree height were in the range 500 - 650 trees/ha and 7 - 14 m, respectively. The understory vegetation includes *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Thymus vulgaris* L., and *Helichrysum stoechas* L.

In July 2020 (Agramón) and July 2021 (Liétor), two wildfires burned large areas in the two forests. The soil burn severity, estimated using the methodology proposed by Vega et al. (2013), was high in both sites with a crown tree mortality of 100%. In order to limit the expected increases in surface runoff and erosion after wildfires, the Forest Service of the Castilla La Mancha Region, applied mulching as post-fire management strategy in both the burned forests. Wheat straw was manually spread on the ground at a dose of 0.3 kg/m^2 of dry matter and a thickness of 3 cm (Lucas-Borja et al., 2018; Lucas-Borja et al., 2020). These values are widely used in literature, to achieve a soil cover of 80% for burned plots (e.g., Girona-García et al., 2021; Kim et al., 2008; Lucas-Borja et al., 2019). The mulching operations were carried out immediately after the fire (July 2020) in Agramón, and four months later (November 2021) in Liétor. The latter application was delayed for economic reasons (no availability of sufficient man workers and money immediately after the wildfire).

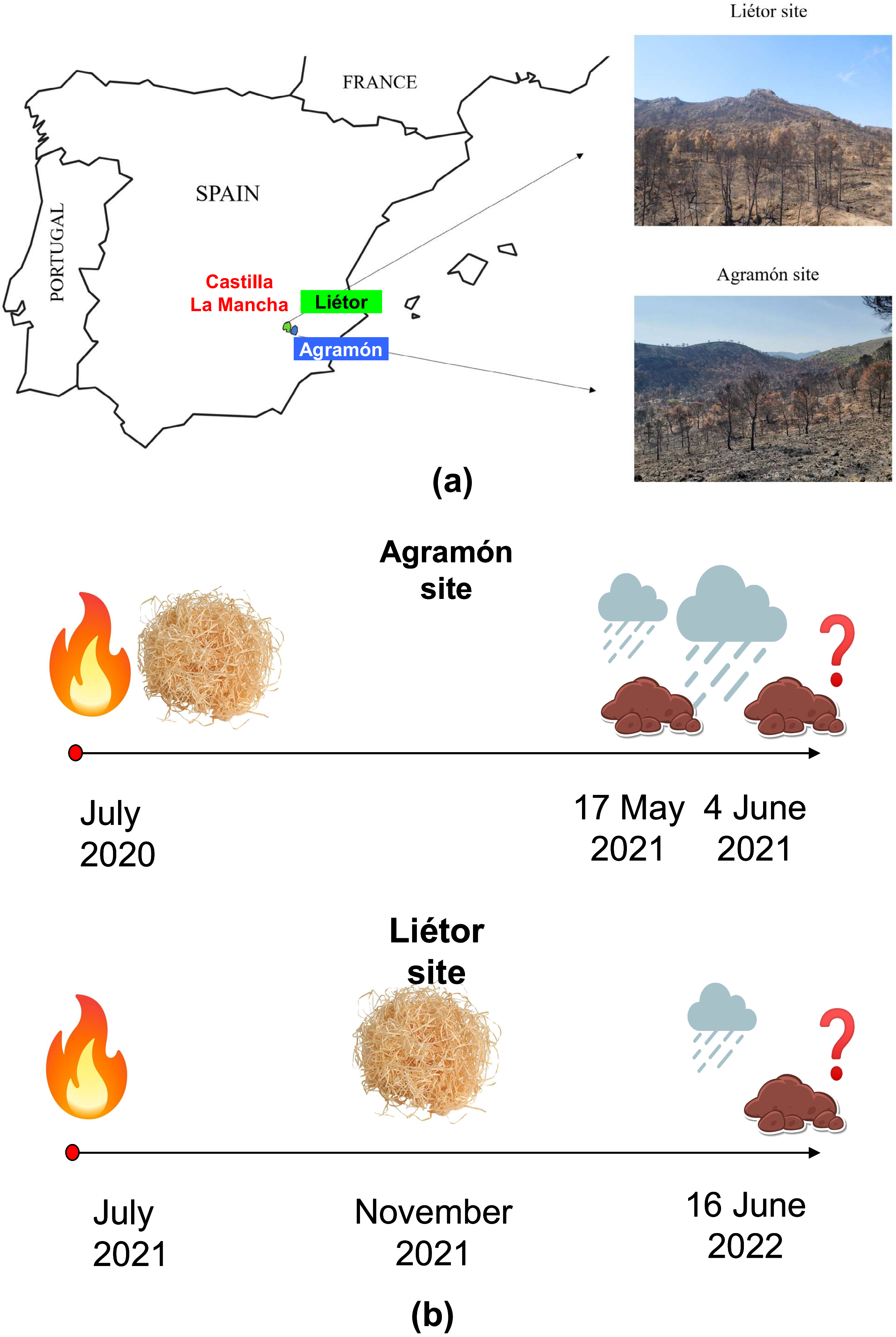
Liétor site
FRANCE
SPAIN
PORTUGAL
Castilla La Mancha
Liétor
Agramón
Agramón site
(a)
Agramón site
July 2020
17 May 2021
4 June 2021
Liétor site
July 2021
November 2021
16 June 2022
(b)

Figure 1 – Geographical location of the study sites (Agramón and Liétor, Castilla La Mancha, Spain) (a), and experimental design (b).

Table 1 – Mean characteristics of the study sites immediately after the wildfire (Agramón and Liétor, Castilla La Mancha, Spain).

		Site			
		Agramón		*Liétor*	
Geographical coordinates		38°25’19”N	-1°38’15”E	38º30’41”N	-1º56’35”E
Altitude (m a.s.l.)		520-770			
Aspect		south-west		north-west	
Soil characteristics	**slope (%)**	29-36		29-31	
	type	Calcic Aridisols			
	texture	silty loamy		sandy loamy	
	condition	burned	mulched	burned	mulched
	sand content (%)	31.7	30.2	53.6	52.3
	silt content (%)	55.5	51.2	29.9	29.2
	clay content (%)	12.8	18.5	16.6	18.5
	organic matter (%)	2.13	2.35	4.31	3.60
	vegetation cover (%)	28.6	24.3	31.4	21.1
	rock cover (%)	50	51	47	41

2.2. *Experimental design*

Two experimental sites were selected in each forest under two different soil conditions (burned and untreated soil, and burned and mulched soil). Immediately after the fire, in these sites, rainfall simulations were carried out (see section 2.3.2), and sixteen experimental plots (eight for each site, and four for each soil condition) were installed to measure soil loss under natural rainfall events (see section 2.3.3). The experimental design consisted of two soil conditions (burned and not treated as well as burned and mulched soils) × four replicated rainfall simulations or plots.

2.3. ***Erosion measurements***

2.3.1. Estimation of soil erodibility

Although the soil type was similar between the two experimental sites, the different texture may result in different soil erodibility. To estimate this soil parameter, the K-factor of the well-known Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) was considered, based on the main physico-chemical properties of the soils (Table 1). According to these authors, *K* is given by the following equation:

$$K = [(2.1 \text{ x } 10^{-4} M^{1.14} (12 – OM) + 3.25 (s - 2) + 2.5 (p - 3)] \text{ x } 10^{-2} \text{ x } 0.1317 \qquad (1)$$

where the textural factor *M* is equal to $(c_{silt} + c_{vfs}) \text{ x } (100 - c_{clay})$, being c_{silt}, c_{vfs} and c_{clay} the textural percent fraction contents (very fine sand, silt and clay), *OM* is the percent organic matter content, *s* is the soil structure class (3, medium or coarse granular), and *p* is the permeability class (1, very rapid, in Agramón, and 2, rapid, in Liétor).

2.3.2. Simulated rainfall

The erodibility of the burned and untreated soils was checked in field conditions using rainfall simulations. For each soil condition, rainfall was simulated in small areas randomly chosen. An Eijelkamp® rainfall simulator was used (Hlavčová et al., 2019; Iserloh et al., 2013), following the methods by Bombino et al. (2019) and Carrà et al. (2021). In detail, the simulator was placed over the ground on a surface area of 0.3 m x 0.3 m, caring that the mulch material applied to the soil was not disturbed by this operation. The height and intensity of the simulated rainfall was setup at 26.7 mm and 320 mm/h, while its duration was 300 s. The drop diameter and the falling height of the precipitation were 5.9 mm and 40 cm, respectively. The precipitation volume in the simulator tank (about 2200 ml) was dosed by varying the pressure head, as suggested in the operating manual. Before the field experiment, the simulator was calibrated in laboratory by generating the same rainfall. Four rainfall simulations were carried out in each site and soil condition. The rainfall rate applied in this study represents an extreme value reported in past literature (e.g., (Quinn and Laflen, 1983; Ma *et al.*, 2016). However, throughout Mediterranean Spain, extreme rainfall rates are being more frequently recorded (Camarasa-Belmonte et al., 2020). For instance, in Júcar (Cuenca, Castilla

La Mancha), rainfall rates have been observed to reach 1000 mm in 24 h (Llasat et al., 2021). Of course, this extreme rainfall rate is not consistent for 24 h, but it varies throughout the storm. According to a recent analysis of high temporal resolution (5-min) rainfall observations in the eastern Iberian Peninsula, rainfall rates may reach sustained intensities that exceed 35 mm in a 5-min period. Thus, we selected an extreme rainfall rate near this maximum that was achievable using an off-the-shelf rainfall simulator. This equates to an intensity with a historical return period of >100 years in the studied area, simulating an extremely heavy event, as representative of a worst-case scenario for the study area (Lucas-Borja et al., 2022).

Throughout the rainfall simulation, the runoff water and sediments were collected in a small bucket. The mixtures of water and sediments were finally transported to the laboratory in small bottles, and then oven dried at 104 °C for 24 h. The weight of the sediments was then referred to the area unit, to calculate the soil loss. The estimated soil loss gives information about the actual erodibility of each forest site under burned conditions.

2.3.3. Natural rainfall

After the wildfire, four plots per site and soil condition, each one being 8-m long and 3-m wide, for an area of 24 m^2, were equipped with as many sediment fences at their outlet (collecting runoff volumes up to 50 litres), to collect the soil loss after rainfall events. The distance between plots was always greater than 300 meters, in order to avoid pseudo-replication. The plots were selected on hillslopes with similar profile slope (between 20 and 25%) and aspect (north), to ensure comparability among the plots.

Soil loss was measured after all the erosive events occurred throughout one year after the wildfires in each site. The accumulated sediment at each sediment trap was removed after each rainfall event and weighted in the field.

2.4. Rainfall characterisation

The precipitation was measured in two rain gauge stations installed in the two sites. From the rainfall depths, recorded each 5 minutes, the rainfall depth, maximum intensity in 30 minutes (I_{30}), and erosivity (EI_{30}) were calculated. The latter parameter was estimated according to Wischmeier and Smith (1978) as the product of the kinetic energy, E, and I_{30}.

2.5. Comparison of erosion in the two forest sites under different rainfall erosivity

The soil loss for each soil condition (burned and untreated, and burned and mulched soils) was measured in the experimental plots after the rainfall event of 16 June 2022 in Liétor. This soil loss was compared to the corresponding values measured in Agramón after two events: (i) the rainfall recorded on 17 May 2021, having an erosivity over seven-fold the EI_{30} of the event measured in Liétor; and (ii) the rainfall of 4 June 2021, whose erosivity was only 37% higher compared to the EI_{30} of the Liétor event. These comparisons aim at quantifying the difference in soil loss between mulched and untreated soils under rainfalls of extremely different or comparable erosivity, which is assumed as effectiveness of the mulching treatment.

Before erosion comparisons, the different soil erodibility between the two sites and soil conditions were taken into account, calculating the soil loss per unit K-factor or, in other words, dividing the measured soil loss per the K-factor of each soil condition in the two sites. Thanks to this standardisation, the difference in soil texture and therefore in soil erodibility plays a minor role on the erosion estimations between the two sites.

2.6. Statistical analysis

A one-way ANOVA was applied to the soil loss measured after the rainfall simulations, in order to evaluate the statistical significance of the differences between the two sites. Then, the soil loss measured after the natural precipitations were statistically processed using again a one-way ANOVA with repeated measures, in order to identify possible differences between the two soil conditions in the two sites. Soil loss was the dependent variable, while the site (for the rainfall simulations) and the soil condition (for the natural rainfalls) were the independent factors. The differences in the soil loss were evaluated using the pairwise comparison by Tukey's test (at $p < 0.05$). The equality of variance and normal distribution are assumptions of the statistical tests; these assumptions were evaluated by normality tests or were square root-transformed, when necessary. Since Mauchly's test revealed that the hypothesis of data sphericity was violated, we applied the Greenhouse-Geisser's correction to the degrees of freedom.

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

3. Results

The erodibility of the burned and untreated soils, expressed by the USLE K-factor, was equal to 0.041 tons ha h/(ha MJ mm) in Agramón, and to 0.017 tons ha h/(ha MJ mm) in Liétor. The burned and mulched soils showed the same K factor in Liétor and a value of 0.034 tons ha h/(ha MJ mm) in Agramón. Therefore, the soil erodibility in Liétor was about 2.5-fold (in burned and untreated conditions) and 2-fold (in burned and mulched conditions) the value estimated in Agramón, and this difference was statistically significant.

Under rainfall simulations, the measured soil losses were equal to 0.29 ± 0.01 tons/ha in Agramón and to 0.90 ± 0.34 tons/ha in Liétor, and this difference was statistically significant ($p < 0.05$) with a ratio of 3.1, which is close to the K-factor estimation by equation (1). This difference derives from the slight changes in soil texture (silty loamy in Agramón, and sandy loamy in Liétor) as well as in the characteristics of soil surface (vegetation and rock cover, Table 1). Although not directly measured in the field, we suppose that the soils of Agramón had a higher infiltration capacity, due to the difference soil texture. This difference was checked using the Rawls' pedotransfer function (Saxton et al., 1986), which showed a soil hydraulic conductivity of 10.3 mm/h in Liétor and 16.2 mm/h in Agramón. This should indicate a lower generation capacity of surface runoff with reduced particle detachment due to the overland flow in Agramón. The sand particles are looser compared to the silt fraction, and therefore their displacement due to the raindrop kinetic energy is higher in Liétor compared to the finer soil in Agramón. This is directly confirmed by the higher soil loss measured by the rainfall simulator, which indicates significantly higher splash erosion in Liétor compared to Agramón.

During the monitoring campaign (June 2020-July 2021 in Agramón, and June 2021-July 2022 in Liétor), one rainfall event with the resulting soils loss was considered in Liétor, and two in Agramón. These events occurred in late spring in both sites (between May and June). The event of Liétor (16 June 2022) was characterised by a rainfall depth of 42.4 mm, a maximum I_{30} of 14.6 mm/h and an EI_{30} of 27.6 MJ mm/ha h. The first rainfall event recorded in Agramón (17 May 2021) had a depth of 5.30 mm (-87.5% compared to Liétor), a maximum I_{30} of 10.4 mm/h (-28.8%) and an EI_{30} of 37.8 MJ mm/ha h (+37.1%), therefore having hydrological characteristics that were similar as the event recorded in Liétor. In contrast, the second rainfall in Agramón (4 June 2021) showed a depth of 19.7 mm (-54% compared to Liétor), but a 7-fold erosivity (201 MJ mm/ha h), due to a maximum I_{30} that was higher by over 200% (Figure 2).

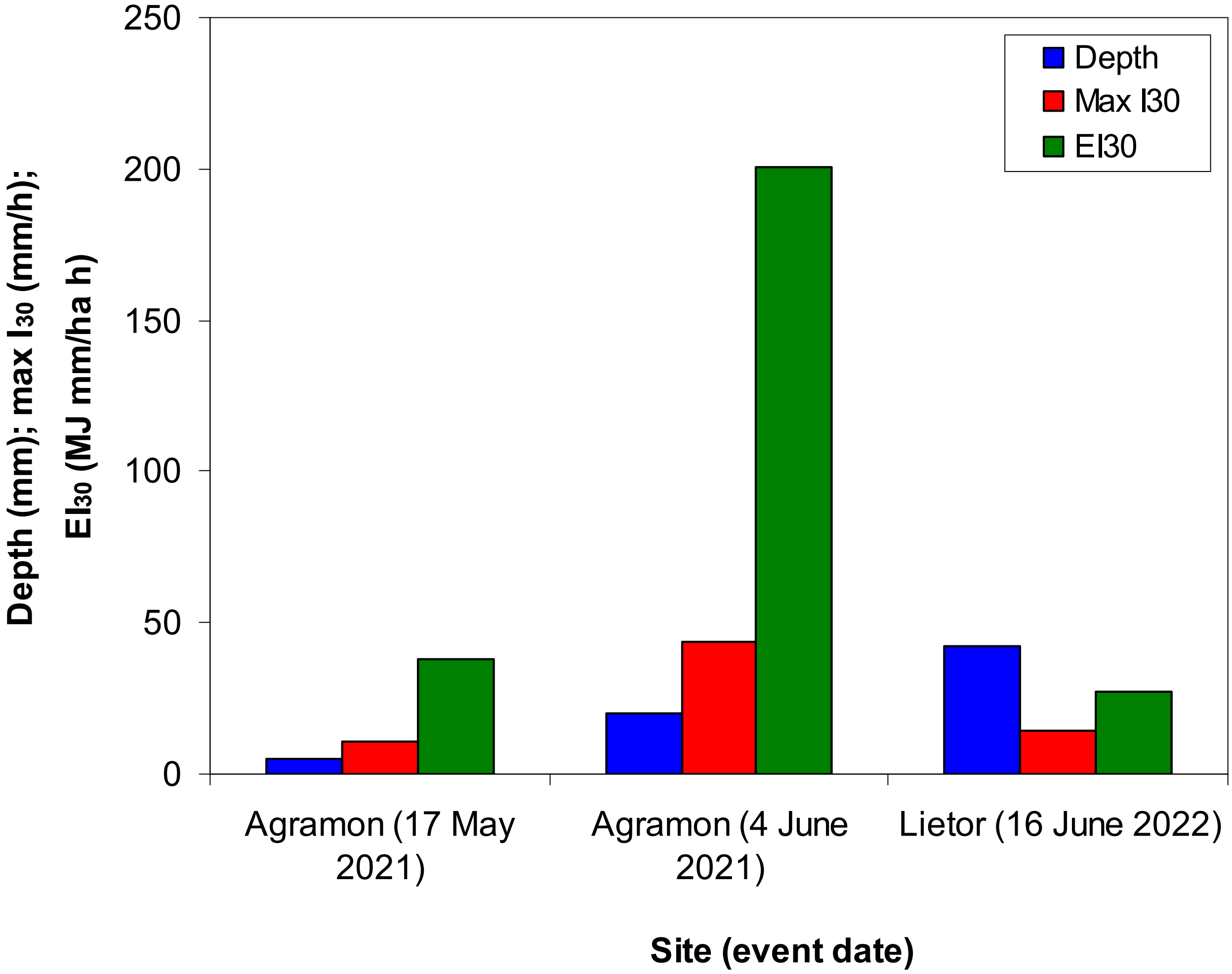

Figure 2 – Comparison of variables of natural rainfalls measured in the study sites (Agramón and Liétor, Castilla La Mancha, Spain).

The comparison of the soil loss measured in burned and untreated soils after the events with comparable erosivity (17 May 2021 in Agramón, and 16 June 2022 in Liétor) showed values of 64.4 ± 34.5 tons/ha per unit K in Agramón, and to 59.3 ± 16.3 tons/ha per unit K in Liétor with no statistical significance. In burned and mulched soils, the soil losses are equal to 21.2 ± 7.11 tons/ha per unit K in Agramón, and to 40 ± 3.96 tons/ha per unit K in Liétor, and also in this case the difference was not significant (Figure 3). This means that the mulching effectiveness is equal to 84.9% in the case of earlier straw application (as done in Agramón) and to 32.6% in the case of delayed mulching operations (as in Liétor). After a rainstorm with very high rainfall erosivity, as the event recorded in Agramón on 4 June 2021, the soil loss increased to 276 ± 153 tons/ha per unit K (a value that was significantly different compared to the other site and soil conditions, which gave a mulching effectiveness of 84.9%.

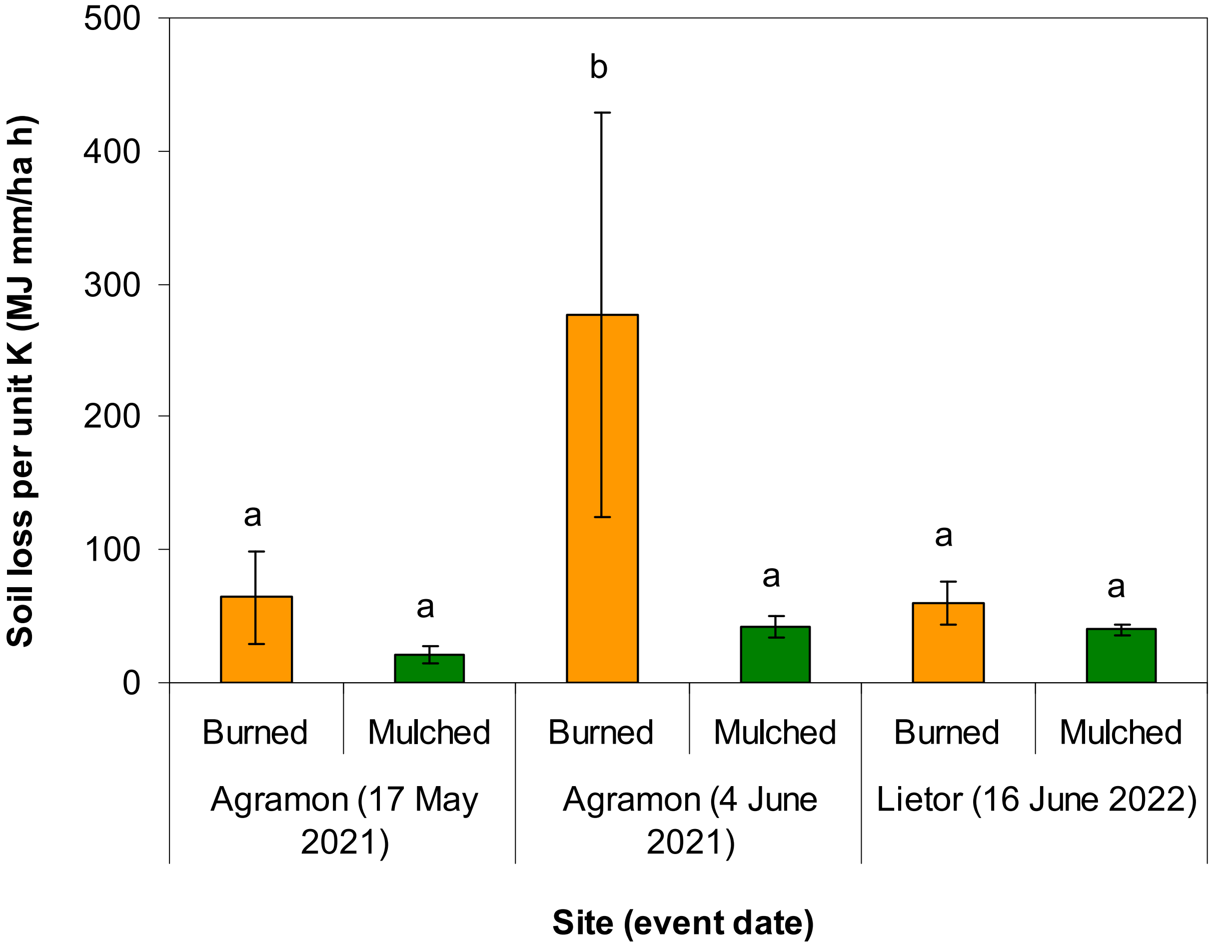

Figure 3 – Comparison of soil loss measured under natural rainfalls in the study sites (Agramón and Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences after Tukey's test ($p < 0.05$).

4. Discussion

In several environments and under different land uses, mulching has generally played many beneficial effects on hydrological properties of soil, such as the protection against rainsplash erosion, increased water storage, reduced velocity of overland flowy, improved aggregate stability, decreased evaporation (Lucas-Borja et al., 2018; Prosdocimi et al., 2016). This investigation has clearly shown that a delayed application of straw over burned plots may reduce the effectiveness of soil mulching by over 50% in the case of moderate rainfalls, and by over 60% after rainstorms with very high erosivity. This result is even more surprising, considering that, after long time from its application (as in Agramón), part of the mulch cover may have been displaced by wind, leaving part of the previously covered areas bare.

The rainfall simulations have shown that burned soil can be easily eroded at high rainfall intensity, and there are differences between mulched and untreated sites in burned areas. Since the soil has already been eroded, as happened in the site of Liétor, the mulching application has low effectiveness, except after very intense precipitations. This means that the rainfall erosivity is a discriminating factor, which suggests the need for mulching in burned forest soils prone to erosion. In contrast, if rainfall intensity is low, there is no effect of the treatments. High-intensity rainfall, however, are common in the Mediterranean forest areas (e.g., in Southern Italy, Fortugno et al., 2017; Northern Iran, Jourgholami et al., 2020; Eastern USA, Wilson et al., 2018).

The low effectiveness of the delayed mulching treatment may be explained by two main reasons: (i) the lower regrowth of vegetation (shown by the low plant cover at the time of erosion survey, which is only 21%) compared to early mulching (on average about 80% of the total plot area), and (ii) the reduced level of incorporation of vegetal residues into the soil.

In more detail, eleven (in Agramón) and seven (in Liétor) months after the soil treatment, the vegetation cover, measured by the photographic method, was much higher in the first site compared to the site subjected to the delayed mulching. The higher post-fire regeneration of vegetation in the site with earlier mulching was due to the straw supply in the dry season, where the low water content of soil is the factor that limits the growth of vegetation (Prats et al., 2016, 2012). In contrast, straw was distributed in Liétor at the start of the wet season, when the soil is wet and the beneficial effect of the mulch cover is much more limited. Moreover, the straw layer is presumably denser and thicker in spring, in occasion of the restart of the annual vegetation regrowth. This may have hampered the supply of heat and light from sun, thus resulting in a lower regeneration of the herbaceous and herbaceous vegetation (Mulumba and Lal, 2008; Prosdocimi et al., 2016).

Furthermore, the earlier mulching operations in Agramón may have favoured the incorporation of the vegetal material supplied with the straw into the soil. This should have resulted in the increase of the organic matter content of soil, and therefore in its aggregate stability, with consequent higher soil microporosity and water infiltration capacity (Hillel, 1998; Shakesby, 2011). This effect, which, however, requires direct measurements of soil hydraulic conductivity and organic matter content in the experimental conditions, was also detected by other authors (e.g., (Carrà et al., 2021b)), who found increased water infiltration and organic matter in mulched soil one year after prescribed burning in Mediterranean forests. Other literature experiences have shown a low effectiveness of straw mulching to reduce soil erosion, which the authors attributed to the moderate precipitations (Fernández-Fernández et al., 2016), non-significant increase in vegetation cover (Fernández et al., 2012) and low mulching rates, high soil burn severity and high precipitation rates (Fernández and Vega, 2016).

Several authors stated that soil texture play an important role on soil erosion (e.g., (Jourgholami and Labelle, 2020)). Undoubtedly, the slightly different soil texture made more erodible the site with delayed mulching, but the standardisation of the observed soil loss per unit K may have reduced this difference in soil erodibility between the two sites.

Since soil erosion may be underestimated in small plots (as those of this study), which mainly measure rainsplash and sheetwash erosion (Fernández and Vega, 2016), we suggest upscaling the related investigations on larger spatial scales, which take into account other important erosion forms, such as rill and gully erosion. Moreover, further validations of these results in sites treated with other mulches (e.g., mulching with wood chips or fresh residues) (Carrà et al., 2022; Díaz et al., 2022) or under other environmental and management conditions (e.g., in sites subjected to machinery or forest management (Jourgholami and Labelle, 2020) are welcome.

5. Conclusion

This study has demonstrated how early application of straw mulch in pine forestsburned by severe wildfires is more effective at reducing soil erosion compared to delayed mulching both under average or extreme precipitations, at least in the experimental conditions. The investigation has shown that an early mulching favours the vegetation regrowth in the dry season and may enhance the fast incorporation of the vegetal residues into the soils over time. These beneficial effects are essential to provide a protective cover of the burned soils against the erosivity of the rainstorms in Mediterranean forests, especially when the rainfall intensity is very high.

The differences in soil loss between soils mulched at different times proposed in this study can be considered as useful indicators of the erosion rates between burned and untreated, and burned and mulched soils. As such, forest managers should carry out soil mulching actions immediately after the wildfire, in order to achieve the highest anti-erosive effectiveness using this post-fire management strategy.

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