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Soil erosion modelling of burned and mulched soils following a Mediterranean forest wildfire

Erosion prediction by WEPP, MMF and USLE-M models in burned and mulched forests

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ABSTRACT

Soil erosion modelling applied to burned forests in different global regions can be unreliable due to a lack of verification data. Here, we evaluated the following three erosion models: (1) Water Erosion Prediction Project (WEPP), (2) Morgan-Morgan-Finney (MMF) and (3) Universal Soil Loss Equation-Modified (USLE-M). Using field plots that were either untreated or mulched with straw, this study involved observations of soil loss at the event scale at a burned pine forest in Central Eastern Spain. The erosion predictions of the three models were analysed for goodness-of-fit. Optimisation of the MMF model with a new procedure to estimate the C-factor resulted in a satisfactory erosion prediction capacity in burned plots with or without the mulching treatment. The WEPP model underestimated erosion in the unburned areas and largely overestimated the soil loss in burned areas. The accuracy of soil loss estimation by the USLE-M model was also poor. Calibration of the Curve Numbers and C-factors did not improve the USLE-M model estimation. Therefore, we conclude that an optimised MMF model was the most accurate way to estimate soil loss and recommend this approach for in Mediterranean burned forests with or without post-fire mulching. This study gives land managers insight about the choice of the most suitable model for erosion predictions in burned forests.

KEYWORDS: soil loss; post-fire management; calibration; erosion model; plot scale; event scale.

1. INTRODUCTION

Models are essential tools to simulate the complex processes in disturbed soils, and to predict the soil response to the hydrological input in a cost-effective and time-efficient way (Filianoti et al., 2020). Many models are capable of predicting soil erosion in different climatic and geomorphological conditions (Bezak et al., 2021; Borrelli et al., 2021). In comparison to the most complex physically-based algorithms, empirical models are easy and quick to apply at specific sites, and their prediction capability is often satisfactory (Aksoy & Kavvas, 2005; Lucas-Borja, Bombino, et al., 2020). Many empirical models, such as the USLE (Universal Soil Loss Equation) equation, have been used as erosion component of many catchment-scale erosion models (e.g., AnnAGNPS and SWAT models). In contrast, where input parameters can be directly measured in the field or are available for a specific environment, the physically-based models theoretically provide more accurate predictions of erosion (Zema, Lucas-Borja, et al., 2020; Zema, Nunes, et al., 2020).

Wildfire is a common natural disturbance in Mediterranean ecosystems, and usually enhances soil erosion, which may increase ecosystem degradation to unsustainable rates. To limit soil degradation in the Mediterranean forests, a proper control of erosion is necessary. On this regard, erosion models, commonly used in agricultural areas (Borrelli et al., 2018; Panagos & Katsoyiannis, 2019), have been also extended to burned areas (Lopes et al., 2021; Vieira et al., 2014). According to Lopes et al. (2021), published literature on post-fire erosion modelling is not homogeneously distributed worldwide. While post-fire prediction models are commonly used in the United States, research is still far from being exhaustive in other regions (Hosseini et al., 2018). In the Mediterranean burned areas, where the hydrological processes are site-specific (Shakesby, 2011; Wagenbrenner et al., 2021), the available erosion models may find limitations in their applicability, especially when the soils are subjected to post-fire management. Therefore, these models require localised optimisation, since these hydrological tools have been developed in other environmental contexts and are not designed to be applied specifically in burned areas (Vieira et al., 2018a).

Erosion models include simple empirical models, such as the USLE-family models, to semi-empirical models (e.g., the Morgan–Morgan–Finney model, MMF), physically-based models (for instance, the Water Erosion Prediction Project, WEPP) or artificial neural networks (Aksoy & Kavvas, 2005; Merritt et al., 2003; Zema, Lucas-Borja, et al., 2020; Zema, Nunes, et al., 2020). Regarding the USLE-family models, only the RUSLE version has been used in wildfire-affected soils (e.g., Fernández et al., 2010; Karamesouti et al., 2016; Larsen & MacDonald, 2007; Vieira et al., 2018b). To the authors' best knowledge, the event-scale USLE-family model (USLE-M) has been applied only by Carrà et al. (2021) in Southern Italy treated with prescribed fire and fern mulching. Erosion predictions using WEPP were carried out by (Covert et al., 2005; Fernández & Vega, 2018; Larsen & MacDonald, 2007; Soto & Díaz-Fierros, 1998) in Mediterranean forests burned by wildfires. The MMF model has been verified in burned areas with or without post-fire treatments under different Mediterranean climates in North-Western and Central-Eastern Spain, and in Central Portugal (Fernández et al., 2010; Vieira et al., 2014, 2018b; Zema, Nunes, et al., 2020). The latter authors suggested an adaptation of this model to uses on the event scale in burned forests, mulched or untreated.

This study evaluated the prediction capability of the USLE-M (coupled to the Curve Number method to estimate the runoff coefficient), MMF and WEPP models in a Mediterranean forest burned by a wildfire and then treated with soil mulching in comparison to unburned areas. The investigation was carried out at the plot and event scales throughout one year in a pine stand of Castilla-La Mancha (Central Eastern Spain). This study is the first application of the USLE-M and WEPP models to wildfire-affected soils subjected to post-fire mulching in Mediterranean forests as well as applying the MMF model in a Mediterranean pine forest on untreated or mulched soils. The erosion prediction capacity of the latter model was successfully evaluated (Zema, Nunes, et al., 2020), but without a further validation in other sites with similar environmental characteristics. Moreover, a new procedure to estimate the C-factor based on the ground cover as input parameter for the MMF model was proposed and evaluated in this modelling exercise. This study aims at providing insight about the choice of the most suitable model for erosion predictions in burned forests to land managers and hydrologists.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located between the municipalities of Liétor and Agramón (geographical coordinates 38°25'19"N, -1°38'15"E, province of Albacete, Castilla-La Mancha, Central Eastern Spain) (Figure 1a). The elevation ranges between 400 and 700 m above the mean seal level.

The area is framed in a semi-arid climate Mediterranean, BSk according to the Köppen-Geiger classification (Kottek et al., 2006), where the average annual precipitation and temperature are 320 mm and 16 ºC, respectively. In the first year after the fire, a total precipitation of 400 mm was recorded. The parental materials that make up this area are limestones, such as dolomites, marls, and clay. The soils are shallow (depth lower than 0.3 m), with low organic matter content, the main types being Inceptisols and Aridisols (USDA, 1999). The soil texture of the study area is presented in Table 1. The vegetation in the area consists of a *Pinus halepensis* forest with a shrub and herbaceous companion layers dominated by *Macrochloa tenacissima* and *Salvia Rosmarinus*, and other minor species, such as *Pistacia lentiscus*, *Quercus coccifera*, *Rhamnus lycioides*, *Thymus vulgaris* and *Cistus clusii*.

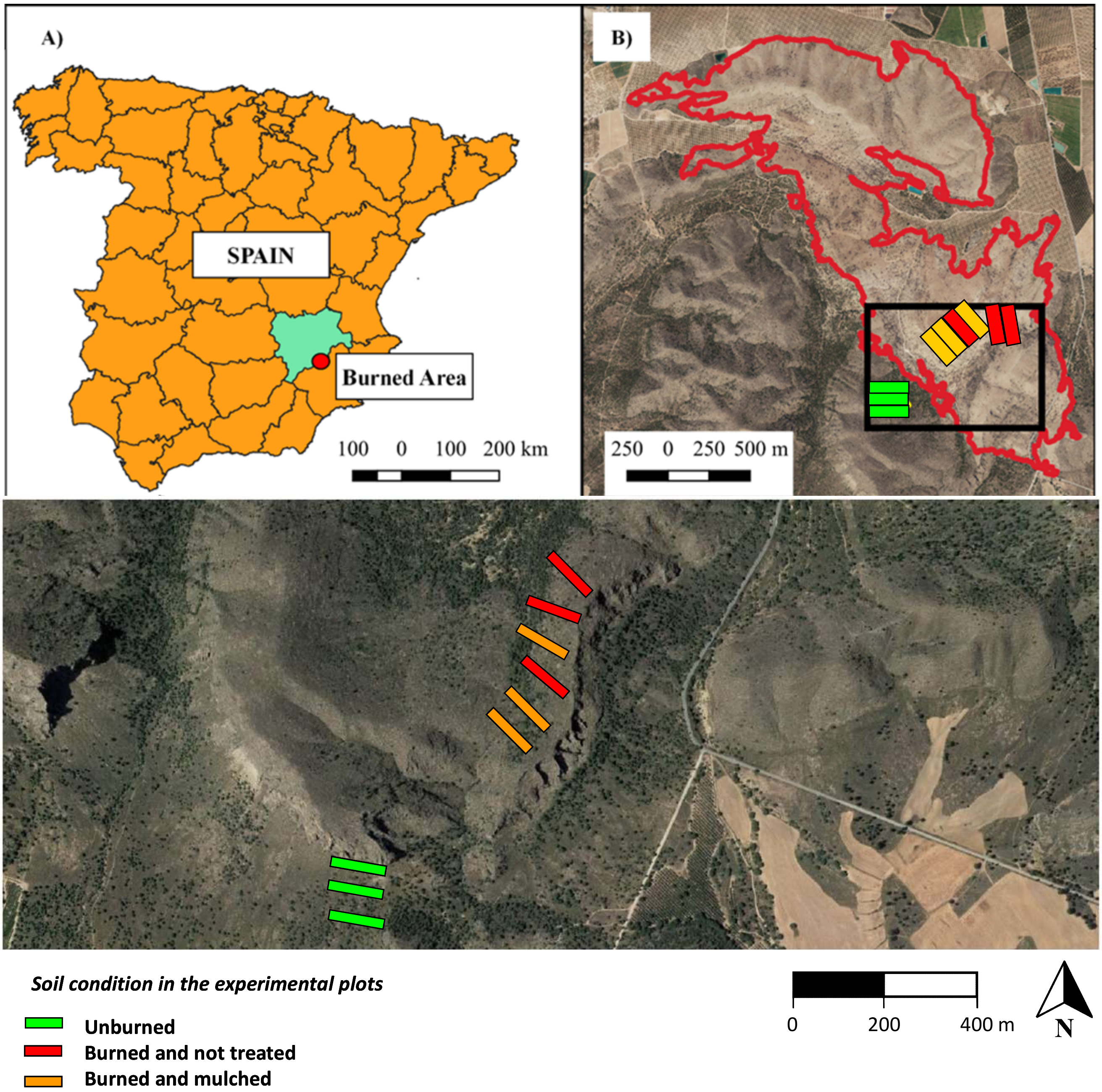


Figure 1 - Geographical location of the study area (A) and of the burned area within the wildfire

perimeter (B) and aerial map of the experimental plots (C) (Agramón, Castilla-La Mancha, Spain).

Table 1 – Soil properties and surface cover of the experimental plots (Agramón, Castilla-La Mancha, Spain) after the wildfire in 2020.

Soil condition	**Plot #**	**Topographic characteristics**		**Soil properties**				
		Slope (%)	Aspect	Sand content (%)	Silt content (%)	Clay content (%)	Organic matter content (%)	Soil cover (%)
Unburned	1	47.8	East	28.7	58.8	14.8	2.40	75.6
	2	47.1	East	24.3	58.1	14.3	2.45	74.3
	3	46.9	East	25.9	61.2	13.9	2.10	75.0
Burned and not treated	1	40.8	South-East	31.5	55.7	12.2	2.01	30.2
	2	41.4	South	33.6	54.2	13.9	2.20	28.6
	3	41.5	South-East	29.9	56.5	12.2	2.17	31.2
Burned and mulched	1	40.1	South-East	33.4	49.2	19.2	2.90	44.1
	2	39.8	South-East	29.1	53.2	17.8	2.86	42.3
	3	40.9	South-East	28.1	51.6	18.6	2.88	39.7

2.2. Experimental design

On 27th July 2020, a wildfire burned approximately 275 ha of forestland in the study area. The soil burn severity, estimated according to Vega et al. (2013), was high. The tree mortality in the study area was 100%.

After the wildfire, nine plots, each one of 0.5 ha (width of 25 m and length of 200 m), were equipped to collect the sediments (Figure 1). The soil slope was between 39.8% and 47.8%, while the aspect south, east or south-east. The soil texture was homogenous, with contents of sand, silt and clay in the range 24.3-33.6%, 49.2-61.2% and 12.2-19.2%, and of organic matter between 2.01% and 2.90% (Table 1). Of the nine plots, three were identified in an unburned area that was adjacent to the burned forest. Other six plots were selected in the burned area, of which three were not treated and other three were subjected to post-fire soil mulching one month after the fire. The mulch material was barley straw, which was manually spread on the plots at a rate of 0.25 kg/m^2 (dry weight) and thickness of 3 cm (Lucas-Borja et al., 2018; Lucas-Borja et al., 2020). This mulch rate was based on a previous study by (Vega et al., 2014), who proposed this dose to achieve a soil cover of 80% for burned plots installed in Northern Spain. The soil cover varied from 28.6% (burned and untreated plots) to 75.6% (burned and mulched plots) (Table 1).

At the outlet of each plot, sediment traps were installed since 1st September 2020 until 31st December 2021 (16 months) and soil loss was measured in this observation period. The accumulated sediment at each sediment trap was removed after each rainfall event, weighted in the field, and oven-dried in laboratory to calculate dry weight. A weather station, located in Liétor (geographical coordinates 38°32'27"N; 1°57'17"W), about 12 km far from the experimental area, provided the precipitation and temperature records. Rainfall depths were available at 15-min intervals, while the air temperatures were on a daily scale.

2.3. Experimental observations of soil erosion

Throughout the observation period, 13 “erosive” events (rainfall >13 mm) according to Wischmeier & Smith (1978) were monitored. Of these events, only seven (all with rainfall depth over 30 mm) produced erosion, while were recorded and used for modelling purposes. In more detail, the rainfall depth was in the range 43.3 - 115.2 mm, the maximum intensity in 30 minutes (I_{30}) was between 9.2 and 64.8 mm/h (Table 2 and Figure 2), and the maximum rainfall erosivity (EI_{30}) was 298 MJ mm/ha h (Figure 2). In the unburned plots, the soil loss was between 0.0005 to 0.0009 tons/ha. The soil loss measured in the burned and not treated plots was in the range

0.96 to 1.63 tons/ha, while the values measured in the burned and mulched plots varied from 0.16 to 0.29 kg/m^2 (Table 2).

Table 2 – Rainfall characteristics and soil loss observations at the experimental site (Agramón, Castilla-La Mancha, Spain).

Event date	**Rainfall**		**Observed soil loss (tons/ha)**		
	depth (mm)	**max 30-min intensity (mm/h)**	**Unburned soil**	**Burned and not treated soil**	**Burned and mulched soil**
10 Nov 2020	79.8	33.0	6.85×10^{-4}	1.227	0.165
16 Dec 2020	43.3	17.6	6.38×10^{-4}	1.600	0.184
22 Mar 2021	104.9	9.2	7.91×10^{-4}	1.463	0.198
4 Jun 2021	115.2	17.2	6.13×10^{-4}	1.631	0.228
5 Jul 2021	65.4	44.0	8.93×10^{-4}	1.399	0.193
14 Sep 2021	64.0	64.8	5.41×10^{-4}	1.338	0.292
10 Oct 2021	60.8	38.6	7.31×10^{-4}	0.959	0.176

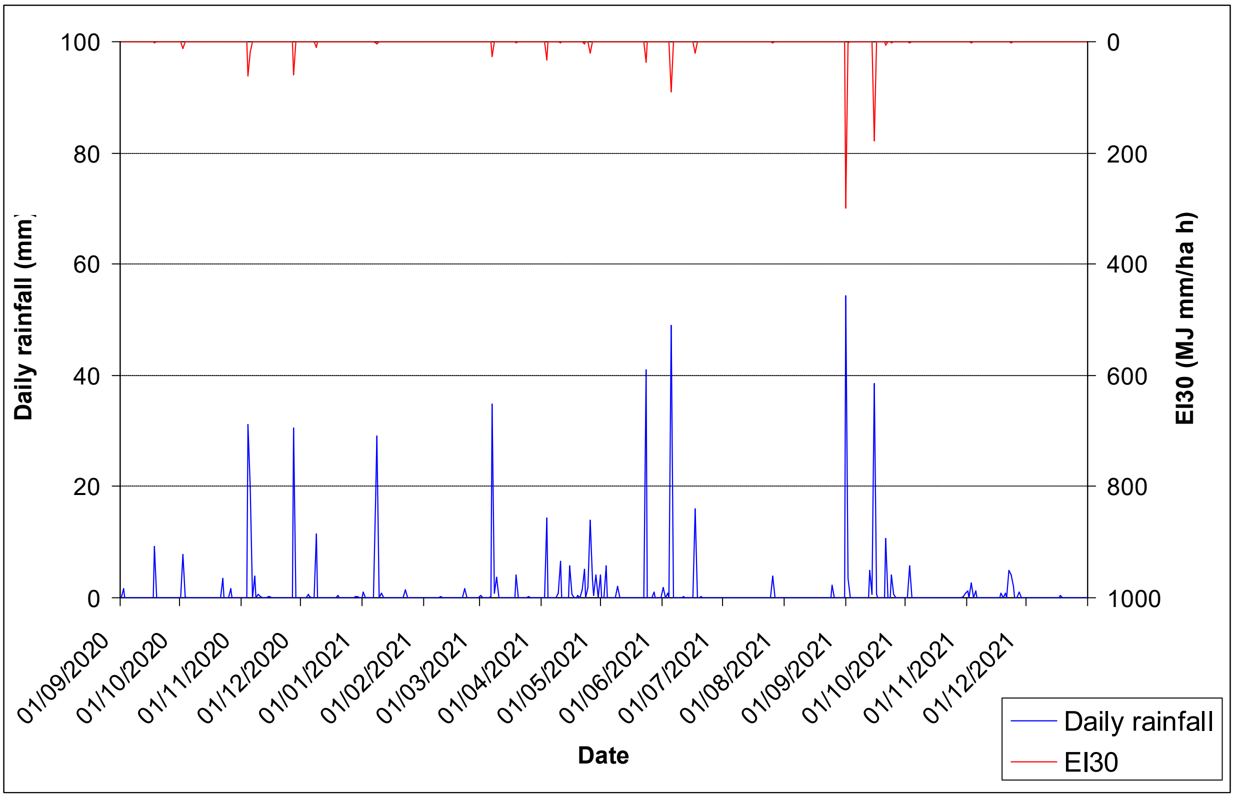


Figure 2 – Rainfall depth and erosivity (EI_{30}) at the experimental site (Agramón, Castilla-La Mancha, Spain).

The hydrological dataset used for model is made of a sample of seven observations of soil loss, which, however, allows the evaluation of the model's prediction capacity for two reasons. First, wildfire opens in the burnt area a so-called "window of disturbance" (Prosser & Williams, 1998; Zavala et al., 2014), when the soil is bare due to the vegetation burning and many of its physico-chemical properties undergo noticeable changes (Moody et al., 2013; Zema, 2021). Both effects result in a strong alteration in the hydrological response of severely-burned soils, which however is only temporary. Although the duration of this window of disturbance may be variable depending on soil, weather and fire characteristics, the pre-fire conditions generally recover after one year, which is the duration of the observation period of this study. The measurements of soil erosion in the experimental area were made in this window of disturbance. Second, in the semi-arid environments (such as the study area), annual erosion is substantially due to few but intense rainstorms (the so-called "erosive events", according to Wischmeier & Smith (1978), that is events with rainfall depth over 13 mm). The events of our dataset are all those events that overcome this threshold and produced erosion, while the other smaller events were not considered.

2.4. Short description of the WEPP, MMF, and USLE-M models

The "Water Erosion Prediction Project" (WEPP, Flanagan & Nearing, 1995) is a physically-based, distributed parameters, continuous simulation model, which was developed by USDA-Natural Resources Conservation Service in late ‘1980s. The model is used to predict the spatial and temporal distribution of net soil loss and deposition for a wide range of time periods and spatial scales. The WEPP hillslope version (Foster & Lane, 1987) was used in this study to predict soil erosion along a single slope profile. More details about the equations governing the erosion simulations by the WEPP model and the input parameters are reported in Flanagan & Nearing (1995) and Foster & Lane (1987).

The "Morgan-Morgan-Finney" model (MMF, Morgan, 2001; Morgan et al., 1984) was developed in early ‘1980s. The model was revised in 2001 by the same authors, in order to improve the accuracy of erosion predictions and to propose guidelines for the optimal choice of the input parameters. The equations for calculating the hydrological variables are reported in the original papers by Morgan (2001) and Morgan et al. (1984).

The “Universal Soil Loss Equation” (USLE) was first developed in USA (Wischmeier & Smith, 1978), in order to predict soil loss in small agricultural catchments. The mean annual soil loss is calculated as the product of six input parameters (the so-called “USLE-factors”), linked to climate, soil cover and properties, topography, and human activities (R, K, L, S, C and P). In 1998, Kinnell & Risse (1998) proposed the USLE-M model (USLE modified), which assumes that the sediment concentration in the runoff is governed by the event rainfall erosivity index (R_e, Wischmeier & Smith, 1978) per unit quantity of rain (P_e, mm). The equations to calculate the soil loss Y and the input factors are reported in the study by Kinnell & Risse (1998).

2.5. Model implementation

2.5.1. General information

The climate data needed by the models was collected at the weather station of Liétor. Three treatments were simulated: (i) unburned soil (control); (ii) burned and not treated soil; and (iii) burned and mulched soil.

2.5.2. WEPP model

The climate data needed as input by WEPP were the storm depth (mm), duration (h) and maximum intensity (mm/h), and the percent duration to peak intensity. These values were derived from rainfall records at the gauging station of Liétor for each modelled event.

A concave profile with three slopes was assumed for each plot. The value of the soil albedo parameter was calculated by Baumer's equation and set to 0.23 (Flanagan & Nearing, 1995). According to the guidelines in the WEPP manual, an initial saturation level of 75% was assumed (Table 1SM).

Three conditions were input according to the WEPP management files into the software interface: (i) "shrub perennial" for the unburned plots; (ii) "25% ground cover - high severity" for the burned and not treated plots; (iii) "fallow initial condition - wheat residues" for the burned and mulched soils. For the three management conditions, some input parameters of the model's default database were updated to the experimental conditions.

2.5.3. MMF model

MMF was run at the event scale and parameterised using the default input data (hereafter "default model") or adjusted values for post-fire conditions ("calibrated model") and for each event. For runs using the default model, the values of the input parameters suggested in the original studies of Morgan et al. (1984) and Morgan (2001) were adopted. For the erosion predictions using the calibrated model, MMF was run simulating the post-fire conditions, according to the adaptations suggested by Fernández et al. (2010), Vieira et al. (2014) and Zema, Nunes, et al. (2020), where more details can be found. To summarise, the input parameters needed by MMF were measured in-field or derived from the guidelines of Morgan (2001), Morgan et al. (1984) and Morgan & Duzant (2008) with the corrections according to Vieira et al. (2014) and Nunes et al. (2016), or estimated from the literature (Doorenbos & Kassam, 1979; Fernández et al., 2010; Vieira et al., 2014; Wischmeier & Smith, 1978; Zema, Nunes, et al., 2020).

2.5.4. USLE-M model

The USLE-M model was initially run with default parameters, estimated from the model guidelines. In this study, the runoff coefficient of the USLE-M equation was calculated as the ratio between the runoff volume, and the rainfall depth (both in mm), while the erosivity factor was estimated as the product of the kinetic energy and the maximum intensity in 30 minutes for each rainfall, following

Due to the lack of measured runoff volumes, needed by the USLE-M model, the runoff volume was estimated by the Soil Conservation Service-Curve Number (SCS-CN) method (SCS, 1985) (as explained below). In more detail, the rainfall depth of each modelled storm event was estimated by aggregating the sub-hourly records collected at the rain gauging station. The Antecedent Moisture Content (AMC) was estimated by aggregating the 5-day rainfall depths prior to each event. The soil hydrological group was identified as "B" ("soils having a moderate infiltration rate when thoroughly wet"). The default values of CN were assumed following the standard procedure by the USDA Soil Conservation Service (SCS, 1985).

The K-factor was calculated according to the procedure proposed by Kinnel et al. (1998), on its turn based on the nomograph of Wischmeier & Smith (1978). The C-factor was calculated using the empirical equation based on canopy cover and aboveground biomass proposed by Bombino et al. (2002). The P-factor was always set to one.

2.6. Model calibration

2.6.1. WEPP model

Since WEPP is a physically-based model with input parameters that should be measured in the field (Aksoy & Kavvas, 2005; Merritt et al., 2003), the model was not deliberately calibrated in this study. This choice also allows a model performance assessment in data-poor environments, that is in the case that no data for calibration/validation is available.

2.6.2. MMF model

The MMF model, commonly used for erosion predictions at the yearly or multi-yearly scale, was implemented at the event scale. Since Zema, Nunes, et al. (2020) have tested the model prediction capacity after rainfall events in burned forest soils for Mediterranean conditions, we adopted these adaptations for the MMF calibration were (Tables 3 and 2SM): (i) input of seasonal values of the moisture content at field capacity (MS), corrected by changes in soil water repellency (SWR) (except for unburned plots), ratio between the actual (E_t) to potential (E_0) evapo-transpiration ($E_t/E_{0)}$, and ground cover (GC), according to Vieira et al. (2014); (ii) model running at the event scale rather to simulate seasonal or annual soil loss, since, in the Mediterranean climate, soil erosion is mainly determined by few but intense rainfall events (e.g., Fortugno et al., 2017); (iii) setup of the MS input parameter to 0.28 for sandy loam soils (Morgan, 2001) with the correction suggested by the "SM-SWR" modelling approach of Vieira et al. (2014) and Nunes et al. (2016), to take into account the effect of soil water repellency on soil wetting (from 0.8 for extreme repellency to 1.1 under wettable conditions (Vieira et al., 2014); (iv) modification of effective hydrological depth (EHD) suggested by Hosseini et al. (2018) and Vieira et al. (2014), considering two soil layers, of which the deeper layer was not or scarcely influenced by the fire effects (50% of the original depth), while the topsoil was affected by the high burn severity and the post-fire treatment.

The C-factor is one of the few empirical factors of the model, which, for this reason, was calibrated. This factor was estimated differently from the previous study by Zema, Nunes, et al. (2020), in order to take into account its seasonal variability, due to growth of the herbaceous vegetation by regeneration in burned areas, and by seasonal natural cycle in unburned plots. More specifically, the following equations were adopted for estimating the C-factor:

$$C_{corr} = C \cdot FC \tag{1}$$

$$FC = \frac{1}{\dfrac{GC - \overline{GC}}{\overline{GC}} + 1} \tag{2}$$

where C_{corr} and C are the corrected and original C-factors, respectively, FC is the correction factor, GC is the ground cover (in percent on the total plot area) at the time of the modelled event, and $\overline{GC}$ is the value of GC averaged throughout the observation period. Of course, FC is undefined and thus can not be calculated, when the soil is totally bare (in this case GC = 0) (Table 3 and 2SM).

Table 3 – Input parameters of the MMF model to predict soil loss at the experimental site (Agramón, Castilla-La Mancha, Spain).

Factor	**Soil condition**					
	Min	Max	Min	Max	Min	Max
	Unburned		*Burned and Not Treated*		*Burned and Mulched*	
	Uncalibrated model					
MS	0.2	0.2	0.4	0.4	0.4	0.4
EHD	0.1	0.1	0.1	0.1	0.1	0.1
A	0	0	0	0	0.3	0.3
Et/E_0	1	1	0.1	0.1	0.9	0.9
C	0.003	0	1	1	0	0
CC	0.7	0.7	0	0	1	1
GC	0.4	0.6	0	0	1	1
PH	0	0	0	0	0.5	0.5
	Calibrated model					
MS	0.35	0.35	0.28	0.28	0.28	0.28
EHD	0.2	0.2	0.09	0.09	0.12	0.12
A	0	0	0	0	0.06	0.06
E_t/E_0	0.80	0.70	0.05	0.05	0.50	0.45
C	0.135	0.156	0.120	0.558	0.029	0.034
CC	0.7	0.7	0.	0	0.05	0.05
GC	0.45	0.39	0.19	0.07	0.56	0.47
PH	0.5	0.5	0	0	0.6	0.6

Notes: MS = moisture content at field capacity; EHD = effective hydrological depth; A = vegetation cover; E_t/E_0 = ratio of actual and potential evapotranspiration; C = cover management factor; CC = percent canopy cover; GC = ground cover; PH = plant height to the ground surface.

2.6.3. USLE-M model

For USLE-M calibration, the most sensitive input parameters (CN for the SCS-CN model and the C-factor for the USLE-M) were chosen (Carra et al., 2021). First, constant CNs and C-factors for all the modelled events were input, then these parameters were increased for the first two rainfall events for the burned catchments, in order to simulate the variable hydrological response of soils throughout the observation period. This choice agrees with several studies (e.g., Carra et al., 2021; Cawson et al., 2012; Lucas-Borja, Bombino, et al., 2020; Vieira et al., 2015). To avoid separate calibration of two factors, the effects of the mulching practice were included in the C-factor, and the P-factor was set to one (Table 4 and 3SM).

For MMF and USLE-M models, the calibration was carried out manually by a trial-and-error procedure until the maximum coefficient of efficiency (see section 2.6) and the minimum error between the mean values of the observations and simulations of soil loss were achieved. Due to the lack of runoff observations, only the erosive sub-model of MMF was optimised. However, the MMF adjustments of the hydrological sub-model previously proposed by Zema, Nunes, et al. (2020), who found good runoff estimations after sub-model optimisation under the same environmental conditions, were embedded in the optimised model.

Table 4 – Input parameters of the USLE-M model to predict soil loss at the experimental site (Agramón, Castilla-La Mancha, Spain).

Model	**Input parameter**	**Measuring unit**	**Soil conditions**					
			Unburned		**Burned and not treated**		**Burned and mulched**	
			Default	**Calibrated**	**Default**	**Calibrated**	**Default**	**Calibrated**
SCS-CN	CN	-	39	7	90 (79)	13	65 (39)	8
USLE-M	C-factor	-	0.0001	0.0002	0.006	0.526	0.0002	0.085

Notes: CN = curve number; C-factor = cover management factor; the values related to the first two modelled events are reported in brackets.

2.7. Model evaluation

The erosion predictions by the three models were analysed for “goodness-of-fit” with the corresponding observations adopting qualitative and quantitative procedures. The qualitative approach consisted of the visual comparison of the observed and the corresponding soil loss in scatterplots. The quantitative procedure used the indicators that are commonly adopted in the literature (e.g., Willmott, 1982; Legates and McCabe, 1999; Loague and Green, 1991; Zema et al., 2017; 2018). More specifically, we used: (i) the main statistics (i.e., the maximum, minimum, mean and standard deviation of both the observed and simulated values); (ii) the coefficient of determination (r^2); (iii) the coefficient of efficiency (NSE, Nash & Sutcliffe, 1970); (iv) the Root Mean Square Error (RMSE); and (v) the percent bias (PBIAS). The equations to calculate these indicators are reported in the studies by Krause et al. (2005), Moriasi et al. (2007), Van Liew & Garbrecht (2003) and Zema et al. (2012). The acceptance or optimal values are as follows (i) r^2 is in the range 0 (no agreement between observed and predicted data) to 1 (perfect agreement), being acceptable when over 0.5 (Santhi et al., 2001; Van Liew et al., 2003; Vieira et al., 2018b); (ii) NSE varies between $-\infty$ and 1, and the model accuracy is "good" if $E \geq 0.75$, "satisfactory" if $0.36 \leq E \leq 0.75$ and "unsatisfactory" if $E \leq 0.36$ (Van Liew et al., 2003); (iii) RMSE is optimal when it approaches to 0 (Fernández et al., 2010), and the predictions are “good”, when RMSE is lower than half the observed standard deviation (Singh et al., 2005); (iv) PBIAS, which is also reported as "coefficient of residual mass", is positive, when a model underestimates the observation, and negative in the case of overestimation (Gupta et al., 1999); a model with CRM/PBIAS below 55% is considered fair for erosion predictions (Moriasi et al., 2007).

3. RESULTS

3.1. WEPP model

The WEPP model gave poor predictions of soil loss under all the modelled soil conditions, as shown by the large scattering of "observations vs. predictions" pairs around the line of perfect agreement (Figure 3). This low prediction accuracy is confirmed by the poor values of the evaluation indicators. In more detail, the difference between the mean observed and predicted soil loss was from 1237% (burned plots) to +23233% (burned and mulched soils). The coefficient of determination was very low (from 0.01 in burned and not treated plots to 0.35 in unburned soils), and the NSE values were even negative (< -12815). Moreover, while the soil loss was largely underestimated in all soil conditions (see the negative PBIAS). The RMSE was from 80% (unburned soils) to several orders of magnitudes (burned plots with or without mulching) higher compared to half the standard deviation of the observed values, and thus unsatisfactory (Table 5).

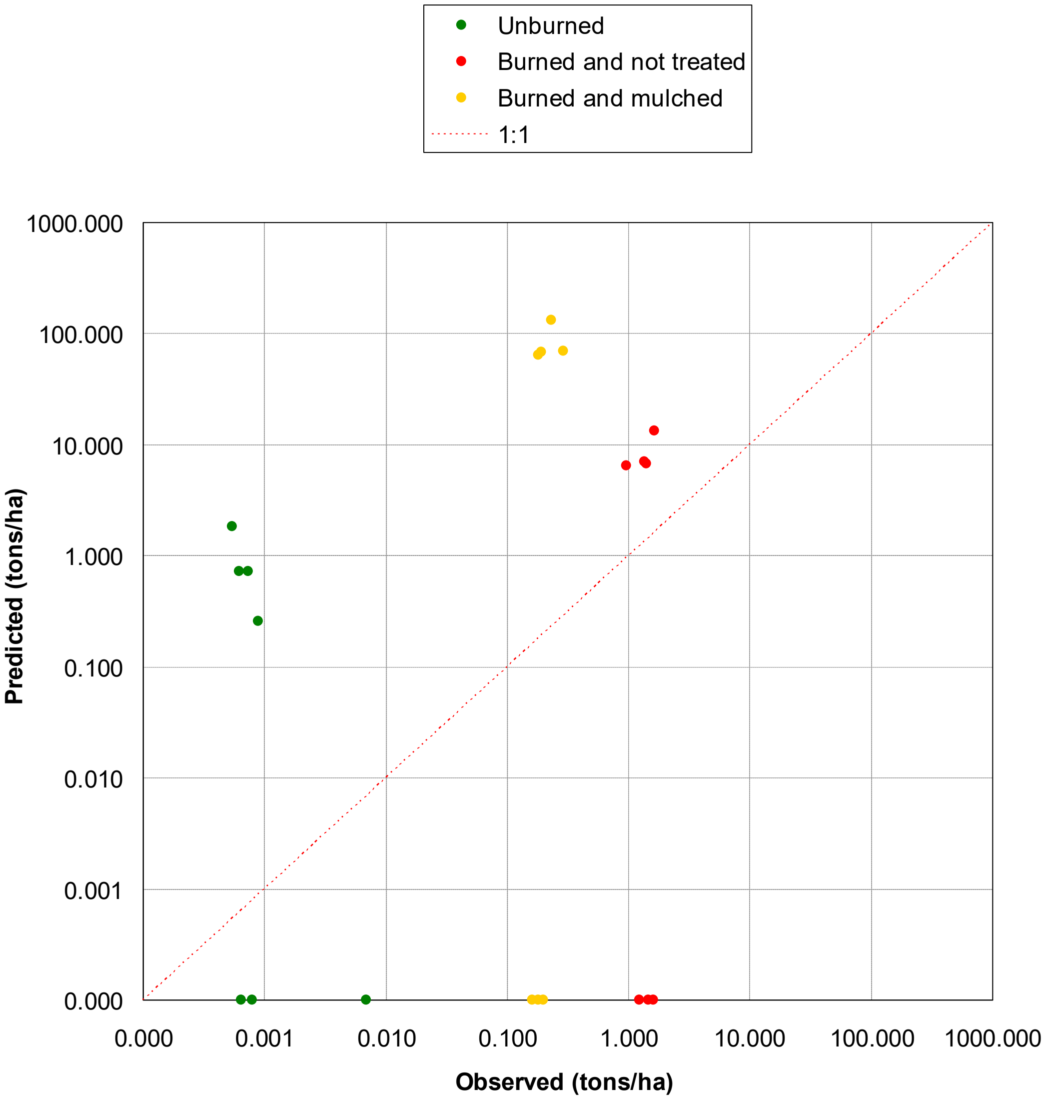


Figure 3 – Scatterplots of observed vs. predict soil loss using the WEPP model at the experimental site (Agramón, Castilla La Mancha, Spain).

Table 5 – Indexes used to evaluate the erosion prediction capacity of the WEPP, MMF and USLE-M models at the experimental site (Agramón, Castilla-La Mancha, Spain).

Soil loss	**Mean (tons/ha)**	**Minimum (tons/ha)**	**Maximum (tons/ha)**	**Standard deviation (tons/ha)**	**r^2**	**E**	**RMSE (tons/ha)**	**PBIAS**
	WEPP model							
	Unburned soil							
Observed	0.001	0.001	0.001	0.000	0.35	-53764953	0.80	-722
Predicted	0.506	0.000	1.835	0.669				
	Burned and not treated soil							
Observed	1.374	0.959	1.631	0.231	0.00	-12815	24.2	-12.4
Predicted	18.368	0.000	47.612	18.682				
	Burned and mulched soil							
Observed	0.205	0.165	0.292	0.043	0.24	-2764390	66.7	-232
Predicted	47.882	0.000	132.530	50.364				
	Uncalibrated MMF model							
	Unburned soil							
Observed	0.001	0.001	0.001	0.000	0.00	-35648	0.00	-23.05
Predicted	0.017	0.003	0.040	0.014				
	Burned and not treated soil							
Observed	1.374	0.959	1.631	0.231	0.16	-1922	0.94	-5.52

Predicted	8.964	2.516	18.931	6.060				
	Burned and mulched soil							
Observed	0.205	0.165	0.292	0.043	0.01	-26.18	0.02	1.00
Predicted	0.000	0.000	0.000	0.000				
	Calibrated MMF model							
	Unburned soil							
Observed	0.001	0.001	0.001	0.000	0.01	-84.6	0.00	-0.13
Predicted	0.017	0.003	0.040	0.014				
	Burned and not treated soil							
Observed	1.374	0.959	1.631	0.231	0.94	0.75	0.01	0.06
Predicted	8.964	2.516	18.931	6.060				
	Burned and mulched soil							
Observed	0.205	0.165	0.292	0.043	0.86	0.43	0.00	-0.13
Predicted	0.000	0.000	0.000	0.000				
	Uncalibrated USLE-M model							
	Unburned soil							
Observed	0.001	0.001	0.001	0.000	0.08	-27.4	0.00	0.80
Predicted	0.000	0.000	0.000	0.000				
	Burned and not treated soil							
Observed	1.374	0.959	1.631	0.231	0.00	-40.3	1.38	0.99
Predicted	0.015	0.001	0.030	0.011				
	Burned and mulched soil							

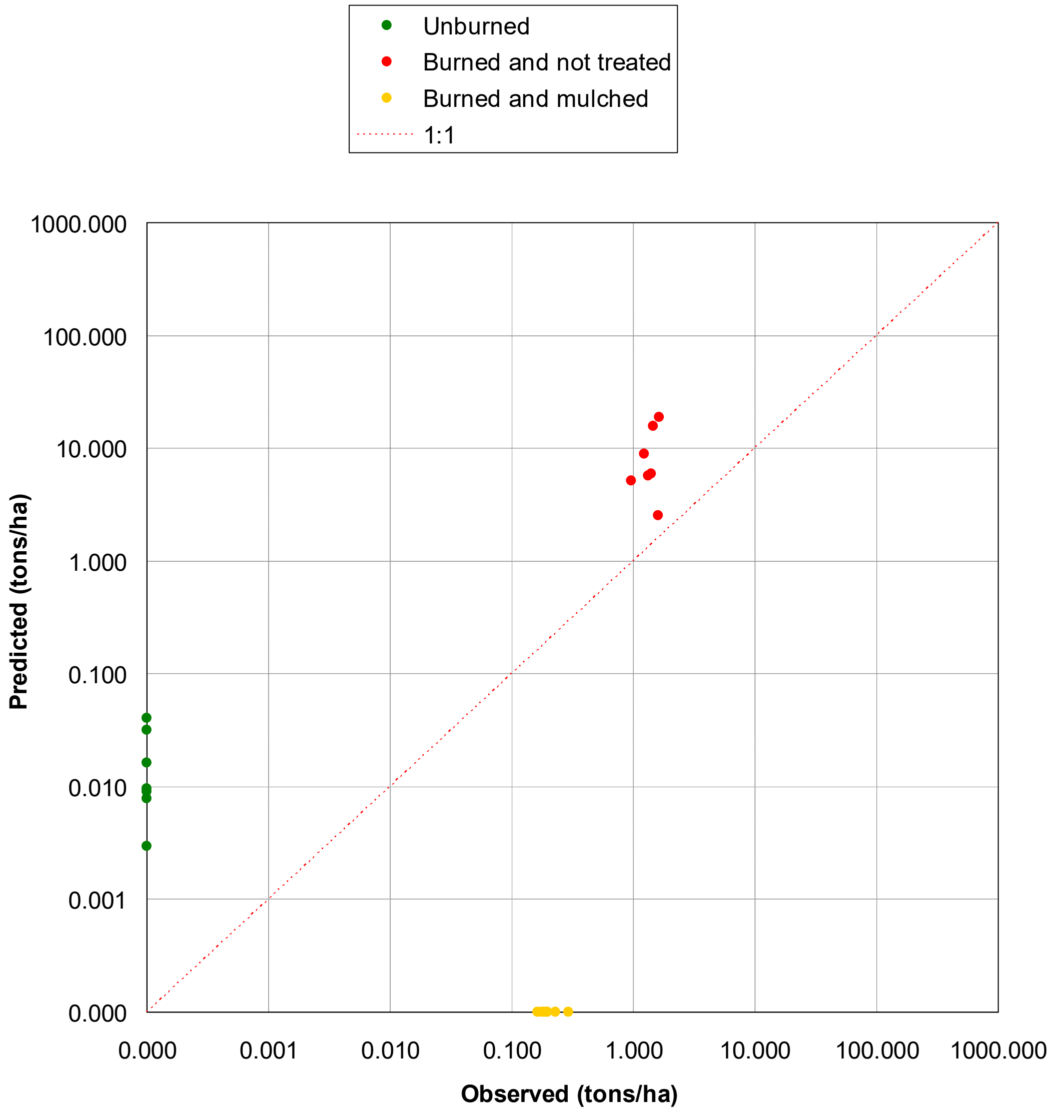
Observed	0.205	0.165	0.292	0.043	0.02	-26.1	0.21	1.00
Predicted	0.000	0.000	0.001	0.000				
	Calibrated USLE-M model							
	Unburned soil							
Observed	0.001	0.001	0.001	0.000	0.08	-15.8	0.00	0.42
Predicted	0.000	0.000	0.001	0.000				
	Burned and not treated soil							
Observed	1.374	0.959	1.631	0.231	0.03	-11.8	0.77	0.24
Predicted	1.038	0.040	1.881	0.749				
	Burned and mulched soil							
Observed	0.205	0.165	0.292	0.043	0.28	-10.3	0.13	0.25
Predicted	0.154	0.000	0.338	0.152				

Notes: r^2 = coefficient of determination; NSE = coefficient of efficiency of Nash and Sutcliffe; RMSE = Root Mean Square Error; PBIAS = Coefficient of Residual Mass.

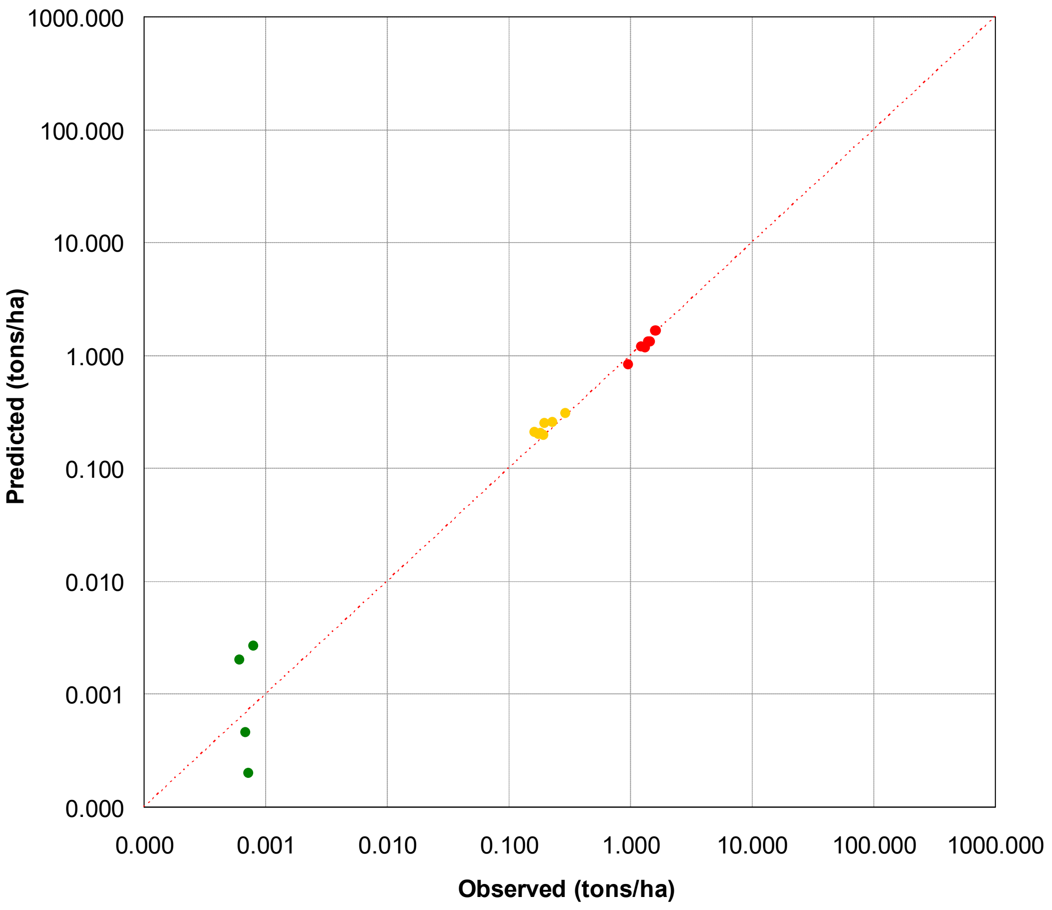
3.2. MMF model

As noticed for WEPP, also the MMF model running with default parameters generally showed a large inaccuracy in predicting the soil loss. This is visually shown in the relevant scatterplot under all the soil conditions (Figure 4a) and confirmed by the poor evaluation indicators. The differences between the mean, maximum and minimum values of the predictions and observations were very large (> 100% for the mean, minimum, and maximum values). The values of r^2 were very low (< 0.16), and negative NSE were achieved (< -26.2). These values, coupled to the very large RMSEs (> 0.02 tons/ha), show the inaccuracy of the default MMF model in predicting the erosion under all the modelled soil conditions (Table 5). This poor prediction capacity is due to the large over-estimation (in unburned, PBIAS = -23.1, and burned plots, PBIAS = -5.52) or under-estimation (in burned and mulched soils, PBIAS of 1) of the observations.

Due to these unsatisfactory performances, MMF was optimised as reported in the section 2.5.2. The model adaptations to the post-fire conditions greatly improved the erosion prediction capacity of MMF, except in the unburned soils. Under this condition, the values of r^2 were close to zero, and NSE was largely negative (-84.6). The differences between the predictions and the corresponding observations were low for the mean values (-12.6%), but high for the other statistics (> 92.5%), although the model tendency to over-prediction was low (PBIAS = -0.13). In burned conditions, the large scattering of the "observations vs. predictions" pairs, which was large in the unburned soils, was reduced, and these pairs were close to the line of perfect agreement (Figure 4b). The improvement of the model performance is confirmed by the quantitative analysis. More specifically, the differences between the mean observed and predicted soil loss were from 5.1% (burned and not treated soils) to 12.9% (burned and mulched plots), while the maximum values differed by 1.41% (burned and not treated soils) to 6% (unburned plots). The r^2 values were between 0.86 (burned and mulched soils) and 0.94 (burned and not treated conditions), and the RMSE values were lower than half the observed standard deviations (except under burned and mulched soil conditions). The soil loss prediction capacity can be considered good in the unburned, and burned and not treated soil conditions (NSE = 0.75), and satisfactory for the burned and mulched plots (NSE = 0.43). The large over- or under-estimation, previously noticed for the default model, disappeared, and the observed soil loss was only slightly under-predicted in burned and not treated soils (PBIAS of 0.06) or over-predicted (burned and mulched plots, PBIAS = -0.13) by the optimised MMF model (Table 5).


Unburned
Burned and not treated
Burned and mulched
1:1
Predicted (tons/ha)
1000.000
100.000
10.000
1.000
0.100
0.010
0.001
0.000
0.000
0.001
0.010
0.100
1.000
10.000
100.000
1000.000
Observed (tons/ha)

(a)



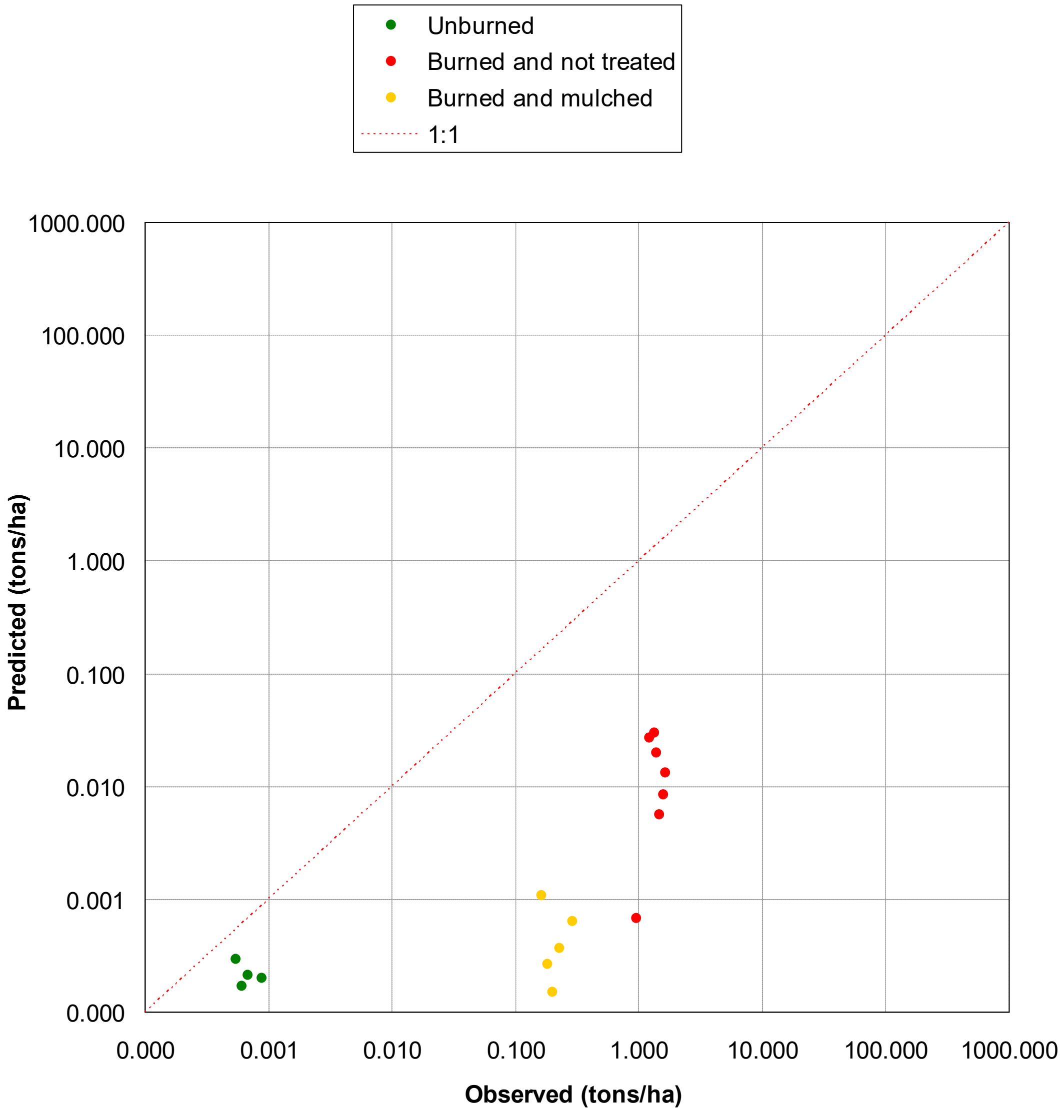
(b)

Figure 4 – Scatterplots of observed vs. predict soil loss using the MMF model (default, a, and calibrated, b) model at the experimental site (Agramón, Castilla-La Mancha, Spain).

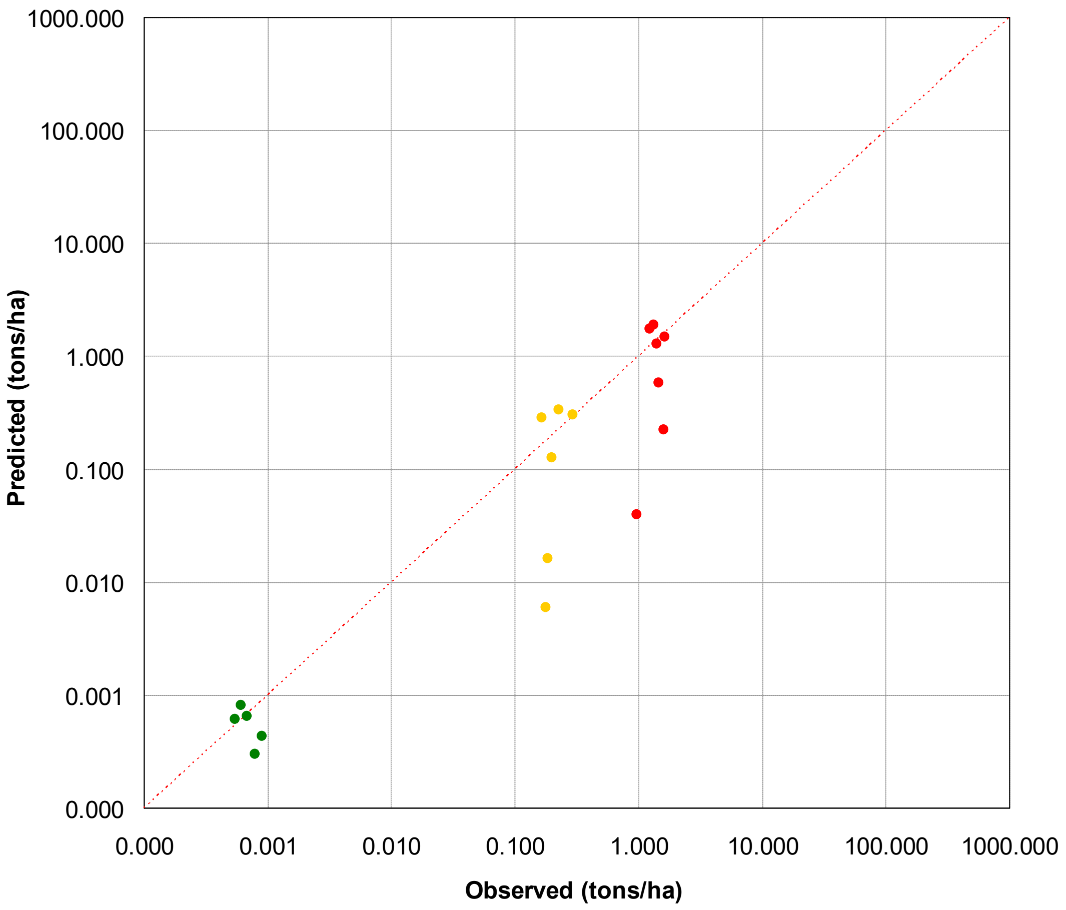
3.3. USLE model

The USLE model, running with default input parameters, showed a poor prediction capacity of erosion under all soil conditions. The visual evaluation highlights a large scattering of data around the line of perfect agreement (Figure 5a), and also the evaluation indicators confirm this poor performance. In more detail, the differences in the main statistics between the observations and the corresponding predictions were large (up to 100% for the mean and maximum values). The values of r^2 did not exceed 0.08 (unburned plots), NSE was always negative (< -26.1), and RMSE was always unsatisfactory (not lower than 10-fold half the observed standard deviation). This poor model performance is due to the large under-estimation (for all soil conditions, PBIAS > 0.80) of the observations (Table 5).

The USLE-M calibration through the setup of the values of CNs and C factors improved the model performance, although its erosion prediction capacity was still unsatisfactory for all the modelled soil conditions (Figure 5b). More specifically, the large differences between the main statistics of the observed and predicted soil loss decreased compared to the default model runs (errors in the mean values lower than -24.4%). The values of r^2 were not higher than 0.28 for the burned and mulched plots, and close to zero for the other soil conditions. NSE was never satisfactory, since always negative (< -10.3). The large under-estimation shown by the default model was reduced by the calibration, and the PBIAS (lower than 0.24) was always significant (Table 5).



(a)



(b)

Figure 5 – Scatterplots of observed vs. predict soil loss using the USLE-M (default, a, and calibrated, b) model at the experimental site (Agramón, Castilla-La Mancha, Spain).

4. Discussion

4.1. WEPP model

The WEPP model gave poor predictions of soil loss in both unburned and burned areas (with and without the post-fire treatment). WEPP underestimated the erosion in the unburned plots, while, in contrast, the soil loss was largely overestimated in burned soils also by several orders of magnitude. The reason of this high inaccuracy could be many. First, the lack of calibration did not balance errors related to model parameterisation and hydrological simulations. The WEPP model requires dozens of input parameters that should be measured in the field. Since these measurements were not available at the experimental site, the modellers were forced to adopt literature values (e.g., for K_e, K_i, K_r, and τ_c) with evident low accuracy at reproducing the observed erosion rates. This problem limits the WEPP applicability in poor-data environments, where the erosion predictions may be generally inaccurate. Second, low erosion rates, as observed at the experimental site, are generally predicted with unsatisfactory reliability by WEPP (e.g., Grønsten & Lundekvam, 2006; Konz et al., 2009; Licciardello et al., 2006; Soto & Díaz-Fierros, 1998), when no runoff is simulated (as in many of our modelled events). This model considers only Hortonian processes and not runoff due to saturated flow (Soto & Díaz-Fierros, 1998), the latter mechanism being common for low-intensity rainfall (Beven & Kirkby, 1979). Third, the overland erosion being zero, it is evident that WEPP also failed at simulating the rainsplash erosion, which may be dominant at the experimental site (Díaz et al., 2022; Lucas-Borja et al., 2022). Fourth, due to the lack of observations about the soil water content at the experimental plots, a constant initial saturation level was input to the model, while the real values were presumably variable, depending on the antecedent precipitation, thus affecting the runoff response simulated by the model. Also other authors found a large inaccuracy of WEPP in erosion predictions under burned conditions, as Soto & Díaz-Fierros (1998) and Fernández & Vega (2018), who applied WEPP in North-Western Spain, and by (Larsen & MacDonald, 2007), who modelled erosion in Colorado (USA). The latter authors confirmed that the model tends to over-predict sediment yields under 1 ton/ha-yr.

4.2. MMF model

The erosion predictions of the default (uncalibrated) MMF were inaccurate for all modelled soil conditions, since the model noticeably over- or under-estimated the soil loss observations. We should remind that MMF has a strong empirical base and was developed using mostly smaller scale erosion plot data derived from agricultural fields (Vieira et al., 2018b). Therefore, the extrapolations to other land uses, such as the burned forestlands, have been made using corrections of the internal algorithms based on an empirical approach. In the burned and mulched plots, these poor performances were due to the inadequate estimation of the sediment transport capacity, since the model did not produce soil loss (which, in MMF, is the lower value between the sediment detachment and the transport capacity). The model, running with a too high default C-factor, simulated a total shadowing effect of the mulch material against rainfall erosivity, which resulted in a soil particle detachment equal to zero. This explanation agrees with the findings of Zema, Nunes, et al. (2020) and Vieira et al. (2014), who also found MMF failures in reproducing the sediment transport capacity. For the other soil conditions (unburned, and burned and not treated soils), the reasons of the low prediction capacity are not so clear as for burned and mulched conditions. A reason may be the inadequate incorporation of the fire effects in the soil parameters, which are variable over time, while all parameters were left constant throughout the modelling period. Wildfire, especially when at high severity, such as in our experiment, noticeably changes some physical properties of soil, and these changes are not easy to be reproduced in empirical models without recurring to correction factors (e.g., the C factor). Also Fernández et al. (2010) highlighted the role played by the C and P factors on reliable predictions of erosion by MMF, which often may lead to poor results, when these parameters are not fully established in the model input procedure.

This model inaccuracy in reproducing the soil loss in the experimental conditions required adjustments in MMF. After calibration, the prediction capacity of MMF noticeably improved compared to the default model, and the soil loss predictions were closer to the corresponding observations in burned soil (with or without mulching). However, the model prediction capacity was still poor in unburned plots. This model inability may be due to the null prediction of the sediment transport capacity, which was too low to convey the sediment detached downstream. In other words, the soil loss due to rainsplash erosion and particle detachment by overland flow is simulated by MMF, but the process of sediment entrapment in the flow is not realistically reproduced. In contrast, the model prediction capacity was acceptable in the mulched plots and satisfactory in the burned and not treated soils. We ascribed the reasons for this model accuracy to the adaptations of the model to the burned conditions using the modifications of the internal algorithms and correction factors reported in methodology. More specifically, the incorporation of SWR effects, the modification of EHD, both following seasonal patterns, and the temporal downscaling to rainstorm events were successful to reproduce the variable dynamics of post-fire hydrology in the experimental soil. In contrast, the input of calibrated C-factors under post-fire management was less effective at modelling erosion in burned and mulched areas. A slight tendency to under-estimation or over-estimation of the observed soil loss remained. This model behaviour has been commonly detected in many MMF applications in burned areas (Fernández et al., 2010; Hosseini et al., 2018; Vieira et al., 2014, 2018b; Zema, Nunes, et al., 2020). It is worth to notice that the optimisation of the C-factor, which was weighted by the vegetal cover, improved the good prediction capacity of erosion under the same environmental conditions reported by Zema, Nunes, et al. (2020). The need of C-factor tuning is in agreement with several studies, which have demonstrated how accurate methodologies to estimate the C-factor are the key to reproduce the fire effects on soils (e.g., Larsen & MacDonald, 2007; Vieira et al., 2014).

The comparison of our results with other MMF modelling experiences in Mediterranean conditions shows that the changes suggested by the previous studies (Hosseini et al., 2018; Vieira et al., 2014, 2018b; Zema, Nunes, et al., 2020), coupled to the C-factor tuning proposed in this investigation, successfully improved the MMF ability to model soil hydrology under variable conditions at the event scale. The model efficiency calculated in our study is similar to the values found by Vieira et al. (2014), who applied MMF in North-Central Portugal, and by Zema, Nunes, et al. (2020) in Central-Eastern Spain. Lower model efficiency (in the range 0.54-0.74) were reported by Vieira et al. (2014) again in North-Central Portugal, and by Fernández et al. (2010) and Hosseini et al. (2018) in North-Western Spain and North-Central Portugal, respectively. However, it should be highlighted that, while our study applied MMF at the event scale, all the other model experiences were carried out at aggregate temporal scales (from seasonal to annual periods). Many studies have shown that the erosion models better perform in predicting the average soil loss rather than erosion rates for specific events (Fernández et al., 2010; Larsen & MacDonald, 2007).

4.3. USLE model

The erosion predictions using the USLE-M model, running with default and calibrated input parameters, were poor. This low performance of the model is common for many erosion models, which generally over-estimate and under-estimate the lower and higher soil losses, respectively (Kinnell, 2003; Larsen & MacDonald, 2007; Nearing, 2000). In our opinion, the most important reason for this inaccuracy was the lack of observed values of the runoff coefficients. Their estimations required the use of the SCS-CN method in our study leading to a worse performance of the USLE-M model compared to MMF (which internally simulates surface runoff). The increases in the CNs of fire-affected areas are suggested by several authors (e.g., Carra et al., 2021; Lucas-Borja, Bombino, et al., 2020; Papathanasiou et al., 2015; Soulis, 2018), in order to simulate the effects of soil water repellency (left by wildfire) and complete removal of vegetation (due to burning) on soil hydrological properties in the "window-of-disturbance".

In accordance with Vieira et al. (2015), another limitation of the USLE-family model is its great dependence on empirical parameters, such as the C and P-factors, to estimate the soil losses. The C-factor values, in spite of calibration, were not able to simulate the effect of the vegetation cover (in unburned and burned but untreated plots) and of the mulch layer against rain splash erosion and overland flow, thus contributing to the unsatisfactory model performances. Also the increase in soil erodibility (expressed by the K-factor) due to the wildfire-induced changes in physical parameters of soil and the lack of parameters simulating the effects of SWR may have played a significant role in this model inaccuracy (Fernández et al., 2010). We also agree with the latter authors about the inefficient use of an inadequate kinetic energy equation of rainfall for the Mediterranean climate by the USLE-family models, which could have affected the simulation of the real rainfall erosivity in the experimental conditions.

The poor prediction capacity of USLE-M indicates that the literature values that were adopted for the input parameters were not suitable for simulating erosion in unburned and burned (with or without mulching) plots. The USLE-M model inaccuracy in reproducing erosion in the unburned plots agrees with the findings by (Carra et al., 2021), who also achieved poor predictions of soil losses in unburned pine stands of Southern Italy. Comparisons of our results with other modelling experiences using USLE-family models in burned forests show satisfactory and inaccurate erosion predictions in Portugal (Vieira et al., 2018b) and in North-Western Spain (Fernández et al., 2010 and Fernández & Vega, 2016; 2018) in the short-term using the RUSLE model. The latter authors demonstrated that neither the model calibration by modifying the soil erosivity and erodibility, and the C-factors or letting the model account for the high organic matter content of soil significantly improved the model accuracy. In Greece, (Karamesouti et al., 2016) reported a large overestimation of erosion using RUSLE, due to inadequate C-factors.

4.4. Comparison of the three models and future research needs

The use of erosive models to predict soil loss under the three soil conditions gave contrasting results. A comparison of the erosion prediction capacity shown by the three models showed that the MMF model performs better and WEPP is the less accurate model in the experimental conditions. Therefore, MMF is the most accurate model for erosion predictions in the experimental environment, and furthermore offers simplicity of use low demand of input parameters. This derives from the availability of input parameters that successfully reproduce the effects of SWR and the post-fire variability of vegetation cover on the hydrological and erosive response of burned soils. Therefore, the MMF model appears as a valuable tool to predict both surface runoff (although this hydrological variable was not directly evaluated in this study) and soil loss in the Mediterranean burned forests, although being of less common use compared to the other two models. As such, the model may be used to prioritise the forest areas for post-management actions, in order to control the hydrogeological hazard and the risk of contamination of downstream water bodies. Furthermore, its process-based nature allows MMF to easily handle hydrological scenarios outside its calibration range, making the model particularly suitable for research purposes and scenario analysis (Beven, 2011; Vieira et al., 2014). In contrast, the USLE-M model must be further improved for erosion simulations in burned conditions, since the suggested values of the CN and C parameters are not able to reproduce the changes in soil hydrology due to wildfire. The use of the WEPP model is not advised in data-poor environments, such as the experimental site, since the scarce availability of input data affects the erosion prediction accuracy. Moreover, the use of MMF and WEPP models is more convenient compared to USLE-M, since the latter model does not predict surface runoff, which may be an essential information in areas that are prone to flooding hazard.

Overall, the comparison of these models to the same dataset, as done in this study, represents an added value (Larsen and MacDonald, 2007; Vieira et al., 2018), since this allows the determination of the structural uncertainty in modelling predictions (Lopes et al., 2021). This is in agreement with Alewell et al. (2019) and Batista et al. (2019), who consider that there is no optimal model for worldwide applications, but the accuracy of the predictions of a model is mainly due to the quality of the input parameters and the calibration process (Lopes et al., 2021). Therefore, comparative studies as the current work are essential for land managers and hydrologists, who must choose the most suitable prediction model for specific environmental conditions.

4.5. Future research needs

The verification of the three models in only one study area represents a limitation of our study, and this should be considered for future uses in other environmental contexts. More research is therefore needed to ensure the model transferability to other environmental contexts.

Widening the spatial scale and reducing the temporal scale supports a better understanding of post-fire impacts from on-site processes (plot or hillslope) to off-site impacts (catchment scale) (Lopes et al., 2021) on one side as well as the improvements of model predictions at the event scale. The latter concept is particularly true in those environments, where the hydrological and erosive response is produced by a low number of small but intense rainfall events (such as in the semi-arid conditions).

Moreover, there is the need for larger field datasets, which should allow a simultaneous model calibration and validation, which leads to a more robust prediction capacity of the tested models for MMF and to the possibility to identify the weakness in the applicability of the other two models.

Finally, we also suggest enlarging the modelling exercises about erosion in burned areas treated with post-fire management techniques, considering that the relevant research is not exhaustive and the number of studies that analyse the post-fire actions through erosion modelling is limited (Zema 2021).

5. Conclusions

In forest soils of Central Eastern Spain, burned by a wildfire and then mulched using straw, the WEPP model noticeably underestimated the erosion in the unburned areas, while, in contrast, the soil loss was largely overestimated in the burned soils also by several orders of magnitude. This large inaccuracy was presumably due to lack of model calibration. The uncalibrated MMF model noticeably over- or under-estimated the soil loss observations for all modeled soil conditions, when running with default input parameters. However, the optimisation of this model with a new procedure to estimate the C-factor, resulted in a satisfactory erosion prediction capacity, in burned plots with or without the mulching treatment. Calibration failed to improve the MMF model simulations in unburned soils. The performances of the USLE-M model were poor before and after calibration CNs and C-factors under all simulated soil management conditions. We conclude that the most accurate prediction model is MMF to estimate the soil loss in Mediterranean burned forests with or without post-fire mulching.

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Conflict of interest statement

All authors declare no conflict of interest.

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SUPPLEMENTARY MATERIAL

Table 1SM – Full list of input parameters of the WEPP model to predict soil loss at the experimental site (Agramón, Castilla-La Mancha, Spain).

Management	**Slope**			**Soil**							
	Position	**Length (m)**	**Slope (%)**	**Albedo**	**Initial saturation level (%)**	**Depth (mm)**	**Sand (%)**	**Clay (%)**	**OM (%)**	**CEC (meq/100g)**	**Rock (%)**
Unburned											
Shrub perennial	*Upper*	12.9	68.3	0.23	75	1000	26.3	14.3	2.88	9.9	50
	Middle	103.5	51								
	Lower	12.9	22.3								
Burned and not treated											
25% ground cover - high severity	*Upper*	13.6	23.7	0.23	75	1000	31.7	12.8	2.13	9.9	50
	Middle	108.8	41								
	Lower	13.6	21.3								
Burned and mulched											
Fallow initial condition - wheat residues	*Upper*	15.4	48.7	0.23	75	1000	30.2	18.5	2.38	9.9	50
	Middle	123.5	40.3								
	Lower	15.4	19								

Notes: OM = organic matter; CEC = cation exchange capacity.

Table 2SM – Full list of input parameters of the MMF model to predict soil loss at the experimental site (Agramón, Castilla-La Mancha, Spain).

Factor	**Soil condition**					
	Min	Max	Min	Max	Min	Max
	Unburned		*Burned and Not Treated*		*Burned and Mulched*	
	Uncalibrated model					
R	43.3	115.2	43.3	115.2	43.3	115.2
R_n	1	1	1	1	1	1
I	10	10	10	10	10	10
MS	0.2	0.2	0.4	0.4	0.4	0.4
BD	1.3	1.3	1.3	1.3	1.3	1.3
EHD	0.1	0.1	0.1	0.1	0.1	0.1
K	0.9	0.9	0.9	0.9	0.9	0.9
COH	2.0	2.0	2.0	2.0	2.0	2.0
S	27	27	22	22	22	22
A	0	0	0	0	0.3	0.3
Et/E_0	1	1	0.1	0.1	0.9	0.9
C	0.003	0	1	1	0	0
CC	0.7	0.7	0	0	1	1
GC	0.4	0.6	0	0	1	1
PH	0	0	0	0	0.5	0.5

	Calibrated model					
R	43.3	115.2	43.3	115.2	43.3	115.2
R_n	1	1	1	1	1.0	1.0
I	10	10	10	10	10.0	10.0
MS	0.35	0.35	0.28	0.28	0.28	0.28
BD	1.3	1.3	1.3	1.3	1.3	1.3
EHD	0.2	0.2	0.09	0.09	0.12	0.12
K	0.9	0.9	0.9	0.9	0.9	0.9
COH	2	2	2	2	2	2
S	27	27	22	22	22	22
A	0.0	0.0	0.0	0.0	0.06	0.06
E_t/E_0	0.80	0.70	0.05	0.05	0.50	0.45
C	0.135	0.156	0.120	0.558	0.029	0.034
CC	0.7	0.7	0	0	0.05	0.05
GC	0.45	0.39	0.19	0.07	0.56	0.47
PH	0.5	0.5	0	0	0.6	0.6

Notes: R = rainfall depth; R_n = rainy days; I = intensity of erosive rains; MS = moisture content at field capacity; BD = bulk density of the topsoil; EHD = effective hydrological depth; K = detachability index; COH = cohesion of surface soil; S = slope steepness; A = vegetation cover; E_t/E_0 = ratio of actual and potential evapotranspiration; C = cover management factor; CC = percent canopy cover; GC = ground cover; PH = plant height to the ground surface.

Table 3SM – Full list of input parameters of the USLE-M model to predict soil loss at the experimental site (Agramón, Castilla-La Mancha, Spain).

Model	**Input**	**Measuring unit**	**Soil conditions**

	parameter			**Unburned**		**Burned and not treated**		**Burned and mulched**	
				Default	**Calibrated**	**Default**	**Calibrated**	**Default**	**Calibrated**
SCS-CN	CN	-		39	7	90 (79)	13	65 (39)	8
	λ	-		0.2					
USLE-M	Q_r	-	max	0.375		0.694		0.570	
			min	0.176		0.409		0.001	
	R_e-factor	MJ mm/ ha h	max	302					
			min	7					
	LS-factor			60.51					
	K_{UM}-factor	tons h/MJ mm		0.002		0.001		0.002	
	C-factor	-		0.0001	0.0002	0.006	0.526	0.0002	0.085
	P-factor	-		1					

Notes: CN = curve number; λ = rainfall depth coefficient; R_e-factor = rainfall erosivity factor; K_{UM}-factor = soil erodibility factor; C-factor = cover management factor; P-factor = conservation practice factor; the values related to the first two modelled events are reported in brackets.