

Università degli Studi Mediterranea di Reggio Calabria

Archivio Istituzionale dei prodotti della ricerca

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

This is the peer reviewd version of the followng article:

Original

Soil erosion modelling of burned and mulched soils following a Mediterranean forest wildfire / Gonzalez-Romero, J; Zema, Da; Carrá, Bg; Neris, J; Fajardo, A; Plaza-Alvarez, Pa; Moya, D; Peña-Molina, E; de las Heras, J; Lucas-Borja, Me. - In: SOIL USE AND MANAGEMENT. - ISSN 0266-0032. - 39:2(2023), pp. 881-899. [10.1111/sum.12884]

Availability: This version is available at: https://hdl.handle.net/20.500.12318/141557 since: 2024-11-22T10:46:28Z

Published DOI: http://doi.org/10.1111/sum.12884

The final published version is available online at:https://bsssjournals.onlinelibrary.wiley.com/doi/10.

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website

Publisher copyright

This item was downloaded from IRIS Università Mediterranea di Reggio Calabria (https://iris.unirc.it/) When citing, please refer to the published version.

| 1 | This is the peer reviewed version of the following article: |
|----|---|
| 2 | |
| 3 | Gonzalez-Romero, J., Zema, D.A., Carrà, B.G., Neris, J., Fajardo, A., Plaza-Álvarez, P.A., |
| 4 | Moya, D., Peña-Molina, E., de las Heras, J., Lucas-Borja, M.E. 2023. Soil erosion modelling |
| 5 | of burned and mulched soils following a Mediterranean forest wildfire. Soil Use and |
| 6 | Management (Wiley), 39(2), 881-899, |
| 7 | |
| 8 | which has been published in final doi |
| 9 | |
| 10 | 10.1111/sum.12884 |
| 11 | |
| 12 | (https://bsssjournals.onlinelibrary.wiley.com/doi/full/10.1111/sum.12884) |
| 13 | |
| 14 | The terms and conditions for the reuse of this version of the manuscript are specified in the |
| 15 | publishing policy. For all terms of use and more information see the publisher's website |

| 16 | Soil erosion modelling of burned and mulched soils following a Mediterranean forest |
|----|--|
| 17 | wildfire |
| 18 | |
| 19 | Erosion prediction by WEPP, MMF and USLE-M models in burned and mulched forests |
| 20 | |
| 21 | Javier Gonzalez-Romero ¹ , Demetrio Antonio Zema ^{2,*} , Bruno Gianmarco Carrà ² , Jonay Neris ³ , |
| 22 | Alvaro Fajardo ¹ , Pedro Antonio Plaza-Álvarez, Daniel Moya ¹ , Jorge de las Heras ¹ , Manuel |
| 23 | Esteban Lucas-Borja ¹ . |
| 24 | |
| 25 | ¹ School of Advanced Agricultural and Forestry Engineering, Campus Universitario s/n, |
| 26 | Castilla-La Mancha University, E-02071 Albacete, Spain |
| 27 | ² Department AGRARIA, "Mediterranea" University of Reggio Calabria, Località Feo di Vito, I- |
| 28 | 89122 Reggio Calabria, Italy |
| 29 | ³ Department of Animal Biology, Edafology and Geology, Faculty of Biology, University of La |
| 30 | La Laguna, Av. Astrofísico Fco. Sánchez s/n, E-38071 La Laguna, Tenerife, Spain. |
| 31 | |
| 32 | * Correspondence: dzema@unirc.it |

34 ABSTRACT

Soil erosion modelling applied to burned forests in different global regions can be unreliable due 35 to a lack of verification data. Here, we evaluated the following three erosion models: (1) Water 36 Erosion Prediction Project (WEPP), (2) Morgan-Morgan-Finney (MMF) and (3) Universal Soil 37 Loss Equation-Modified (USLE-M). Using field plots that were either untreated or mulched with 38 straw, this study involved observations of soil loss at the event scale at a burned pine forest in 39 Central Eastern Spain. The erosion predictions of the three models were analysed for goodness-40 of-fit. Optimisation of the MMF model with a new procedure to estimate the C-factor resulted in 41 a satisfactory erosion prediction capacity in burned plots with or without the mulching treatment. 42 The WEPP model underestimated erosion in the unburned areas and largely overestimated the 43 soil loss in burned areas. The accuracy of soil loss estimation by the USLE-M model was also 44 poor. Calibration of the Curve Numbers and C-factors did not improve the USLE-M model 45 estimation. Therefore, we conclude that an optimised MMF model was the most accurate way to 46 estimate soil loss and recommend this approach for in Mediterranean burned forests with or 47 without post-fire mulching. This study gives land managers insight about the choice of the most 48 suitable model for erosion predictions in burned forests. 49

51 **KEYWORDS:** soil loss; post-fire management; calibration; erosion model; plot scale; event 52 scale.

53

54 1. INTRODUCTION

55

Models are essential tools to simulate the complex processes in disturbed soils, and to predict the 56 soil response to the hydrological input in a cost-effective and time-efficient way (Filianoti et al., 57 2020). Many models are capable of predicting soil erosion in different climatic and 58 geomorphological conditions (Bezak et al., 2021; Borrelli et al., 2021). In comparison to the 59 most complex physically-based algorithms, empirical models are easy and quick to apply at 60 specific sites, and their prediction capability is often satisfactory (Aksoy & Kavvas, 2005; Lucas-61 Borja, Bombino, et al., 2020). Many empirical models, such as the USLE (Universal Soil Loss 62 Equation) equation, have been used as erosion component of many catchment-scale erosion 63 models (e.g., AnnAGNPS and SWAT models). In contrast, where input parameters can be 64 directly measured in the field or are available for a specific environment, the physically-based 65 models theoretically provide more accurate predictions of erosion (Zema, Lucas-Borja, et al., 66 2020; Zema, Nunes, et al., 2020). 67

Wildfire is a common natural disturbance in Mediterranean ecosystems, and usually enhances 68 soil erosion, which may increase ecosystem degradation to unsustainable rates. To limit soil 69 degradation in the Mediterranean forests, a proper control of erosion is necessary. On this regard, 70 erosion models, commonly used in agricultural areas (Borrelli et al., 2018; Panagos & 71 Katsoyiannis, 2019), have been also extended to burned areas (Lopes et al., 2021; Vieira et al., 72 2014). According to Lopes et al. (2021), published literature on post-fire erosion modelling is not 73 homogeneously distributed worldwide. While post-fire prediction models are commonly used in 74 the United States, research is still far from being exhaustive in other regions (Hosseini et al., 75 2018). In the Mediterranean burned areas, where the hydrological processes are site-specific 76 (Shakesby, 2011; Wagenbrenner et al., 2021), the available erosion models may find limitations 77 in their applicability, especially when the soils are subjected to post-fire management. Therefore, 78 these models require localised optimisation, since these hydrological tools have been developed 79 in other environmental contexts and are not designed to be applied specifically in burned areas 80 (Vieira et al., 2018a). 81

Erosion models include simple empirical models, such as the USLE-family models, to semiempirical 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 84 & Kavvas, 2005; Merritt et al., 2003; Zema, Lucas-Borja, et al., 2020; Zema, Nunes, et al., 85 2020). Regarding the USLE-family models, only the RUSLE version has been used in wildfire-86 affected soils (e.g., Fernández et al., 2010; Karamesouti et al., 2016; Larsen & MacDonald, 87 2007; Vieira et al., 2018b). To the authors' best knowledge, the event-scale USLE-family model 88 (USLE-M) has been applied only by Carrà et al. (2021) in Southern Italy treated with prescribed 89 fire and fern mulching. Erosion predictions using WEPP were carried out by (Covert et al., 2005; 90 Fernández & Vega, 2018; Larsen & MacDonald, 2007; Soto & Díaz-Fierros, 1998) in 91 Mediterranean forests burned by wildfires. The MMF model has been verified in burned areas 92 with or without post-fire treatments under different Mediterranean climates in North-Western 93 and Central-Eastern Spain, and in Central Portugal (Fernández et al., 2010; Vieira et al., 2014, 94 2018b; Zema, Nunes, et al., 2020). The latter authors suggested an adaptation of this model to 95 uses on the event scale in burned forests, mulched or untreated. 96

This study evaluated the prediction capability of the USLE-M (coupled to the Curve Number 97 method to estimate the runoff coefficient), MMF and WEPP models in a Mediterranean forest 98 burned by a wildfire and then treated with soil mulching in comparison to unburned areas. The 99 investigation was carried out at the plot and event scales throughout one year in a pine stand of 100 Castilla-La Mancha (Central Eastern Spain). This study is the first application of the USLE-M 101 and WEPP models to wildfire-affected soils subjected to post-fire mulching in Mediterranean 102 forests as well as applying the MMF model in a Mediterranean pine forest on untreated or 103 mulched soils. The erosion prediction capacity of the latter model was successfully evaluated 104(Zema, Nunes, et al., 2020), but without a further validation in other sites with similar 105 environmental characteristics. Moreover, a new procedure to estimate the C-factor based on the 106 ground cover as input parameter for the MMF model was proposed and evaluated in this 107 modelling exercise. This study aims at providing insight about the choice of the most suitable 108 model for erosion predictions in burned forests to land managers and hydrologists. 109

- 110
- 111

1 2. MATERIALS AND METHODS

112

113 **2.1. Study area**

114

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 118 classification (Kottek et al., 2006), where the average annual precipitation and temperature are 119 320 mm and 16 °C, respectively. In the first year after the fire, a total precipitation of 400 mm 120 was recorded. The parental materials that make up this area are limestones, such as dolomites, 121 marls, and clay. The soils are shallow (depth lower than 0.3 m), with low organic matter content, 122 the main types being Inceptisols and Aridisols (USDA, 1999). The soil texture of the study area 123 is presented in Table 1. The vegetation in the area consists of a Pinus halepensis forest with a 124 shrub and herbaceous companion layers dominated by Macrochloa tenacissima and Salvia 125 Rosmarinus, and other minor species, such as Pistacia lentiscus, Quercus coccifera, Rhamnus 126 lycioides, Thymus vulgaris and Cistus clusii. 127



Burned and mulched



- 130 perimeter (B) and aerial map of the experimental plots (C) (Agramón, Castilla-La Mancha,
- 131 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 (%) | | |
| | 1 | 47.8 | East | 28.7 | 58.8 | 14.8 | 2.40 | 75.6 | | |
| Unburned | 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 | 1 | 40.8 | South-East | 31.5 | 55.7 | 12.2 | 2.01 | 30.2 | | |
| treated | 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 | 1 | 40.1 | South-East | 33.4 | 49.2 | 19.2 | 2.90 | 44.1 | | |
| mulched | 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 | | |

- 135 2.2. Experimental design
- 136

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 140 equipped to collect the sediments (Figure 1). The soil slope was between 39.8% and 47.8%, 141 while the aspect south, east or south-east. The soil texture was homogenous, with contents of 142 sand, silt and clay in the range 24.3-33.6%, 49.2-61.2% and 12.2-19.2%, and of organic matter 143 between 2.01% and 2.90% (Table 1). Of the nine plots, three were identified in an unburned area 144that was adjacent to the burned forest. Other six plots were selected in the burned area, of which 145 three were not treated and other three were subjected to post-fire soil mulching one month after 146 the fire. The mulch material was barley straw, which was manually spread on the plots at a rate 147 of 0.25 kg/m² (dry weight) and thickness of 3 cm (Lucas-Borja et al., 2018; Lucas-Borja et al., 148 2020). This mulch rate was based on a previous study by (Vega et al., 2014), who proposed this 149 dose to achieve a soil cover of 80% for burned plots installed in Northern Spain. The soil cover 150 varied from 28.6% (burned and untreated plots) to 75.6% (burned and mulched plots) (Table 1). 151

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.

159

160 2.3. Experimental observations of soil erosion

161

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 (I₃₀) was between 9.2 and 64.8 mm/h (Table 2 and Figure 2), and the maximum rainfall erosivity (EI₃₀) 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

- 169 0.96 to 1.63 tons/ha, while the values measured in the burned and mulched plots varied from 170 0.16 to 0.29 kg/m² (Table 2).
- 171
- 172 Table 2 Rainfall characteristics and soil loss observations at the experimental site (Agramón,
- 173 Castilla-La Mancha, Spain).
- 174

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



Figure 2 – Rainfall depth and erosivity (EI₃₀) at the experimental site (Agramón, Castilla-La
Mancha, Spain).

176

The hydrological dataset used for model is made of a sample of seven observations of soil loss, 181 which, however, allows the evaluation of the model's prediction capacity for two reasons. First, 182 wildfire opens in the burnt area a so-called "window of disturbance" (Prosser & Williams, 1998; 183 Zavala et al., 2014), when the soil is bare due to the vegetation burning and many of its physico-184 chemical properties undergo noticeable changes (Moody et al., 2013; Zema, 2021). Both effects 185 result in a strong alteration in the hydrological response of severely-burned soils, which however 186 is only temporary. Although the duration of this window of disturbance may be variable 187 depending on soil, weather and fire characteristics, the pre-fire conditions generally recover after 188 one year, which is the duration of the observation period of this study. The measurements of soil 189 erosion in the experimental area were made in this window of disturbance. Second, in the semi-190 arid environments (such as the study area), annual erosion is substantially due to few but intense 191 rainstorms (the so-called "erosive events", according to Wischmeier & Smith (1978), that is 192 events with rainfall depth over 13 mm). The events of our dataset are all those events that 193 overcome this threshold and produced erosion, while the other smaller events were not 194 considered. 195

197 2.4. Short description of the WEPP, MMF, and USLE-M models

198

The "Water Erosion Prediction Project" (WEPP, Flanagan & Nearing, 1995) is a physically-199 based, distributed parameters, continuous simulation model, which was developed by USDA-200 Natural Resources Conservation Service in late '1980s. The model is used to predict the spatial 201 and temporal distribution of net soil loss and deposition for a wide range of time periods and 202 spatial scales. The WEPP hillslope version (Foster & Lane, 1987) was used in this study to 203 predict soil erosion along a single slope profile. More details about the equations governing the 204 erosion simulations by the WEPP model and the input parameters are reported in Flanagan & 205 Nearing (1995) and Foster & Lane (1987). 206

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, 212 1978), in order to predict soil loss in small agricultural catchments. The mean annual soil loss is 213 calculated as the product of six input parameters (the so-called "USLE-factors"), linked to 214 climate, soil cover and properties, topography, and human activities (R, K, L, S, C and P). In 215 1998, Kinnell & Risse (1998) proposed the USLE-M model (USLE modified), which assumes 216 that the sediment concentration in the runoff is governed by the event rainfall erosivity index (Re, 217 Wischmeier & Smith, 1978) per unit quantity of rain (Pe, mm). The equations to calculate the 218 soil loss Y and the input factors are reported in the study by Kinnell & Risse (1998). 219

220

221 **2.5. Model implementation**

222

223 2.5.1. General information

224

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.

229 2.5.2. WEPP model

230

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.

243

244 2.5.3. MMF model

245

MMF was run at the event scale and parameterised using the default input data (hereafter 246 "default model") or adjusted values for post-fire conditions ("calibrated model") and for each 247 event. For runs using the default model, the values of the input parameters suggested in the 248 original studies of Morgan et al. (1984) and Morgan (2001) were adopted. For the erosion 249 predictions using the calibrated model, MMF was run simulating the post-fire conditions, 250 according to the adaptations suggested by Fernández et al. (2010), Vieira et al. (2014) and Zema, 251 Nunes, et al. (2020), where more details can be found. To summarise, the input parameters 252 needed by MMF were measured in-field or derived from the guidelines of Morgan (2001), 253 Morgan et al. (1984) and Morgan & Duzant (2008) with the corrections according to Vieira et al. 254 (2014) and Nunes et al. (2016), or estimated from the literature (Doorenbos & Kassam, 1979; 255 Fernández et al., 2010; Vieira et al., 2014; Wischmeier & Smith, 1978; Zema, Nunes, et al., 256 2020). 257

259 2.5.4. USLE-M model

260

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 266 was estimated by the Soil Conservation Service-Curve Number (SCS-CN) method (SCS, 1985) 267 (as explained below). In more detail, the rainfall depth of each modelled storm event was 268 estimated by aggregating the sub-hourly records collected at the rain gauging station. The 269 Antecedent Moisture Content (AMC) was estimated by aggregating the 5-day rainfall depths 270 prior to each event. The soil hydrological group was identified as "B" ("soils having a 271 moderate infiltration rate when thoroughly wet"). The default values of CN were assumed 272 following the standard procedure by the USDA Soil Conservation Service (SCS, 1985). 273

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.

278

279 **2.6. Model calibration**

280

282

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.

287

288 2.6.2. *MMF model*

289

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

^{281 2.6.1.} WEPP model

prediction capacity after rainfall events in burned forest soils for Mediterranean conditions, we 292 adopted these adaptations for the MMF calibration were (Tables 3 and 2SM): (i) input of 293 seasonal values of the moisture content at field capacity (MS), corrected by changes in soil water 294 repellency (SWR) (except for unburned plots), ratio between the actual (E_t) to potential (E_0) 295 evapo-transpiration (E_t/E_0), and ground cover (GC), according to Vieira et al. (2014); (ii) model 296 running at the event scale rather to simulate seasonal or annual soil loss, since, in the 297 Mediterranean climate, soil erosion is mainly determined by few but intense rainfall events (e.g., 298 Fortugno et al., 2017); (iii) setup of the MS input parameter to 0.28 for sandy loam soils 299 (Morgan, 2001) with the correction suggested by the "SM-SWR" modelling approach of Vieira 300 et al. (2014) and Nunes et al. (2016), to take into account the effect of soil water repellency on 301 soil wetting (from 0.8 for extreme repellency to 1.1 under wettable conditions (Vieira et al., 302 2014); (iv) modification of effective hydrological depth (EHD) suggested by Hosseini et al. 303 (2018) and Vieira et al. (2014), considering two soil layers, of which the deeper layer was not or 304 scarcely influenced by the fire effects (50% of the original depth), while the topsoil was affected 305 by the high burn severity and the post-fire treatment. 306

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:

312

$$_{313} \qquad C_{corr} = C \cdot FC \tag{1}$$

314

$$FC = \frac{1}{\frac{\overline{GC - \overline{GC}}}{\overline{GC}} + 1}$$
(2)

315 316

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).

- 322
- 323

Table 3 - Input parameters of the MMF model to predict soil loss at the experimental site 324 (Agramón, Castilla-La Mancha, Spain). 325

326

| | | | Soil co | ndition | | | | |
|-----------|-------|-------|-----------|-----------|-------|------------|--|--|
| | Min | Max | Min | Max | Min | Max | | |
| Factor | Unh | umad | Burned | and Not | Burne | Burned and | | |
| | Undi | лпец | Tree | ated | Mul | ched | | |
| | | | Uncalibra | ted 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 | | |
| С | 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 | | |
| | | 1 | Calibrate | ed model | | I | | |
| 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 | | |
| С | 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 | | |

327

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 =328 ground cover; PH = plant height to the ground surface. 329

330

2.6.3. USLE-M model 331

332

For USLE-M calibration, the most sensitive input parameters (CN for the SCS-CN model and 333 the C-factor for the USLE-M) were chosen (Carra et al., 2021). First, constant CNs and C-factors 334 for all the modelled events were input, then these parameters were increased for the first two 335

- rainfall events for the burned catchments, in order to simulate the variable hydrological response 336 of soils throughout the observation period. This choice agrees with several studies (e.g., Carra et 337 al., 2021; Cawson et al., 2012; Lucas-Borja, Bombino, et al., 2020; Vieira et al., 2015). To avoid 338 separate calibration of two factors, the effects of the mulching practice were included in the C-339
- factor, and the P-factor was set to one (Table 4 and 3SM). 340

- For MMF and USLE-M models, the calibration was carried out manually by a trial-and-error 341
- procedure until the maximum coefficient of efficiency (see section 2.6) and the minimum error 342 between the mean values of the observations and simulations of soil loss were achieved. Due to 343
- the lack of runoff observations, only the erosive sub-model of MMF was optimised. However, 344
- 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 346
- environmental conditions, were embedded in the optimised model. 347

³⁴⁸ Table 4 – Input parameters of the USLE-M model to predict soil loss at the experimental site (Agramón, Castilla-La Mancha, Spain).

349

| Model | | | Soil conditions | | | | | | | |
|--------|-----------|----------------|-----------------|------------|------------|---------------|--------------------|------------|--|--|
| | Input | | Unburned | | Burned and | l not treated | Burned and mulched | | | |
| | parameter | Weasuring unit | 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.

352 **2.7. Model evaluation**

353

The erosion predictions by the three models were analysed for "goodness-of-fit" with the 354 corresponding observations adopting qualitative and quantitative procedures. The qualitative 355 approach consisted of the visual comparison of the observed and the corresponding soil loss in 356 scatterplots. The quantitative procedure used the indicators that are commonly adopted in the 357 literature (e.g., Willmott, 1982; Legates and McCabe, 1999; Loague and Green, 1991; Zema et 358 al., 2017; 2018). More specifically, we used: (i) the main statistics (i.e., the maximum, minimum, 359 mean and standard deviation of both the observed and simulated values); (ii) the coefficient of 360 determination (r^2) ; (iii) the coefficient of efficiency (NSE, Nash & Sutcliffe, 1970); (iv) the Root 361 Mean Square Error (RMSE); and (v) the percent bias (PBIAS). The equations to calculate these 362 indicators are reported in the studies by Krause et al. (2005), Moriasi et al. (2007), Van Liew & 363 Garbrecht (2003) and Zema et al. (2012). The acceptance or optimal values are as follows (i) r^2 is 364 in the range 0 (no agreement between observed and predicted data) to 1 (perfect agreement), 365 being acceptable when over 0.5 (Santhi et al., 2001; Van Liew et al., 2003; Vieira et al., 2018b); 366 (ii) NSE varies between $-\infty$ and 1, and the model accuracy is "good" if $E \ge 0.75$, "satisfactory" if 367 $0.36 \le E \le 0.75$ and "unsatisfactory" if $E \le 0.36$ (Van Liew et al., 2003); (iii) RMSE is optimal 368 when it approaches to 0 (Fernández et al., 2010), and the predictions are "good", when RMSE is 369 lower than half the observed standard deviation (Singh et al., 2005); (iv) PBIAS, which is also 370 reported as "coefficient of residual mass", is positive, when a model underestimates the 371 observation, and negative in the case of overestimation (Gupta et al., 1999); a model with 372 CRM/PBIAS below 55% is considered fair for erosion predictions (Moriasi et al., 2007). 373

374

375 **3. RESULTS**

376

377 **3.1. WEPP model**

378

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).

Unburned

Burned and not treated







392

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).
- 398

| Soil loss | Mean (tons/ha) | Minimum (tons/ha) | Maximum (tons/ha) | Standard deviation (tons/ha) | r ² | Е | 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 | 0.55 | | | -122 | | | | | |
| | 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 | 0.00 | | | | | | | | |
| | | 1 | Bı | irned and m | ulched soil | 1 | 1 | | | | | | |
| Observed | 0.205 | 0.165 | 0.292 | 0.043 | 0.24 | 27(4200 | ((7 | 222 | | | | | |
| Predicted | 47.882 | 0.000 | 132.530 | 50.364 | 0.24 | -2704390 | 00.7 | -232 | | | | | |
| | | 1 | Uno | calibrated N | MMF mod | el | 1 | | | | | | |
| | | | | Unburne | ed soil | | | | | | | | |
| Observed | 0.001 | 0.001 | 0.001 | 0.000 | 0.00 | 25649 | 0.00 | 22.05 | | | | | |
| Predicted | 0.017 | 0.003 | 0.040 | 0.014 | 0.00 | -33048 | 0.00 | -23.03 | | | | | |
| | | 1 | Bur | rned and not | t treated so | il | I | | | | | | |
| 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 | | | | | | | | |
|-----------|---------------------------|-----------------------------|--------|-------------|-------------|--------|------|-------|--|--|--|--|
| | | | Bı | urned and m | ulched soil | 1 | 1 | 1 | | | | |
| 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 | 0.01 | -20.18 | 0.02 | 1.00 | | | | |
| | Calibrated MMF model | | | | | | | | | | | |
| | | | | Unburne | ed 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 | 0.01 | -04.0 | 0.00 | -0.15 | | | | |
| | | 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 | 0.74 | 0.75 | 0.01 | 0.00 | | | | |
| | | 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 | 0.00 | | | -0.15 | | | | |
| | 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 | 0.00 | 27.1 | 0.00 | 0.00 | | | | |
| | | 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 | 0.00 | | 1.50 | | | | | |
| | | 1 | Bı | urned and m | ulched soil | 1 | 1 | 1 | | | | |

| 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 | 0.02 | -20.1 | 0.21 | |
| | | | Cali | ibrated US | LE-M mod | lel | | • |
| | | | | Unburne | ed 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 | 0.00 | -15.0 | 0.00 | 0.12 |
| | | | Bui | rned and no | t treated so | il | 1 | 1 |
| Observed | 1.374 | 0.959 | 1.631 | 0.231 | 0.03 | 11.0 | 0.77 | 0.24 |
| Predicted | 1.038 | 0.040 | 1.881 | 0.749 | 0.05 | 11.0 | 0.77 | 0.24 |
| | | | Bı | irned and n | nulched soil | | I | 1 |
| 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 | 0.20 | 10.5 | 0.15 | 0.20 |

Notes: r^2 = coefficient of determination; NSE = coefficient of efficiency of Nash and Sutcliffe; RMSE =

400 Root Mean Square Error; PBIAS = Coefficient of Residual Mass.

402 **3.2.** *MMF model*

403

As noticed for WEPP, also the MMF model running with default parameters generally showed a 404 large inaccuracy in predicting the soil loss. This is visually shown in the relevant scatterplot 405 under all the soil conditions (Figure 4a) and confirmed by the poor evaluation indicators. The 406 differences between the mean, maximum and minimum values of the predictions and 407 observations were very large (> 100% for the mean, minimum, and maximum values). The 408 values of r^2 were very low (< 0.16), and negative NSE were achieved (< -26.2). These values, 409 coupled to the very large RMSEs (> 0.02 tons/ha), show the inaccuracy of the default MMF 410model in predicting the erosion under all the modelled soil conditions (Table 5). This poor 411 prediction capacity is due to the large over-estimation (in unburned, PBIAS = -23.1, and burned 412 plots, PBIAS = -5.52) or under-estimation (in burned and mulched soils, PBIAS of 1) of the 413 observations. 414

Due to these unsatisfactory performances, MMF was optimised as reported in the section 2.5.2. 415 The model adaptations to the post-fire conditions greatly improved the erosion prediction 416 capacity of MMF, except in the unburned soils. Under this condition, the values of r^2 were close 417 to zero, and NSE was largely negative (-84.6). The differences between the predictions and the 418 corresponding observations were low for the mean values (-12.6%), but high for the other 419 statistics (> 92.5%), although the model tendency to over-prediction was low (PBIAS = -0.13). 420 In burned conditions, the large scattering of the "observations vs. predictions" pairs, which was 421 large in the unburned soils, was reduced, and these pairs were close to the line of perfect 422 agreement (Figure 4b). The improvement of the model performance is confirmed by the 423 quantitative analysis. More specifically, the differences between the mean observed and 424 predicted soil loss were from 5.1% (burned and not treated soils) to 12.9% (burned and mulched 425 plots), while the maximum values differed by 1.41% (burned and not treated soils) to 6% 426 (unburned plots). The r^2 values were between 0.86 (burned and mulched soils) and 0.94 (burned 427 and not treated conditions), and the RMSE values were lower than half the observed standard 428 deviations (except under burned and mulched soil conditions). The soil loss prediction capacity 429 can be considered good in the unburned, and burned and not treated soil conditions (NSE = 430 0.75), and satisfactory for the burned and mulched plots (NSE = 0.43). The large over- or under-431 estimation, previously noticed for the default model, disappeared, and the observed soil loss was 432 only slightly under-predicted in burned and not treated soils (PBIAS of 0.06) or over-predicted 433 (burned and mulched plots, PBIAS = -0.13) by the optimised MMF model (Table 5). 434















442

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).

445

446 **3.3. USLE model**

447

The USLE model, running with default input parameters, showed a poor prediction capacity of 448 erosion under all soil conditions. The visual evaluation highlights a large scattering of data 449 around the line of perfect agreement (Figure 5a), and also the evaluation indicators confirm this 450 poor performance. In more detail, the differences in the main statistics between the observations 451 and the corresponding predictions were large (up to 100% for the mean and maximum values). 452 The values of r^2 did not exceed 0.08 (unburned plots), NSE was always negative (< -26.1), and 453 RMSE was always unsatisfactory (not lower than 10-fold half the observed standard deviation). 454 This poor model performance is due to the large under-estimation (for all soil conditions, PBIAS 455 > 0.80) of the observations (Table 5). 456

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).

466





- 468
- 469
- 470
- 471



473

(b)

Figure 5 - Scatterplots of observed vs. predict soil loss using the USLE-M (default, a, and 474 calibrated, b) model at the experimental site (Agramón, Castilla-La Mancha, Spain). 475

476

4. Discussion 477

478

4.1. WEPP model 479

480

The WEPP model gave poor predictions of soil loss in both unburned and burned areas (with and without the post-481 fire treatment). WEPP underestimated the erosion in the unburned plots, while, in contrast, the soil loss was largely 482 overestimated in burned soils also by several orders of magnitude. The reason of this high inaccuracy could be 483 many. First, the lack of calibration did not balance errors related to model parameterisation and hydrological 484 simulations. The WEPP model requires dozens of input parameters that should be measured in the field. Since these 485 measurements were not available at the experimental site, the modellers were forced to adopt literature values (e.g., 486 for K_e, K_i, K_r, and τ_c) with evident low accuracy at reproducing the observed erosion rates. This problem limits the 487 WEPP applicability in poor-data environments, where the erosion predictions may be generally inaccurate. Second, 488 low erosion rates, as observed at the experimental site, are generally predicted with unsatisfactory reliability by 489 WEPP (e.g., Grønsten & Lundekvam, 2006; Konz et al., 2009; Licciardello et al., 2006; Soto & Díaz-Fierros, 1998), 490 491 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-492 intensity rainfall (Beven & Kirkby, 1979). Third, the overland erosion being zero, it is evident that WEPP also failed 493 at simulating the rainsplash erosion, which may be dominant at the experimental site (Díaz et al., 2022; Lucas-Borja 494

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
l ton/ha-yr.

503 4.2. MMF model

504

502

The erosion predictions of the default (uncalibrated) MMF were inaccurate for all modelled soil 505 conditions, since the model noticeably over- or under-estimated the soil loss observations. We 506 should remind that MMF has a strong empirical base and was developed using mostly smaller 507 scale erosion plot data derived from agricultural fields (Vieira et al., 2018b). Therefore, the 508 extrapolations to other land uses, such as the burned forestlands, have been made using 509 corrections of the internal algorithms based on an empirical approach. In the burned and mulched 510 plots, these poor performances were due to the inadequate estimation of the sediment transport 511 capacity, since the model did not produce soil loss (which, in MMF, is the lower value between 512 the sediment detachment and the transport capacity). The model, running with a too high default 513 C-factor, simulated a total shadowing effect of the mulch material against rainfall erosivity, 514 which resulted in a soil particle detachment equal to zero. This explanation agrees with the 515 findings of Zema, Nunes, et al. (2020) and Vieira et al. (2014), who also found MMF failures in 516 reproducing the sediment transport capacity. For the other soil conditions (unburned, and burned 517 and not treated soils), the reasons of the low prediction capacity are not so clear as for burned 518 and mulched conditions. A reason may be the inadequate incorporation of the fire effects in the 519 soil parameters, which are variable over time, while all parameters were left constant throughout 520 the modelling period. Wildfire, especially when at high severity, such as in our experiment, 521 noticeably changes some physical properties of soil, and these changes are not easy to be 522 reproduced in empirical models without recurring to correction factors (e.g., the C factor). Also 523 Fernández et al. (2010) highlighted the role played by the C and P factors on reliable predictions 524 of erosion by MMF, which often may lead to poor results, when these parameters are not fully 525 established in the model input procedure. 526

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 532 other words, the soil loss due to rainsplash erosion and particle detachment by overland flow is 533 simulated by MMF, but the process of sediment entrapment in the flow is not realistically 534 reproduced. In contrast, the model prediction capacity was acceptable in the mulched plots and 535 satisfactory in the burned and not treated soils. We ascribed the reasons for this model accuracy 536 to the adaptations of the model to the burned conditions using the modifications of the internal 537 algorithms and correction factors reported in methodology. More specifically, the incorporation 538 of SWR effects, the modification of EHD, both following seasonal patterns, and the temporal 539 downscaling to rainstorm events were successful to reproduce the variable dynamics of post-fire 540 hydrology in the experimental soil. In contrast, the input of calibrated C-factors under post-fire 541 management was less effective at modelling erosion in burned and mulched areas. A slight 542 tendency to under-estimation or over-estimation of the observed soil loss remained. This model 543 behaviour has been commonly detected in many MMF applications in burned areas (Fernández 544et al., 2010; Hosseini et al., 2018; Vieira et al., 2014, 2018b; Zema, Nunes, et al., 2020). It is 545 worth to notice that the optimisation of the C-factor, which was weighted by the vegetal cover, 546 improved the good prediction capacity of erosion under the same environmental conditions 547 reported by Zema, Nunes, et al. (2020). The need of C-factor tuning is in agreement with several 548 studies, which have demonstrated how accurate methodologies to estimate the C-factor are the 549 key to reproduce the fire effects on soils (e.g., Larsen & MacDonald, 2007; Vieira et al., 2014). 550 The comparison of our results with other MMF modelling experiences in Mediterranean 551 conditions shows that the changes suggested by the previous studies (Hosseini et al., 2018; 552 Vieira et al., 2014, 2018b; Zema, Nunes, et al., 2020), coupled to the C-factor tuning proposed in 553 this investigation, successfully improved the MMF ability to model soil hydrology under 554 variable conditions at the event scale. The model efficiency calculated in our study is similar to 555 the values found by Vieira et al. (2014), who applied MMF in North-Central Portugal, and by 556

Zema, Nunes, et al. (2020) in Central-Eastern Spain. Lower model efficiency (in the range 0.54-557 0.74) were reported by Vieira et al. (2014) again in North-Central Portugal, and by Fernández et 558 al. (2010) and Hosseini et al. (2018) in North-Western Spain and North-Central Portugal, 559 respectively. However, it should be highlighted that, while our study applied MMF at the event 560 scale, all the other model experiences were carried out at aggregate temporal scales (from 561 seasonal to annual periods). Many studies have shown that the erosion models better perform in 562 predicting the average soil loss rather than erosion rates for specific events (Fernández et al., 563 2010; Larsen & MacDonald, 2007). 564

The erosion predictions using the USLE-M model, running with default and calibrated input 568 parameters, were poor. This low performance of the model is common for many erosion models, 569 which generally over-estimate and under-estimate the lower and higher soil losses, respectively 570 (Kinnell, 2003; Larsen & MacDonald, 2007; Nearing, 2000). In our opinion, the most important 571 reason for this inaccuracy was the lack of observed values of the runoff coefficients. Their 572 estimations required the use of the SCS-CN method in our study leading to a worse performance 573 of the USLE-M model compared to MMF (which internally simulates surface runoff). The 574 increases in the CNs of fire-affected areas are suggested by several authors (e.g., Carra et al., 575 2021; Lucas-Borja, Bombino, et al., 2020; Papathanasiou et al., 2015; Soulis, 2018), in order to 576 simulate the effects of soil water repellency (left by wildfire) and complete removal of 577 vegetation (due to burning) on soil hydrological properties in the "window-of-disturbance". 578

In accordance with Vieira et al. (2015), another limitation of the USLE-family model is its great 579 dependence on empirical parameters, such as the C and P-factors, to estimate the soil losses. The 580 C-factor values, in spite of calibration, were not able to simulate the effect of the vegetation 581 cover (in unburned and burned but untreated plots) and of the mulch layer against rain splash 582 erosion and overland flow, thus contributing to the unsatisfactory model performances. Also the 583 increase in soil erodibility (expressed by the K-factor) due to the wildfire-induced changes in 584 physical parameters of soil and the lack of parameters simulating the effects of SWR may have 585 played a significant role in this model inaccuracy (Fernández et al., 2010). We also agree with 586 the latter authors about the inefficient use of an inadequate kinetic energy equation of rainfall for 587 the Mediterranean climate by the USLE-family models, which could have affected the 588 simulation of the real rainfall erosivity in the experimental conditions. 589

The poor prediction capacity of USLE-M indicates that the literature values that were adopted 590 for the input parameters were not suitable for simulating erosion in unburned and burned (with or 591 without mulching) plots. The USLE-M model inaccuracy in reproducing erosion in the unburned 592 plots agrees with the findings by (Carra et al., 2021), who also achieved poor predictions of soil 593 losses in unburned pine stands of Southern Italy. Comparisons of our results with other 594 modelling experiences using USLE-family models in burned forests show satisfactory and 595 inaccurate erosion predictions in Portugal (Vieira et al., 2018b) and in North-Western Spain 596 (Fernández et al., 2010 and Fernández & Vega, 2016; 2018) in the short-term using the RUSLE 597 model. The latter authors demonstrated that neither the model calibration by modifying the soil 598 erosivity and erodibility, and the C-factors or letting the model account for the high organic 599

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.

602

603 4.4. Comparison of the three models and future research needs

604

The use of erosive models to predict soil loss under the three soil conditions gave contrasting 605 results. A comparison of the erosion prediction capacity shown by the three models showed that 606 the MMF model performs better and WEPP is the less accurate model in the experimental 607 conditions. Therefore, MMF is the most accurate model for erosion predictions in the 608 experimental environment, and furthermore offers simplicity of use low demand of input 609 parameters. This derives from the availability of input parameters that successfully reproduce the 610 effects of SWR and the post-fire variability of vegetation cover on the hydrological and erosive 611 response of burned soils. Therefore, the MMF model appears as a valuable tool to predict both 612 surface runoff (although this hydrological variable was not directly evaluated in this study) and 613 soil loss in the Mediterranean burned forests, although being of less common use compared to 614 the other two models. As such, the model may be used to prioritise the forest areas for post-615 management actions, in order to control the hydrogeological hazard and the risk of 616 contamination of downstream water bodies. Furthermore, its process-based nature allows MMF 617 to easily handle hydrological scenarios outside its calibration range, making the model 618 particularly suitable for research purposes and scenario analysis (Beven, 2011; Vieira et al., 619 2014). In contrast, the USLE-M model must be further improved for erosion simulations in 620 burned conditions, since the suggested values of the CN and C parameters are not able to 621 reproduce the changes in soil hydrology due to wildfire. The use of the WEPP model is not 622 advised in data-poor environments, such as the experimental site, since the scarce availability of 623 input data affects the erosion prediction accuracy. Moreover, the use of MMF and WEPP models 624 is more convenient compared to USLE-M, since the latter model does not predict surface runoff, 625 which may be an essential information in areas that are prone to flooding hazard. 626

Overall, the comparison of these models to the same dataset, as done in this study, represents an added value (Larsen and MacDonald, <u>2007</u>; Vieira et al., <u>2018</u>), since this allows the determination of the structural uncertainty in modelling predictions (Lopes et al., 2021). This is in agreement with Alewell et al. (<u>2019</u>) and Batista et al. (<u>2019</u>), 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.

636

637 4.5. Future research needs

638

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).

656

657 **5.** Conclusions

658

In forest soils of Central Eastern Spain, burned by a wildfire and then mulched using straw, the 659 WEPP model noticeably underestimated the erosion in the unburned areas, while, in contrast, the 660 soil loss was largely overestimated in the burned soils also by several orders of magnitude. This 661 large inaccuracy was presumably due to lack of model calibration. The uncalibrated MMF model 662 noticeably over- or under-estimated the soil loss observations for all modeled soil conditions, 663 when running with default input parameters. However, the optimisation of this model with a new 664 procedure to estimate the C-factor, resulted in a satisfactory erosion prediction capacity, in 665 burned plots with or without the mulching treatment. Calibration failed to improve the MMF 666 model simulations in unburned soils. The performances of the USLE-M model were poor before 667

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.

671

672 Acknowledgements

673

This study was supported by the Spanish Institute for Agricultural Research and Technology 674 (INIA) with National Research Project "VIS4FIRE (RTA2017-0042-C05-03)" and regional 675 funds from the "Junta de Comunidades Castilla-La Mancha (PRESFIRE: 676 SBPLY/19/180501/000130/1)" and funds from the Ministry for Science and Innovation (Code 677 project PID2021-126946OB-I00). 678

679

680 **Conflict of interest statement**

681

683

684 **References**

685

Aksoy, H., & Kavvas, M. L. (2005). A review of hillslope and watershed scale erosion and
 sediment transport models. *Catena*, 64(2–3), 247–271.

Alewell, C., Borrelli, P., Meusburger, K., & Panagos, P. (2019). Using the USLE: changes,
challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research*, 7(3): 203–225.

Bautísta, S., Robichaud, P.R., Bladé, C. (2009). Post-fire mulching. In Fire Effects on Soils and *Restoration Strategies*, A Cerdà, PR Robichaud (eds.), Land and Management, Vol. 5. Science
Publishers: Enfield; 356–375.

Beven, K. J. (2011). Rainfall-runoff modelling: The primer. John Wiley & Sons.

Beven, K. J., & Kirkby, M. J. (1979). A physically based, variable contributing area model of
basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin
versant. *Hydrological Sciences Journal*, 24(1), 43–69.

⁶⁸² All authors declare no conflict of interest.

- Bezak, N., Mikoš, M., Borrelli, P., Alewell, C., Alvarez, P., Anache, J. A. A., Baartman, J.,
- Ballabio, C., Biddoccu, M., & Cerdà, A. (2021). Soil erosion modelling: A bibliometric analysis. *Environmental Research*, *197*, 111087.
- Bombino, G., Porto, P., & Zimbone, S. M. (2002). Evaluating the crop and management factor C
 for applying RUSLE at plot scale. *2002 ASAE Annual Meeting*, 1.
- Borrelli, P., Alewell, C., Alvarez, P., Anache, J. A. A., Baartman, J., Ballabio, C., Bezak, N.,
- ⁷⁰⁴ Biddoccu, M., Cerdà, A., & Chalise, D. (2021). Soil erosion modelling: A global review and
- statistical analysis. *Science of the Total Environment*, 146494.
- Borrelli, P., Meusburger, K., Ballabio, C., Panagos, P., & Alewell, C. (2018). Object oriented
 soil erosion modelling: A possible paradigm shift from potential to actual risk assessments in
 agricultural environments. *Land Degradation & Development*, *29*(4), 1270–1281.
- Carra, B. G., Bombino, G., Lucas-Borja, M. E., Denisi, P., Plaza-Álvarez, P. A., & Zema, D. A.
 (2021). Modelling the Event-Based Hydrological Response of Mediterranean Forests to
 Prescribed Fire and Soil Mulching with Fern Using the Curve Number, Horton and USLEFamily (Universal Soil Loss Equation) Models. *Land*, *10*(11), 1166.
- Cawson, J. G., Sheridan, G. J., Smith, H. G., & Lane, P. N. J. (2012). Surface runoff and erosion
- after prescribed burning and the effect of different fire regimes in forests and shrublands: A
- review. International Journal of Wildland Fire, 21(7), 857–872.
- Covert, A., Robichaud, P. R., Elliot, W. J., & Link, T. E. (2005). Evaluation of runoff prediction
 from WEPP-based erosion models for harvested and burned forest watersheds. *Transactions of the ASAE*, 48(3), 1091–1100.
- 719 Díaz, M. G., Lucas-Borja, M. E., Gonzalez-Romero, J., Plaza-Alvarez, P. A., Navidi, M., Liu,
- Y.-F., Wu, G.-L., & Zema, D. A. (2022). Effects of post-fire mulching with straw and wood
- chips on soil hydrology in pine forests under Mediterranean conditions. *Ecological Engineering*,
- 722 *182*, 106720. https://doi.org/10.1016/j.ecoleng.2022.106720
- Doorenbos, J., & Kassam, A. H. (1979). Yield response to water. *Irrigation and Drainage Paper*, 33, 257.

- Fernández, C., & Vega, J. A. (2016). Evaluation of RUSLE and PESERA models for predicting
 soil erosion losses in the first year after wildfire in NW Spain. *Geoderma*, 273, 64–72.
 https://doi.org/10.1016/j.geoderma.2016.03.016
- Fernández, C., & Vega, J. A. (2018). Evaluation of the rusle and disturbed wepp erosion models
- for predicting soil loss in the first year after wildfire in NW Spain. Environmental Research, 165,
- 730 279–285. https://doi.org/10.1016/j.envres.2018.04.008
- 731 Fernández, C., Vega, J. A., & Vieira, D. C. S. (2010). Assessing soil erosion after fire and
- rehabilitation treatments in NW Spain: Performance of RUSLE and revised Morgan-Morgan-
- Finney models. *Land Degradation & Development*, 21(1), Article 1.
- Filianoti, P., Gurnari, L., Zema, D. A., Bombino, G., Sinagra, M., & Tucciarelli, T. (2020). An
 evaluation matrix to compare computer hydrological models for flood predictions. *Hydrology*,
 7(3), 42.
- Flanagan, D. C., & Nearing, M. A. (1995). USDA-Water Erosion Prediction Project: Hillslope
 profile and watershed model documentation. *Nserl Rep*, *10*, 1–123.
- Fortugno, D., Boix Fayos, C., Bombino, G., Denisi, P., Quinonero Rubio, J. M., Tamburino,
 V., & Zema, D. A. (2017). Adjustments in channel morphology due to land use changes and
 check dam installation in mountain torrents of Calabria (southern Italy). *Earth Surface Processes*
- 742 *and Landforms*, *42*(14), Article 14.
- Foster, G. R., & Lane, L. J. (1987). User requirements: USDA, water erosion prediction project
 (WEPP) Draft 6.3. *NSERL Report (USA)*.
- Grønsten, H. A., & Lundekvam, H. (2006). Prediction of surface runoff and soil loss in
 southeastern Norway using the WEPP Hillslope model. *Soil and Tillage Research*, 85(1–2), 186–
 199.
- Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1999). Status of automatic calibration for
 hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering*, 4(2), Article 2.
- Hosseini, M., Nunes, J. P., Pelayo, O. G., Keizer, J. J., Ritsema, C., & Geissen, V. (2018).
 Developing generalized parameters for post-fire erosion risk assessment using the revised

- Morgan-Morgan-Finney model: A test for north-central Portuguese pine stands. CATENA, 165,
- 754 358–368. https://doi.org/10.1016/j.catena.2018.02.019
- Karamesouti, M., Petropoulos, G. P., Papanikolaou, I. D., Kairis, O., & Kosmas, K. (2016).
- Erosion rate predictions from PESERA and RUSLE at a Mediterranean site before and after a wildfire: Comparison & implications. *Geoderma*, 261, 44–58.
- 758 https://doi.org/10.1016/j.geoderma.2015.06.025
- Kinnell, P. I. A. (2003). Event erosivity factor and errors in erosion predictions by some
 empirical models. *Soil Research*, *41*(5), Article 5.
- Kinnell, P. I. A., & Risse, L. M. (1998). USLE M: Empirical modeling rainfall erosion through
- runoff and sediment concentration. *Soil Science Society of America Journal*, 62(6), 1667–1672.
- Konz, N., Bänninger, D., Nearing, M., & Alewell, C. (2009). Does WEPP meet the specificity of
- soil erosion in steep mountain regions? *Hydrology & Earth System Sciences Discussions*, 6(2).
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-*Geiger climate classification updated*.
- Krause, P., Boyle, D. P., & Bäse, F. (2005). Comparison of different efficiency criteria for
 hydrological model assessment. *Advances in Geosciences*, *5*, 89–97.
- ⁷⁶⁹ Larsen, I. J., & MacDonald, L. H. (2007). Predicting postfire sediment yields at the hillslope
- scale: Testing RUSLE and Disturbed WEPP: PREDICTING POSTFIRE SEDIMENT YIELDS.
- 771 Water Resources Research, 43(11), Article 11. https://doi.org/10.1029/2006WR005560
- Licciardello, F., Amore, E., Nearing, M. A., & Zimbone, S. M. (2006). 18 Runoff and Erosion
- Modelling by WEPP in an Experimental Mediterranean Watershed. Soil Erosion and Sediment *Redistribution in River Catchments: Measurement, Modelling and Management*, 186.
- Lopes, A. R., Girona García, A., Corticeiro, S., Martins, R., Keizer, J. J., & Vieira, D. C. S.
- (2021). What is wrong with post fire soil erosion modelling? A meta analysis on current
- approaches, research gaps, and future directions. *Earth Surface Processes and Landforms*, 46(1),
- 778 Article 1. https://doi.org/10.1002/esp.5020
- Lucas-Borja, M. E., Bombino, G., Carrà, B. G., D'Agostino, D., Denisi, P., Labate, A., Plaza-
- Alvarez, P. A., & Zema, D. A. (2020). Modeling the Soil Response to Rainstorms after Wildfire

- and Prescribed Fire in Mediterranean Forests. *Climate*, 8(12), 150.
 https://doi.org/10.3390/cli8120150
- ⁷⁸³ Lucas-Borja, M. E., Ortega, R., Miralles, I., Plaza-Álvarez, P. A., González-Romero, J., Peña-
- wildfire and logging on soil functionality in the short-term in Pinus halepensis M. forests.

Molina, E., Moya, D., Zema, D. A., Wagenbrenner, J. W., & De las Heras, J. (2020). Effects of

- *European Journal of Forest Research*, *139*(6), 935–945.
- Lucas-Borja, M. E., Plaza-Àlvarez, P. A., Uddin, S. M., Parhizkar, M., & Zema, D. A. (2022).
 Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by
 Macrochloa tenacissima (L.) Kunth. *Journal of Arid Environments*, *198*, 104702.
- Lucas-Borja, M. E., Zema, D. A., Carrà, B. G., Cerdà, A., Plaza-Alvarez, P. A., Cózar, J. S.,

Gonzalez-Romero, J., Moya, D., & de las Heras, J. (2018). Short-term changes in infiltration

⁷⁹² between straw mulched and non-mulched soils after wildfire in Mediterranean forest ecosystems.

Ecological Engineering, *122*, 27–31.

- Merritt, W. S., Letcher, R. A., & Jakeman, A. J. (2003). A review of erosion and sediment
 transport models. *Environmental Modelling & Software*, *18*(8–9), 761–799.
- Moody, J. A., Shakesby, R. A., Robichaud, P. R., Cannon, S. H., & Martin, D. A. (2013).
 Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews*, *122*, 10–37.
- Morgan, R. P. C. (2001). A simple approach to soil loss prediction: A revised Morgan–Morgan–
 Finney model. *CATENA*, 44(4), 305–322. https://doi.org/10.1016/S0341-8162(00)00171-5
- Morgan, R. P. C., & Duzant, J. H. (2008). Modified MMF (Morgan–Morgan–Finney) model for
 evaluating effects of crops and vegetation cover on soil erosion. *Earth Surface Processes and Landforms*, 33(1), 90–106. https://doi.org/10.1002/esp.1530
- Morgan, R. P. C., Morgan, D. D. V., & Finney, H. J. (1984). A predictive model for the
 assessment of soil erosion risk. *Journal of Agricultural Engineering Research*, *30*, 245–253.
 https://doi.org/10.1016/S0021-8634(84)80025-6
- Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L.
 (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed
 simulations. *Transactions of the ASABE*, 50(3), Article 3.

- Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I—
 A discussion of principles. *Journal of Hydrology*, *10*(3), Article 3.
- Nearing, M. A. (2000). Evaluating soil erosion models using measured plot data: Accounting for
 variability in the data. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 25(9), Article 9.
- Nunes, J. P., Malvar, M., Benali, A. A., Rial Rivas, M. E., & Keizer, J. J. (2016). A simple water
 balance model adapted for soil water repellency: Application on Portuguese burned and
 unburned eucalypt stands. *Hydrological Processes*, *30*(3), 463–478.
- Panagos, P., & Katsoyiannis, A. (2019). Soil erosion modelling: The new challenges as the result
 of policy developments in Europe. In *Environmental Research* (Vol. 172, pp. 470–474).
 Elsevier.
- Papathanasiou, C., Makropoulos, C., & Mimikou, M. (2015). Hydrological modelling for flood
- forecasting: Calibrating the post-fire initial conditions. *Journal of Hydrology*, *529*, 1838–1850.
- Prosser, I. P., & Williams, L. (1998). The effect of wildfire on runoff and erosion in native
 Eucalyptus forest. *Hydrological Processes*, *12*(2), Article 2.
- Santhi, C., Arnold, J. G., Williams, J. R., Dugas, W. A., Srinivasan, R., & Hauck, L. M. (2001).
- Validation of the swat model on a large rwer basin with point and nonpoint sources 1. JAWRA
- *Journal of the American Water Resources Association*, 37(5), Article 5.
- SCS, U. (1985). National engineering handbook, section 4: Hydrology. US Soil Conservation
 Service, USDA, Washington, DC.
- Shakesby, R. A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future
 research directions. *Earth-Science Reviews*, *105*(3–4), Article 3–4.
- 832 Singh, J., Knapp, H. V., Arnold, J. G., & Demissie, M. (2005). Hydrological modeling of the
- Iroquois river watershed using HSPF and SWAT 1. JAWRA Journal of the American Water
 Resources Association, 41(2), Article 2.
- Soto, B., & Díaz-Fierros, F. (1998). Runoff and soil erosion from areas of burnt scrub:
 Comparison of experimental results with those predicted by the WEPP model. *Catena*, *31*(4),
 257–270.

- Soulis, K. X. (2018). Estimation of SCS Curve Number variation following forest fires. 838 9. Hydrological Sciences Journal. 63(9), Article 839 https://doi.org/10.1080/02626667.2018.1501482 840
- Van Liew, M. W., Arnold, J. G., & Garbrecht, J. D. (2003). Hydrologic simulation on 841 agricultural watersheds: Choosing between two models. Transactions of the ASAE, 46(6), Article 842 6. 843
- Van Liew, M. W., & Garbrecht, J. (2003). Hydrologic simulation of the little Washita river 844 experimental watershed using SWAT 1. JAWRA Journal of the American Water Resources 845 Association, 39(2), 413-426. 846
- Vega, J. A., Fernandez, C., Fonturbel, T., Gonzalez-Prieto, S., & Jimenez, E. (2014). Testing the 847 effects of straw mulching and herb seeding on soil erosion after fire in a gorse shrubland. 848 Geoderma, 223, 79-87. 849
- Vega, J. A., Fontúrbel, T., Merino, A., Fernández, C., Ferreiro, A., & Jiménez, E. (2013). 850 Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical 851 and microbial properties in pine forests and shrubland. Plant and Soil, 369(1-2), 73-91. 852
- Vieira, D. C. S., Fernández, C., Vega, J. A., & Keizer, J. J. (2015). Does soil burn severity affect 853 the post-fire runoff and interrill erosion response? A review based on meta-analysis of field 854 rainfall simulation Journal of Hydrology, 523. 452-464. data. 855 https://doi.org/10.1016/j.jhydrol.2015.01.071 856
- Vieira, D. C. S., Prats, S. A., Nunes, J. P., Shakesby, R. A., Coelho, C. O. A., & Keizer, J. J. 857 (2014). Modelling runoff and erosion, and their mitigation, in burned Portuguese forest using the 858 revised Morgan-Morgan-Finney model. Forest Ecology and Management, 314, 150-165. 859
- Vieira, D. C. S., Serpa, D., Nunes, J. P. C., Prats, S. A., Neves, R., & Keizer, J. J. (2018). 860 Predicting the effectiveness of different mulching techniques in reducing post-fire runoff and 861 erosion at plot scale with the RUSLE, MMF and PESERA models. Environmental Research, 862 165(May), 365-378. https://doi.org/10.1016/j.envres.2018.04.029
- Wagenbrenner, J. W., Ebel, B. A., Bladon, K. D., & Kinoshita, A. M. (2021). Post-wildfire 864 hydrologic recovery in Mediterranean climates: A systematic review and case study to identify 865
- current knowledge and opportunities. Journal of Hydrology, 126772. 866

- Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses: A guide to conservation planning* (Issue 537). Department of Agriculture, Science and Education
 Administration.
- Zavala, L. M. M., de Celis Silvia, R., & López, A. J. (2014). How wildfires affect soil properties.
- A brief review. Cuadernos de Investigación Geográfica/Geographical Research Letters, 40,
 311–331.
- Zema, D. A. (2021). Postfire management impacts on soil hydrology. *Current Opinion in Environmental Science & Health*, *21*, 100252. https://doi.org/10.1016/j.coesh.2021.100252
- Zema, D. A., Bingner, R. L., Denisi, P., Govers, G., Licciardello, F., & Zimbone, S. M. (2012).
 Evaluation of runoff, peak flow and sediment yield for events simulated by the AnnAGNPS
 model in a Belgian agricultural watershed. *Land Degradation & Development*, *23*(3), Article 3.
- Zema, D. A., Lucas-Borja, M. E., Fotia, L., Rosaci, D., Sarnè, G. M. L., & Zimbone, S. M.
 (2020). Predicting the hydrological response of a forest after wildfire and soil treatments using
 an Artificial Neural Network. *Computers and Electronics in Agriculture*, 170.
 https://doi.org/10.1016/j.compag.2020.105280
- Zema, D. A., Nunes, J. P., & Lucas-Borja, M. E. (2020). Improvement of seasonal runoff and
 soil loss predictions by the MMF (Morgan-Morgan-Finney) model after wildfire and soil
 treatment in Mediterranean forest ecosystems. *Catena*, *188*, 104415.

886 SUPPLEMENTARY MATERIAL

887

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

889

| | | Slope | | | Soil | | | | | | | |
|-------------------|----------|---------------|--------------|--------|------------------------------------|---------------|-------------|-------------|-----------|-------------------|-------------|--|
| Management | Position | Length (m) | Slope (%) | Albedo | Initial saturation level (%) | Depth (mm) | Sand (%) | Clay (%) | OM (%) | CEC (meq/100g) | Rock (%) | |
| | | | | | Unburned | | | | | | | |
| | Upper | 12.9 | 68.3 | | | | | | | | | |
| Shrub perennial | Middle | 103.5 | 51 | 0.23 | 75 | 1000 | 26.3 | 14.3 | 2.88 | 9.9 | 50 | |
| | Lower | 12.9 | 22.3 | | | | | | | | | |
| | | <u> </u> | | Burn | ed and not tre | eated | | I | L | | | |
| 25% ground cover | Upper | 13.6 | 23.7 | | | | | | | | | |
| high severity | Middle | 108.8 | 41 | 0.23 | 75 | 1000 | 31.7 | 12.8 | 2.13 | 9.9 | 50 | |
| lingh severity | Lower | 13.6 | 21.3 | - | | | | | | | | |
| | | | | Bur | ned and mulc | hed | | | | | | |
| Fallow initial | Upper | 15.4 | 48.7 | | | | | | | | | |
| condition - wheat | Middle | 123.5 | 40.3 | 0.23 | 75 | 1000 | 30.2 | 18.5 | 2.38 | 9.9 | 50 | |
| residues | 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).

| | Soil condition | | | | | | | | | |
|----------|----------------|-------|-----------|-----------|------------|-------|--|--|--|--|
| | Min | Max | Min | Max | Min | Max | | | | |
| Factor | Link | umad | Burned | and Not | Burned and | | | | | |
| | Cnoi | irneu | Tre | ated | Mul | ched | | | | |
| | | | Uncalibra | ted model | I | | | | | |
| R | 43.3 | 115.2 | 43.3 | 115.2 | 43.3 | 115.2 | | | | |
| R_n | 1 | 1 | 1 | 1 | 1 | 1 | | | | |
| Ι | 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 | | | | |
| СОН | 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 | | | | |
| С | 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 | | | | | |
| Ι | 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 | | | | | |
| СОН | 2 | 2 | 2 | 2 | 2 | 2 | | | | | |
| S | 27 | 27 | 22 | 22 | 22 | 22 | | | | | |
| Α | 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 | | | | | |
| С | 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.

⁸⁹⁷ 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 | Qr | _ | max | 0.375 | | 0.694 | | 0.570 | | |
| | | | min | 0.176 | | 0.409 | | 0.001 | | |
| | R factor | MJ mm/ | max | 302 | | | | | | |
| | R _{e-} nuctor | ha h | 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 | | | | | | |

899 Notes: CN = curve number; $\lambda = rainfall depth coefficient$; R_{e} -factor = rainfall erosivity factor; K_{UM} -factor = soil erodibility factor; C-factor = cover 900 management factor; P-factor = conservation practice factor; the values related to the first two modelled events are reported in brackets.