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1 **Improvement of seasonal runoff and soil loss predictions by the MMF (Morgan-Morgan-**
2 **Finney) model after wildfire and soil treatment in Mediterranean forest ecosystems**

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16 **ABSTRACT**

17
18 The negative hydrological effects of wildfire are very difficult to predict in Mediterranean forest
19 ecosystems, due the intrinsic climate and soil characteristics of these areas. Among the hydrological
20 models simulating surface runoff and soil erosion in these environmental contexts, the semi-
21 empirical Morgan-Morgan-Finney (MMF) model can ensure the representation of the main physical
22 processes, while offering ease of use and limiting the number of input parameters. However,
23 literature reports very few modelling studies using MMF in burned areas of the Mediterranean
24 environment with or without post-fire rehabilitation measures. To fill this gap, the capacity of the
25 MMF model to predict the seasonal surface runoff and soil loss in a Mediterranean forest was
26 verified and improved for unburned plots and areas affected by a wildfire, with and without post-
27 fire straw mulch treatment. The application of MMF with default input parameters (set up according
28 to the original guidelines of the model's developers) led to poor performance. Conversely, after
29 introducing some changes in input data for both the hydrological and erosive components (seasonal
30 values of evapotranspiration, reduction of the soil hydrological depth, including soil water
31 repellency effects in burned soils, and modelling erosive precipitation only), MMF was able to
32 predict seasonal runoff volumes and soil loss with good reliability in all the experimented
33 conditions.

This modelling experiment has shown the capacity of the MMF model to simulate the seasonal hydrological and erosion response of the experimental unburned and burned soils of Mediterranean semi-arid forests. Although more research is needed to validate the model's prediction capacity in these conditions, the use of MMF as a management tool may be suggested to predict the hydrogeological risk in these delicate ecosystems threatened by wildfire, as well as to evaluate the potential efficiency of soil treatments after fire.

KEYWORDS: erosion; hydrological model; effective hydrological layer; soil water repellency; straw mulching.

1. INTRODUCTION

Although many Mediterranean ecosystems are highly resilient to fire (e.g., shrublands and oak forest, for which there is no evidence of strong changes in species composition and dominance after fire), some are fire-sensitive (e.g. pine woodlands, which often are being taken over by shrublands) (Baeza et al., 2007; Pausas et al., 2008). Wildfires are one of the most important threats to pine forest health, since the vegetation cover and soil disturbance they cause is a critical factor for increased runoff and soil erosion and, hence, for land degradation (Shakesby, 2011; Santana et al., 2014). Observed erosion rates are, in some cases, relatively high, especially in high fire severity conditions (Pausas et al., 2008). In fact, wildfires reduce or eliminate the protective soil cover of vegetation and litter (Shakesby, 2011; Moody et al., 2013) and promote changes in soil properties, such as the reduction of the aggregate stability (Varela et al., 2010; Mataix-Solera et al., 2011) and the increase of soil water repellency (SWR, Malvar et al., 2016; Stoof et al., 2011). Exported fine sediment and ashes may also affect downstream water quality (Nunes et al., 2018b). The hydrological impacts of wildfires may be more severe in Mediterranean forests due to the dry and hot summers followed by frequent and high-intensity rains in the autumn, immediately after the wildfire season (Shakesby, 2011; Lucas-Borja et al., 2018). Moreover, increases in wildfire frequency and burned area are commonly expected under the forecasted climate scenarios for the Mediterranean region (IPCC, 2013; Bedia et al., 2014). However, many of these impacts can be reduced by post-fire operations, such as soil mulching with straw immediately after fire, which increase soil cover (Prats et al., 2012; 2016; Prosdocimi et al., 2016; Santana et al., 2014; Lucas-Borja et al., 2018; 2019).

The need to predict and control the negative impacts of wildfires on runoff and erosion has increased the demand for hydrological models (Moody et al., 2013). The availability of reliable hydrological models may support land managers in adopting the most efficient actions for land rehabilitation after fire (Moody et al., 2013). However, the hydrology of burned forests is extremely complex, depending on several factors such as climate and edaphoclimatic conditions, fire severity, soil, vegetation, morphology, and land management after fire (Shakesby, 2011; Moody et al., 2013; Nunes et al., 2018b). Since most hydrological models were developed for agricultural regions, they may find limited applicability for burned ecosystems in Mediterranean environments and therefore require testing and, eventually, modification (Esteves et al., 2012; Vieira et al., 2014; 2018).

- (i) Previous trials of erosion models in burned forests have used simple empirical models, such as the Universal Soil Loss Equation (USLE) and its revised version, the RUSLE model (e.g., Larsen and McDonald, 2007; Vieira et al., 2018);
- (ii) physically-based models, such as the Water Erosion Prediction Project (WEPP, e.g. Larsen and McDonald, 2007), the Pan-European Soil Erosion Risk Assessment (PESERA, e.g. Esteves et al., 2012; Vieira et al., 2018) and the Soil and Water Assessment Tool model (SWAT, e.g. Nunes et al., 2018a);
- (iii) semi-empirical models, such as the Morgan–Morgan–Finney model (MMF) in its revised version (Fernandez et al., 2010; Vieira et al., 2014, 2018; Hosseini et al., 2018).

Of these approaches, MMF stands out as allowing a basic representation of physical processes governing runoff and erosion phenomena typical of the process-based models, while maintaining the easiness of use and the limited number of input parameters of the empirical models (Devia et al., 2015; Choi et al., 2017). This allows MMF to assess complex issues such as post-fire soil treatment operations for which empirical models are not appropriate, highlighting its potential as a tool for rapid post-fire erosion risk assessment (Vieira et al., 2018). Since its development, MMF has successfully been used to predict with accuracy annual runoff and soil loss in many environments (South-East Asia, Morgan and Finney, 1982; Besler, 1987; Shrestha and Jetten, 2018; East Asia, Shrestha, 1997; Morgan, 2001; Li et al., 2017; North America, Morgan, 1985; Central America, Febles-González et al., 2012; Sub-Saharan Africa, Vigiak et al., 2005; Shrestha and Jetten, 2018; Mediterranean basin, Lopéz-Vicente et al., 2008). For instance, regarding the latter environment, Lopéz-Vicente et al. (2008), simulating erosion rates in rainfed agro-systems of the south-central Pyrenees, detected close agreement between the estimated and measured rates, which were under the tolerance limit for soils under Mediterranean conditions.

The model has also been applied for burned areas with humid Mediterranean climate in North-West Spain (Fernández et al., 2010) and Portugal (Vieira et al., 2014; 2018; Hosseini et al., 2018). In two

102 burned forest areas in NW of Spain with different levels of fire severity, Fernàndez et al. (2010)
103 reported that for the first year following fire the MMF model presented reasonable accuracy in the
104 predictions of soil erosion after three rehabilitation treatments. Vieira et al. (2014) introduced
105 simple model enhancements in MMF, which performed well in simulating soil losses in recently
106 burned pine and eucalypt forested areas in north-central Portugal, subjected to post-wildfire
107 rehabilitation treatments. In the same environment, again Vieira et al. (2018) applied MMF to
108 predict the effectiveness of different mulching techniques in reducing post-fire runoff and erosion at
109 plot scale and found that the model was reasonably able to reproduce the hydrological and erosive
110 processes occurring in these burned forest areas. Hosseini et al. (2018) found more accurate
111 predictions of erosion than that of runoff, using MMF - adapted for burnt areas by implementing
112 seasonal changes in model parameters - in microplots of recently burned maritime pine plantations
113 of north-central Portugal with contrasting fire regimes.

114 However, the model has not been tested for burned areas in the many large drylands of the
115 Mediterranean region, although they are also exposed to wildfire risks. Therefore, further modelling
116 exercises using MMF in dry Mediterranean burned areas are needed, in order to (i) further improve
117 the model prediction capacity in these particular environments and (ii) support land managers in
118 simulating the hydrological effects of post-fire mitigation measures prior to their implementation.
119 The objective of this study was to evaluate the MMF model in natural pine forests subjected to
120 wildfire under Mediterranean semi-arid conditions, in order to test and improve its hydrological and
121 erosion prediction capacity. Specifically, surface runoff and soil loss were firstly measured in (i)
122 unburned plots (assumed as control); (ii) plots subjected to a wildfire and not rehabilitated with any
123 post-fire measures (burned and non-mulched); (iii) plots subjected to a wildfire and treated with
124 mulching throughout one year (burned and mulched). Based on these observations (aggregated at
125 the seasonal scale), the model was applied with default parameters and then modified to optimise
126 simulations, taking into account local climatic and forest management conditions.

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130 2. MATERIALS AND METHODS

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132 2.1 Study area

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134 The Sierra de las Quebradas area (Liétor, Castilla La Mancha, SE Spain, Figure 1a) is located in the
135 southeast of the Iberian Peninsula in the Segura Region of the Albacete province and is lodged
136 between the Rivers Mundo to the north and Segura to the south. In geological terms, the mountain
137 range lies among pre-Baetic mountain chains with limestone and dolomite outcrops alternating with
138 marly intercalations that date back to the quaternary. The study area has an elevation between 520
139 and 770 m a.s.l. and its aspect is W-SW. The climate of this area is of the semiarid Mediterranean
140 type (BSk, Köppen-Geiger classification; Kottek et al., 2006) with mean annual rainfall and
141 temperature of 282 mm and 16 °C, respectively. According to the USDA taxonomy (1999), soils are
142 *Inceptisols* and *Aridisols* with sandy-loam texture.

143 Forestry was an important economic driver from the 17th century until halfway through the 20th
144 century, and logging was the main historic disturbance of forest stands in the area, which favoured
145 their growth. Forest management practices are designed to stimulate bole wood productivity and it
146 is usually held that pines growing in managed stands show lower growth sensitivity to water
147 availability and greater resilience and resistance to drought events than pines in unmanaged stands
148 (e.g., Adams et al., 2009).

149 Progressive human abandonment and the reforestation action taken by the Public Administration
150 have shaped a forest landscape composed of Aleppo pines of a natural origin growing in shaded
151 areas and watercourses. In the 1980s the same species was repopulated in accessible public lands
152 with little soil, with termophilic scrublands in sunny spots (spartals and rosemary scrublands). The
153 present-day forest vegetation belongs to the *Quercus cocciferae-Pinus halepensis* S. series, where
154 Aleppo pine comprises most of the tree cover strata and kermes oak mostly occupies the shrub
155 strata. The main species of shrubs and herbs of the forest were *Rosmarinus officinalis* L.,
156 *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus*
157 *vulgaris* L., *Helichrysum stoechas* (L.), *Stipa tenacissima* (L.), *Quercus coccifera* L. and *Plantago*
158 *albicans* L. Tree cover consists mainly of *Pinus halepensis* M. with mean density between 500 and
159 650 trees ha⁻¹ and height between 7 and 14 m. Serotiny was observed in the stands affected by
160 wildfire.

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162

2.2 Hydrological monitoring

2.2.1 Experimental design

In July 2016 about 830 ha of forest land was burned by a crown wildfire (tree mortality of 100%). Immediately after the wildfire, a forest land of about five hectares was selected for the study (Figure 1b). In addition, an area not affected by the wildfire, 7 km away from the burned site, was selected as control; soil and forest stand characteristics were very similar to those of the burned area. Mean soil stoniness was 30-40%, while plot slope was about 10.5%. After the wildfire, the soil burn severity was characterized following the methodology proposed by (Vega et al., 2013). All the experimental plots were characterized as burned with high severity (level 5 of the above-cited classification). Two sets of four experimental plots (each one covering an area of $9 \times 1 \text{ m}^2$ with the longest dimension along the maximum slope direction) in the burned area and an additional plot in the unburned area ("control") were established (Figure 1b). The distance between burned plots was about 20 m. In September 2016, mulching treatment was assigned at random to four replicate plots located in the burned area (henceforth "burned and mulched"). The soil of the plots was manually mulched, applying 0.2 kg/m^2 (dry weight) of straw. This dose is in close accordance with the value suggested by Vega et al. (2014) for Northern Spain, since a soil cover higher than 80% was achieved in their burned plots. Initial cover and depth of the mulched plots were 95% of the total area and 3 cm, respectively. The other four plots in the burned area were left undisturbed (henceforth "burned and non-mulched") (Figure 1b). All the plots in the unburned, burned and treated areas present similar species and site characteristics in order to make results comparable.

2.2.2 Experimental equipment

The upstream and lateral borders of the experimental plots were hydraulically isolated from the external area by geotextile fabrics inserted into the soil to a depth of 20 cm, in order to prevent external inputs of water and sediments. In each plot, three neighbouring metallic fences (with a triangular shape, 1 m wide and 0.5 m high) were installed in the downstream side. These fences enabled periodic collection of water and sediments. Runoff was collected using a pipe installed in each fence and discharging into a 50-L tank. Two rain gauging stations (WatchDog 2000 Series model), one in the burned area and another in the control plot, measured the precipitation amount and intensity during the study period.

197 2.2.3 Hydrological data collection

198

199 Throughout one year (September 2016 - August 2017), the runoff volume collected by the tank was
200 measured immediately after each storm. Before emptying each tank, water was manually shaken
201 and about 0.5 litres were sampled. From these water samples, total dissolved sediments (TDS) and
202 suspended sediments (SS) were measured in the laboratory (Lucas-Borja et al., 2019). Moreover,
203 eroded soil deposited at each sediment fence was manually collected and then weighed in the field
204 to obtain the dry soil (DS). All soil samples were oven dried (105 °C) for 24 hours in the laboratory.
205 The total soil loss produced by the storm was the sum of DS, TDS and SS.

206

207 2.3 Hydrological modelling

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209 2.3.1 Outline of the MMF model

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211 Morgan (2001) developed a revised version of the original MMF model (Morgan et al., 1984), in
212 order to improve the accuracy of erosion simulations, suggesting also guidelines about the optimal
213 choice of input parameter values.

214 The revised MMF model requires 15 input parameters, classified into four groups. A first group
215 comprises rainfall parameters as annual rainfall (R , mm), number of rain days per year in the season
216 (R_n , -) and the typical value for intensity of erosive rain (I , mm/h). The second group is related to
217 soil characteristics, as soil moisture content at field capacity (MS , % w/w), bulk density of the top
218 soil layer (BD , Mg/m^3), effective hydrological depth of soil (EHD , m), soil detachability index (K ,
219 g/J) and cohesion of the surface soil (COH , kPa) parameters. The third group is related with
220 landform, and only includes slope steepness (S , °). The fourth group includes land cover parameters,
221 as the proportion of the rainfall intercepted by the vegetation or crop cover (A , -), ratio (E_t/E_0 , -) of
222 actual (E_t) to potential (E_0) evapo-transpiration, crop cover management factor (C , -), percentage
223 canopy cover (CC , %), percentage ground cover (GC , %) and plant height (PH , m) to the ground
224 surface.

225 In MMF the soil erosion process is separated in two phases, of which one (the "water phase")
226 estimates the rainfall kinetic energy available for soil particle detachment and the runoff volume,
227 and the second phase ("erosion phase") determines the soil particle detachment rates due to rainfall
228 and runoff as well as the transport capacity of runoff (Fernández et al., 2010). More specifically, in
229 the water phase an exponential rainfall distribution is assumed, following the method proposed by

230 Kirkby (1976), and runoff (Q , mm) is produced when daily rainfall (R_0 , mm) exceeds soil water
 231 storage capacity (R_c , mm):

232

$$233 \quad Q = R \cdot \exp\left(-\frac{R_c}{R_0}\right) \quad (1)$$

234

235 being:

236

$$237 \quad R_c = 1000 \cdot MS \cdot BD \cdot EHD \cdot \frac{E_t}{E_0} \quad (2)$$

238

239 This is suitable for climates with low intensity precipitation and non-seasonal rainfall regimes, but it
 240 can be questionable in semi-arid climates, where precipitation is less frequent but has a higher
 241 intensity and a clear seasonal pattern. Therefore, in this study this approach has been modified to
 242 adapt MMF to the rainfall regime of Mediterranean areas.

243 The sediment phase estimates soil particle detachment as the sum of raindrop splash (F , kg/m²,
 244 calculated from kinetic energy, KE , J/m², and erodibility of the soil, K , g/J) and runoff detachment
 245 (H , kg/m², calculated from Q , S , GC , and soil resistance, Z):

$$246 \quad F = K \cdot KE \cdot 10^{-3} \quad (3)$$

247

$$248 \quad H = Z \cdot Q^{1.5} \cdot \sin S (1 - GC) \cdot 10^{-3} \quad (4)$$

249

250 being:

251

$$252 \quad Z = \frac{1}{0.5 \cdot COH} \quad (5)$$

253

254 and

255

$$256 \quad KE = RA(1 - CC)(11.9 - 8.7 \cdot \log I) + (15.8 \cdot PH^{0.5}) - 5.87 \quad (6)$$

257

258 Sediment transport capacity due to runoff (TC , kg/m²) is calculated from Q , S , and a crop or plant
 259 cover factor (C), taken as the product of the C and P factors of the Universal Soil Loss Equation

(Morgan, 2001) (henceforth indicated as "USLE-C factor" and "USLE-P" factor, respectively), as follows:

$$TC = C \cdot Q \cdot \sin S \cdot 10^{-3} \quad (7)$$

Soil erosion (E , kg/m^2) equals the lower value between sediment detachment and transport capacity. The equations for calculating the hydrological variables were chosen from the literature according to their prediction accuracy, simplicity of use, and ease determination of the input parameters (Morgan et al., 1984).

2.3.2 Model implementation

Following Vieira et al. (2014) and Hosseini et al. (2018), MMF was implemented for the experimental plots, simulating surface runoff and soil erosion for the entire period and for the individual seasons (autumn, winter, spring and summer) throughout one year immediately after the wildfire (from September 2016 to August 2017). Three soil conditions were simulated using MMF: (i) unburned soil (control); (ii) burned and not treated soil ("burned and non-mulched" plots); and (iii) soil burned and treated with straw mulching ("burned and mulched" plots).

Two model parameterizations were applied: one using the default parameterization for MMF, and another using adjusted values for post-fire conditions. The default parameterization followed the guidelines for model implementation given in the original studies of Morgan et al. (1984) and Morgan (2001), which report the values of the input parameters for a wide range of climatic and geomorphological contexts. When measuring input parameters is not possible or very expensive and time consuming, users of MMF are forced to adopt literature values, as it has been done in this study. If the runoff and erosion predictions were accurate in this case, the model would be able to also be used in data-poor environments.

The MMF model adaptation to post-fire conditions used some of the post-fire adaptations described by Fernández et al. (2010) and Vieira et al. (2014), as described below. Of the 15 model input parameters, seven were measured in-field, five were derived from the guidelines of Morgan et al. (1984), Morgan (2001) and Morgan and Duzant (2008) with a correction for MS, according to Vieira et al. (2014) and Nunes et al. (2016), while the remaining three values had to be estimated from literature (Doorenbos and Kassam, 1986; Wischmeier and Smith, 1978; Fernández et al., 2010; Vieira et al., 2014; Nunes et al., 2016). More details about the model parameterisation are reported in the following section.

294 The input parameters were divided in two sets: the first set consisted of the parameters with the
 295 same values for all plots regardless of the applied treatment (e.g., rainfall and most of soil data),
 296 while the second dataset comprised the parameters, whose value was different for each treatment
 297 (mulching application or not, burned or non-burned soil) or site-specific conditions (that is,
 298 different for each plot), such as the remaining soil parameters of soils, which are influenced by the
 299 treatments, as well as the vegetation cover.

300 Rainfall data (R and R_n) were collected at the rain gauges installed in each study site. For the typical
 301 I, the value of 30 mm/h for climates with strongly seasonal nature (as the Mediterranean type) was
 302 set as suggested by Morgan (2001). The precipitation input was considered different for runoff and
 303 soil erosion estimations, as detailed in the following sub-section.

304 Soil parameters, except for BD (measured in field), were estimated according to Morgan (2001),
 305 based on soil textural data: COH and K. Changes in the parameterisation of the MS and EHD input
 306 values were introduced into the MMF model in order to take into account the post-fire conditions,
 307 as detailed in the following sub-sections (Table 1).

308 S , determined in the field by topographic measurements, was equal for all the plots (6°) (Table 1).

309 Regarding land cover parameters, A was estimated according to previous studies made in the same
 310 environment (Rodriguez et al., 2016) for pine stands and shrub lands. E_t and E_0 were estimated by
 311 the Penman-Monteith model, deriving the crop coefficients from FAO guidelines (Doorenbos and
 312 Kassam, 1986). CC and PH were estimated by measuring all the plants and trees covering each plot
 313 in the control plots and set to zero in burned (mulched and non-mulched) plots, considering that
 314 these latter sites were burned areas. GC of each plot was measured on a quadrat (1 m x 1 m)
 315 delimiting a sample of soil. From the image caught by a digital photo-camera, the portion of the
 316 area covered by vegetation was estimated (Table 1).

317 The USLE-P factor mainly takes into account the anti-erosive practices implemented by soil
 318 mechanical tillage (such as terracing, contour lines, etc.) (Wischmeier and Smith, 1978). For the
 319 MMF application of this study it was set to one, due to the absence of such practices. The C-factor
 320 was estimated as described for the USLE model (Wischmeier and Smith, 1978), taking also into
 321 account the effect of straw mulching in treated plots compared with the untreated areas (Table 1).

322 According to Vieira et al. (2014), the seasonal modelling approach involved the input of the
 323 seasonal values of MS, corrected by changes in SWR (except for unburned plots), E_t/E_0 , GC and
 324 USLE-C factor. Conversely, under the annual modelling approach the annual mean values over the
 325 full post-treatment period were provided to the model.

326

2.3.3 Model adaptation for burned areas in semi-arid environments

The precipitation input was considered different for runoff and soil erosion estimations, as detailed in the following sub-section. To predict runoff, the seasonal precipitation and the number of days of rain were considered. Considering that, in the Mediterranean climate, soil erosion is mainly determined by few but intense rainfall events (e.g., Zema et al., 2014; 2016; Fortugno et al., 2017), MMF was adapted by only taking the days with precipitation over 13 mm (considered as "erosive events" by Wischmeyer and Smith, 1978) to simulate erosion.

In order to take into account post-fire conditions, the MS and EHD input parameters of the MMF model were estimated differently from previous studies. Vieira et al. (2014) and Fernández et al. (2010), in their calibration/validation experiments with MMF, approximated MS to the soil moisture content measured by sensors; in this study, due to the lack of measuring devices, the maximum field capacity was determined as suggested by Morgan (2001), equal to 0.280 for sandy loam soils, which was thought to be able to simulate the high storage capacity of Mediterranean forest soils. The effects of repellence on soil wetting - not considered by the original version of MMF - were taken into account adopting the "SM-SWR" modelling approach of Vieira et al. (2014) and Nunes et al. (2016); more specifically, the seasonal value of field capacity (assumed for the MS parameter) was corrected by a coefficient, which allowed SWR decrease with increasing fire severity (from 0.8 for extreme repellency to 1.1 under wettable conditions; Vieira et al., 2014) (Table 1), as follows:

$$MS_c = c \cdot MS \quad (7)$$

where MS is the value proposed by Morgan (2001), c is the correction coefficient proposed by Vieira et al. (2014) and MS_c is the corrected value.

According to Hosseini et al. (2018) and Vieira et al. (2014), EHD must be properly modified to improve MMF results. The seasonal values of EHD were estimated by these authors as a linear function of GC. However, since this latter is not the only parameter influencing EHD, this study embedded in EHD estimation also the "history" of a forest soil, since wildfire is a noticeable disturbance for soil, whose effects remain for long time. Therefore, the original EHD of the control soil was separated into two layers: one (50% of the original depth) was the deeper layer, not or scarcely influenced by the fire effects; and the second, the topsoil, whose properties suffer from fire effects due to the high burning severity and evolve in time according to the applied treatment. For

361 this surface layer, EHDs of "bare soil without surface crust" and "grass/pasture" were adopted for
362 the burned and non-mulched plots and burned and mulched plots, respectively. This latter value of
363 EHD was chosen, since straw usually contains seeds that can germinate and emerge after mulching
364 application, resulting in herbal layer growing on the site (Lucas-Borja et al., 2018) (Table 1). If this
365 choice is successful, the need of continuous control and adjustment of soil moisture in the model (as
366 suggested by Vieira et al., 2014) can be overcome.

367 For erosion prediction, the C-factor was parameterized in the MMF model considering the seasonal
368 variability due to growth of the herbaceous vegetation by regeneration in burned areas and by
369 seasonal natural cycle in unburned plots (Table 1).

370

371 *2.3.4 Model evaluation*

372

373 The runoff and erosion simulations of MMF were analysed for “goodness-of-fit” with the
374 corresponding observations. First, observed and simulated values of the water runoff volumes and
375 soil losses were visually compared in scatter-plots.

376 Then, the following indicators, commonly used in the literature (e.g., Willmott, 1982; Legates and
377 McCabe, 1999; Loague and Green, 1991; Zema et al., 2017; 2018), were adopted: (i) the main
378 statistics (i.e. the maximum, minimum, mean and standard deviation of both the observed and
379 simulated values); (ii) a set of summary and difference measures, such as the coefficient of
380 determination (R^2), coefficient of efficiency (E), Root Mean Square Error (RMSE), and Coefficient
381 of Residual Mass (CRM). The related equations are reported in the works of Zema et al. (2012),
382 Krause et al. (2005), Moriasi et al. (2007) and Van Liew and Garbrecht (2003). These indicators are
383 based on the analysis of the errors (in some cases in the squared form) between simulations and
384 predictions of the modelled hydrological variables.

385 To summarise:

- 386 - R^2 ranges from 0 (no agreement between model and data variance) to 1 (perfect agreement);
- 387 values over 0.5 are acceptable (Santhi et al., 2001; Van Liew et al., 2003; Vieira et al., 2018);
- 388 - E (Nash and Sutcliffe, 1970) is the most common measure of model accuracy and ranges from $-\infty$
- 389 to 1; the model accuracy is "good" if $E \geq 0.75$, "satisfactory" if $0.36 \leq E \leq 0.75$ and "unsatisfactory"
- 390 if $E \leq 0.36$ (Van Liew and Garbrecht, 2003);
- 391 - RMSE, which measures the standard deviation between observations and predictions, should be as
- 392 close as possible to zero (Fernandez et al., 2010); RMSE is considered good if it predicted value is
- 393 lower than 0.5 of the observed standard deviation (Singh et al., 2004);

- CRM (also reported as "percent bias", PBIAS), if positive, indicates model underestimation, whereas, if negative, overestimation (Gupta et al., 1999); CRM/PBIAS below 25% and 55% for runoff and erosion, respectively, are considered fair (Moriasi et al., 2007).

3. RESULTS

3.1 Hydrological monitoring

In every season the burned soils (both in mulched and in non-mulched plots) produced higher runoff (on average +2500%) and erosion (on average +2900%) compared to unburned plots. Control plots showed the highest runoff volumes in winter (on average 0.12 mm) and the highest soil losses in spring (on average 0.0006 kg/m²). In burned soils the highest runoff (2.61 and 3.16 mm for mulched and non-mulched soil, respectively) and soil loss (0.0052 and 0.008 kg/m² for treated and untreated soils, respectively) were observed in autumn (Figure 2a and 2b). This may be due to the higher SWR of burned plots compared to non-burned soils recorded in autumn, that is, a few weeks after wildfire (Vieira et al., 2014; Plaza-Alvarez et al., 2018b). In this season, soil treatment with mulching reduced erosion by over 60%. It is interesting to notice that in the wet seasons (autumn and winter) erosion in burned soils was less than half of that of autumn, in contrast to unburned plots where it increased (Figure 2b), presumably due to the seasonal vegetation cover patterns of soil.

Natural vegetation cover in burned soils was very low (on average 14.5% against 47% of unburned soils), with small variability between the different burned plots (13% non-mulched soil, 16% mulched soil, Figure 3).

3.2 Hydrological modelling

3.2.1 Runoff volume

Running the MMF model using default input parameters gave generally poor predictions of both surface runoff and soil loss (Figures 4a and 4b). Model efficiency was negative for runoff predictions ($E = -0.08$) in unburned plots and satisfactory ($E = 0.43$) for burned and mulched plots with large differences between observations and predictions (more than 50% between mean values). This was due to the strong under-estimation of runoff volumes, shown by the high and positive

values of CRM (from 0.55 to 0.61). However, the model was successful in predicting runoff in burned and non-mulched plots, for which a good value of E (0.82) and a limited over-estimation (CRM = -0.12) was achieved (Table 2).

By adopting the above-mentioned changes in the MS and EHD input parameters of the hydrological sub-model, under the two conditions of burned soils, runoff predictions provided by the MMF model greatly improved. This is shown by the visual comparison of simulated and observed runoff volumes (Figure 5a), which are closer to each other ($R^2 = 0.85-0.99$; see also the proximity to the identity line) compared to the default model performance ($R^2 = 0.22-0.63$) (Table 2), which gave more scattered data around the 1:1 line (Figure 4a). The analysis of the evaluation criteria confirmed the optimisation of model performances given by this procedure: for runoff predictions the differences between the predicted and observed means were lower than 28%, the model efficiency increased to very good values ($E > 0.82$, with a maximum value of 0.92 for runoff predictions in burned and non-mulched plots) and the RMSE became lower than half the standard deviations of observed data. MMF showed a tendency to underestimate runoff in control (CRM = 0.13) and burned/mulched (CRM = 0.12) plots and overestimated the observations in burned and non-mulched soils (CRM = -0.28) (Table 2).

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445 3.2.2 Soil erosion

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The erosion prediction accuracy of the MMF model running with default input parameters was unsatisfactory for all the soil conditions, since the model did not produce soil loss. All erosion quantities were always zero, since they were dictated by the zero-simulated transport capacity (Vieira et al., 2014). Thus, the observed means were very far from the corresponding observation (with discrepancy of more than 100%) and the evaluation criteria were very low (e.g. $E < 0$, RMSE < 0.5 std. dev. and CRM = 1) (Table 2 and Figure 4b).

Moreover, introducing the changes into the hydrological sub-model to improve the runoff simulations but leaving the mean seasonal precipitation, as suggested by the model guidelines, also led to inaccurate predictions of soil loss by MMF. As a matter of fact, the model efficiency was poor ($E < 0$) and the discrepancies between the predicted and observed soil loss were high (on the average 90%) (Table 2 and Figure 4b).

Conversely, the capacity of MMF to predict soil losses drastically improved when only the erosive precipitation was considered, and the seasonal variability of the crop cover was incorporated into the C-factor. On a quantitative approach, the improvement of MMF performance in simulating erosion was confirmed by the increases of model efficiency (E equal to 0.79 in unburned plots and

to 0.92 in burned and mulched soils) and the closeness between the observed and predicted mean values of soil losses (Table 2 and Figure 5b). Only in burned and non-mulched soils MMF performances slightly worsened, although remaining satisfactory ($E = 0.75$).

4. DISCUSSION

4.1 Hydrological monitoring

From the monitoring of surface runoff volumes and soil loss during the observations period in the experimental plots, it was evident (i) how wildfire worsens the soil hydrological response and (ii) that straw mulching limits the hydrological risk compared to bare soil (Figure 2). As a matter of fact, in the burned soils the soil is much prone to produce runoff and be eroded compared to unburned plots. However, in these soils, the natural cover of vegetation reduces the runoff generation aptitude in unburned soil (for instance, because of higher interception, evapo-transpiration and infiltration) and, as a consequence, soil detachment and transport downstream (also thanks to the stem presence, which reduces overland flow velocity, and the protective action of leafs against raindrop impact). In general, straw mulching in burned soils successfully counteracted the higher exposition of plots to rainfall erosivity, acting as an artificial cover. Soil cover with straw was more efficient as countermeasure of erosion rather than for reducing runoff, since in plots treated with straw mulching runoff was reduced by 14% and soil erosion by 61% in comparison to non-mulched soils. This may be due to the reduction of kinetic energy of rainfall, which allows limitation of soil particle displacement due to raindrop impact rather than lower runoff production (Chow et al., 1988; Ran et al., 2012).

4.2 Hydrological modelling

4.2.1 Runoff volume

The results show that the inaccuracy of the MMF model in simulating the runoff produced by the unburned soils (control) is due to the fact that MMF artificially splits the seasonal rainfall in many days of low input, which are not able to produce runoff: a large share of precipitation is thought to infiltrate into the soil, since the value of the R_c parameter tends to be high and the runoff tends to decrease. However, when runoff is very low, as observed in this study for the unburned plots, good

496 simulations by hydrological models are normally not expected (e.g., Nearing, 1998). Vice versa, in
 497 soils such as burned and non-treated plots with a natural aptitude to produce more runoff compared
 498 to unburned as well as burned and mulched plots, this model's tendency to over-estimate infiltration
 499 is reduced; thus, the simulated runoff volumes are closer to the corresponding observations.

500 From these findings it was evident that the MMF model was not able to reproduce surface runoff in
 501 forest soils under the Mediterranean climate for all the experimental conditions. Thus, the model
 502 needed the substantial changes discussed above, in order to improve its prediction capacity of
 503 surface runoff and soil loss.

504 First, the role of vegetation cover (which varies throughout the year) cannot be neglected when the
 505 model must be implemented at the seasonal scale (Eekhout et al., 2018), since evapotranspiration is
 506 not constant in time (as it was assumed for the default model). Replacing the constant value of the
 507 input parameter E_t/E_0 (0.95 for the default model) with variable values considering the actual crop
 508 cover of each season, MMF increased the runoff production in all the soil conditions and the
 509 simulated seasonal means were closer to the corresponding observations (with difference not higher
 510 than 28%) (Table 2). The noticeable seasonal differences of E_t/E_0 reduced (in the warm season) or
 511 increased (during the humid period) the water availability to generate surface runoff. These results
 512 were already observed in burned areas by Vieira et al. (2014) and Hosseini et al. (2018). Since the
 513 errors in predicting runoff by MMF may be caused by the inaccuracy of evapo-transpiration
 514 estimations (Fernandez et al., 2010), the use of observed values of evapo-transpiration may be
 515 suggested for further improvements in model predictions.

516 Second, the low water storage capacity highlighted by MMF for the burned soil, which showed high
 517 field water losses (mainly due to excessive infiltration) and thus scarce capacity to generate runoff,
 518 has been removed by decreasing the EHD parameter (that is, the topsoil depth, which is the most
 519 hydrologically active layer of soil in storing the infiltrating precipitation) from the value of 0.20
 520 (adopted for unburned plots) to 0.145 (burned and non-mulched plots) or 0.16 (burned and mulched
 521 plots). As a matter of fact, in the Mediterranean climate, where the runoff generation process is
 522 governed by “infiltration excess” mechanisms (Hillel, 1998; Lucas-Borja et al., 2018), models with
 523 the hydrological component simulates runoff production by the “saturation excess” mechanism (as
 524 in MMF) must quickly saturate the soil before runoff begins, and this requires an adequate
 525 reduction of surface soil depth. Surface runoff generated by infiltration excess is a very important
 526 process in areas where the highest soil erosion rates are generated by events with high rainfall
 527 intensity (Mulligan, 1998; López-Bermúdez et al., 2002; Eekhout et al., 2018), and therefore the
 528 runoff generation mechanism of MMF might be considered a limitation. Presumably, the runoff
 529 prediction capacity of the MMF model in semi-arid soils may be further improved by modifying its

530 water phase, which should take into account the relationships between rainfall intensity and the soil
531 infiltration rate.

532 After this correction, the MMF model reduced the soil infiltration capacity and thus the water stored
533 into the topsoil, therefore increasing the precipitation share which is converted into surface runoff.
534 Since the hydrological depth of soil is a parameter whose reliable estimation is affected by high
535 uncertainty (Morgan, 2001), a better knowledge of the related input value may improve the
536 accuracy of runoff and erosion predictions (Fernandez et al., 2010).

537 Third, the above-mentioned corrections were still not sufficient to optimise the MMF capacity of
538 predicting runoff for burned soil (both mulched and non-mulched), since the SWR effect was not
539 taken into account. Decreasing the MS parameter from the fire date throughout the year after
540 burning in the model by SWR corrections allowed an increase of the runoff generation capacity of
541 recently burned soils, and to progressively decrease it in the following seasons. Thanks to this
542 correction, the burned soil was able to store less water just after the fire (due to the higher SWR)
543 and gradually to increase this storage capacity after some months, when the effects of soil
544 repellency become negligible. A similar mechanism to address SWR has been proposed by Vieira et
545 al. (2014), although the authors took into account the seasonal recovery of SWR in their study sites.
546 After these changes, runoff predictions provided by the MMF model were adequate for all the
547 studied soil conditions, as confirmed by both the visual comparisons between the observed and
548 simulated values and the quantitative evaluation criteria.

549

550 4.2.2 Soil erosion

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552 It has been reported that, when the MMF model runs according the guidelines given by Morgan
553 (2001), the simulations are strongly influenced by the transport capacity of runoff (Fernandez et al.,
554 2010). In this study, the poor performance of the default MMF in simulating surface runoff
555 reflected on the erosion prediction accuracy, which was unsatisfactory for all the soil conditions,
556 since the model did not produce soil loss (presumably dictated by the zero-simulated transport
557 capacity, as observed also in the study of Vieira et al., 2014). The model failed in reproducing the
558 sediment transport capacity, which was not able to route the eroded sediment downstream either for
559 the most intense precipitation events. Accurate runoff simulations are required for reliable erosion
560 predictions (Zema et al., 2012), but this is not in general sufficient. Erosion simulations by MMF
561 are influenced not only by the runoff generation rates, but also by other factors such as slope, soil
562 erodibility or vegetation cover (Morgan, 2001; Hosseini et al., 2018). Therefore, after achieving
563 satisfactory predictions of surface runoff, the erosive sub-model of MMF also needed modifications.

564 Many literature studies show that under semi-arid conditions soil erosion is produced by a low
 565 number of intense precipitation events instead of precipitation with low variability throughout the
 566 year (e.g., Fortugno et al., 2017; Zema et al., 2014). Because soil erosion is a highly nonlinear
 567 process, a few rainstorms with high intensity may produce most of the annual soil loss (Jetten et al.,
 568 2003); this particular hydrological response, typical of semi-arid areas with low annual erosion, in
 569 general is not accurately simulated by models, which are developed for annual estimations
 570 (Shrestha and Jetten, 2018). Therefore, this peculiarity of the Mediterranean climate must be taken
 571 into account by hydrological and erosion models in these environmental contexts. In this study,
 572 only the precipitation with higher amounts, generating higher surface runoff volumes and thus
 573 increased sediment transport capacity of flow, was considered for soil erosion modelling, as this is
 574 normally the limiting factor for erosion.

575 Moreover, the seasonal variability of the crop cover factor must be considered, the C-factor being
 576 one of the most important input parameters for erosion simulations, by which the MMF model is
 577 greatly influenced (Morgan, 2001). The C-factor is very important for accurate simulations of
 578 erosion, because the vegetation cover of soil is the most influencing factor for soil loss after fire (e.g.
 579 Pierson et al., 2001; Pannkuk and Robichaud, 2003; Vega et al., 2005, Wagenbrenner et al., 2006;
 580 Fernandez et al., 2010); moreover, the C-factor is highly variable among soil management
 581 techniques and in time (interannually and seasonally) and is correlated with burn severity
 582 (Fernandez et al., 2016).

583 In the experimental conditions, the capacity of MMF to predict soil losses improved compared to
 584 the default model, since the predicted values of soil losses basically match the corresponding
 585 observations. The model's tendency to underestimate erosion, particularly for the data collected in
 586 burned and non-mulched soils, may be due to the slight underestimation of the highest values of
 587 erosion observed in winter under this soil condition. A model tendency to under-estimate soil
 588 erosion rates was also reported by Fernandez et al. (2010).

589 Further improvement in erosion modelling capacity of MMF can be achieved by working on the C-
 590 factor estimation methodology, which requires the assessment of the fire effects on the RUSLE sub-
 591 factors together with the accuracy of equations for calculating the C-factor (González-Bonorino and
 592 Osterkamp, 2004; Vieira et al., 2014). Unfortunately, in spite of a large number of applications of
 593 the RUSLE models, most studies of post-fire erosion provide estimations of C sub-factors over time
 594 affected by large errors (Larsen and MacDonald, 2007; Vieira et al., 2014).

595 The results of this study are in tune with other MMF modelling experiences made by other authors
 596 working in Mediterranean conditions. The accurate erosion predictions achieved using the MMF
 597 model in this study and in other burned study sites (Fernández et al., 2010; Vieira et al., 2014;

598 Hosseini et al., 2018) indicate that, in spite of the suitability of the model structure for burned areas,
599 some site-specific conditions are not simulated with accuracy by MMF, such as the seasonality of
600 the soil properties and surface cover (Hosseini et al., 2018). According to Hosseini et al. (2018) and
601 Vieira et al. (2014), MMF is not able to reproduce the recovery of vegetation and soil parameters
602 after fire, although the model can simulate erosion rates under different land uses and fire severity
603 (Fernández et al., 2010).

604 In general, the changes introduced in this modelling experience successfully improved model
605 performance compared to the seasonal prediction capacity of the other studies, which have instead
606 shown that MMF generally has difficulty in simulating seasonal erosion values. Limiting the
607 evaluation criteria to model efficiency, the highest coefficient E were achieved in our study (up to
608 0.98) compared the maximum value ($E = 0.78$) reported in the study of Vieira et al. (2014), carried
609 out on mulched soils of humid areas after low to severe fires at the seasonal scale. The model's
610 capacity to simulate erosion in our experimental conditions was better than MMF performances
611 reported by Fernandez et al. (2010): $E = 0.74$ at the annual scale on soils treated with straw wood
612 chip and cut shrub barriers under humid and oceanic climate and after moderate to severe fires; also
613 better than those by Hosseini et al. (2018): $E = 0.54$ at the seasonal scale in soils burned by
614 moderate fires without any treatment in humid conditions; and comparable with the findings of
615 Vieira et al. (2014), which achieved a maximum E equal to 0.93 in their experimental conditions
616 (Table 3).

617 Many studies have shown that erosion models perform better for predicting average soil loss rather
618 than erosion rates for particular years (Larsen and MacDonald, 2007; Fernandez et al., 2010). For
619 both the undisturbed and burned soils and the post-fire rehabilitation treatment (with straw
620 mulching) predictions, MMF performed accurately for the pine stands, but it needs further
621 verifications in other Mediterranean sites, in order to ensure the successful transferability of the
622 model in this specific ecosystem.

623 This encouraging performance has indicated that the MMF model, integrating the suggested
624 improvements, may represent a useful tool for forest ecosystem management, thanks to its
625 simplicity of use and the low demand of input parameters. In spite of the recent development of
626 physically-based models, simple empirical models, such as MMF, are still easier to use and often
627 more accurate for soil erosion predictions (De Roo, 1996).

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631 5. CONCLUSIONS

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633 The accuracy of the MMF model in predicting seasonal runoff and soil loss in dry Mediterranean
634 forests was evaluated in unburned plots and in areas affected by wildfire and then treated with straw
635 mulch or not. The poor performance of the model when applied with default parameters (setup
636 according to the original guidelines of the model's developers) required some changes in input data
637 in both the hydrological and erosive components.

638 For accurate runoff simulations the study suggested the need of introducing seasonal values of
639 evapo-transpiration in the model, reducing the hydrological depth of the soil and considering the
640 effects of soil water repellency in burned soils, in order to increase the surface runoff production
641 and taking into account the seasonal variability of soil hydrological behaviour (which are not
642 accurately reproduced by the default model). If these changes are integrated in the erosive sub-
643 model and only the erosive precipitation are modelled, MMF is able to predict seasonal soil losses
644 with good reliability, thus limiting the MMF inaccuracy in modelling the sediment transport
645 capacity when applied with default parameters.

646 This modelling experiment has shown the capacity of the MMF model in simulating the seasonal
647 hydrological response of both unburned and burned soils (these latter mulched or not) under
648 Mediterranean semi-arid conditions. Thus, the potential applicability of the model is promising as a
649 management tool for predicting and controlling the hydrogeological risk in Mediterranean forest
650 ecosystems threatened by wildfire as well as to evaluate the efficiency of post-fire treatments;
651 however, further experimental tests are needed to assure model's applicability to these climatic,
652 geomorphological and ecological contexts.

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661 LIST OF ABBREVIATIONS

662

A	Proportion (between 0 and 1) of the rainfall intercepted by the vegetation or crop cover
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BD	Bulk density of the topsoil layer (Mg/m^3)
C	Crop cover management factor; combines the C and P factors of the Universal Soil Loss Equation
CC	Percentage canopy cover, expressed as a proportion between 0 and 1
COH	Cohesion of the surface soil (kPa) as measured with a torvane under saturated conditions
EHD	Effective hydrological depth of soil (m); will depend on vegetation / crop cover, presence or absence of surface crust, presence of impermeable layer within 0.15 m of the surface
E	Soil erosion (kg/m^2)
E_t/E_0	Ratio of actual (E_t) to potential (E_0) evapo-transpiration
F	Raindrop splash (kg/m^2)
GC	Percentage ground cover, expressed as a proportion between 0 and 1
H	Runoff detachment (kg/m^2)
I	Typical value for intensity of erosive rain (mm/h)
K	Soil detachability index (g/J) defined as the weight of soil detached from the soil mass per unit of rainfall energy
KE	Kinetic energy (J/m^2)
MS	Soil moisture content at field capacity or 1/3 bar tension (% w/w)
PH	Plant height (m), representing the height from which raindrops fall from the crop or vegetation cover to the ground surface
Q	Runoff (mm)
R	rainfall (mm)
R_0	Daily rainfall (mm)
R_c	Soil water storage capacity (mm)
R_n	Number of rain days
S	Slope steepness ($^\circ$)
SWR	Soil water repellency
TC	Sediment transport capacity due to runoff (kg/m^2)
USLE-C	C factor of the Universal Soil Loss Equation (Morgan, 2001)
USLE-P	P factor of the Universal Soil Loss Equation (Morgan, 2001)
Z	Soil resistance (kPa^{-1})

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914

917 Table 1 - Values of the input parameters for evaluating surface runoff and soil loss by the MMF model in the experimental plots (Liétor, Spain).

919 (a) default model

Factor	Time														
	Year	Autumn	Winter	Spring	Summer	Year	Autumn	Winter	Spring	Summer	Year	Autumn	Winter	Spring	Summer
	Unburned					Burned and Mulched					Burned and Non-mulched				
R	391.7	140	150.1	68.1	33.5	391.7	140	150.1	68.1	33.5	391.7	140	150.1	68.1	33.5
R _n	63	22	29	7	5	63	22	29	7	5	63	22	29	7	5
I	25														
MS	0.28														
BD	1.2														
EHD	0.20					0.12					0.09				
K	0.7														
COH	2														
S	6														
A	0.06														
E _t /E ₀	0.95					0.86									
C	0.003					0.0001					0.009				
CC	0.7					0					0				
GC	0.47	0.44	0.41	0.63	0.38	0.16	0.09	0.17	0.22	0.16	0.1275	0.07	0.14	0.17	0.13
PH	1.2	1.2	0.7	1.1	1.8	0.6	0.1	0.1	0.8	1.2	0.4	0	0.1	0.6	1

(b) modified model (for surface runoff predictions)

Factor	Time														
	Year	Autumn	Winter	Spring	Summer	Year	Autumn	Winter	Spring	Summer	Year	Autumn	Winter	Spring	Summer
	Unburned					Burned and Mulched					Burned and Non-mulched				
R	391.7	140	150.1	68.1	33.5	391.7	140	150.1	68.1	33.5	391.7	140	150.1	68.1	33.5
R _n	63	22	29	7	5	63	22	29	7	5	63	22	29	7	5
MS	0.280					0.280	0.252	0.252	0.308	0.308	0.28	0.252	0.252	0.308	0.308
BD	1.2														
EHD	0.20					0.16					0.145				
E _d /E ₀	0.78	0.81	0.60	0.95	0.76	0.58	0.54	0.53	0.64	0.60	0.55	0.53	0.52	0.60	0.57
GC	0.47	0.44	0.41	0.63	0.38	0.16	0.09	0.17	0.22	0.16	0.13	0.07	0.14	0.17	0.13

(c) modified model (for soil loss predictions)

Factor	Time									
	Year	Autumn	Winter	Spring	Summer	Year	Autumn	Winter	Spring	Summer
	Unburned					Burned and Mulched				
R	266.2	85.8	91.1	62.3	13.5	266.2	85.8	91.1	62.3	13.5
R _n	12	3	6	2	1	12	3	6	2	1
I	25									
MS	0.28					0.28	0.252	0.252	0.308	0.308
BD	1.2									
EHD	0.200					0.160				
K						0.7				
COH						2				
S						6				
A	0.06									
E _d /E ₀	0.78	0.81	0.60	0.95	0.76	0.58	0.54	0.53	0.64	0.60
C	0.046	0.051	0.058	0.023	0.065	0.116	0.156	0.111	0.09	0.116
CC	0.7					0				
GC	0.47	0.44	0.41	0.63	0.38	0.16	0.09	0.17	0.22	0.16
PH	1.2	1.2	0.7	1.1	1.8	0.6	0.1	0.1	0.8	1.2
						0.4	0	0.1	0.6	1

Table 2 - Values of the criteria adopted for MMF model evaluation in the experimental plots (Liétor, Spain).

Plot	Hydrological variable	Model implementation	Mean (mm, SR, kg/m ² , SL)	Min (mm, SR, kg/m ² , SL)	Max (mm, SR, kg/m ² , SL)	Std. Dev. (mm, SR, kg/m ² , SL)	E	CRM	RMSE	R ²
Surface runoff (SR)										
Unburned	Observed	-	0.09	0.01	0.24	0.09	-	-	-	-
	Predicted	Default	0.04	0.00	0.11	0.05	-0.08	0.55	0.08	0.35
		Modified	0.08	0.02	0.21	0.08	0.82	0.13	0.03	0.85
Burned and Mulched	Observed	-	2.24	0.18	5.61	2.07	-	-	-	-
	Predicted	Default	0.88	0.18	1.93	0.79	0.43	0.61	2.13	0.22
		Modified	1.97	0.18	4.93	1.81	0.98	0.12	0.36	1.00
Burned and Non-mulched	Observed	-	2.62	0.21	6.55	2.44	-	-	-	-
	Predicted	Default	2.94	0.69	5.98	2.32	0.82	-0.12	1.41	0.63
		Modified	3.35	0.34	8.38	3.06	0.92	-0.28	0.94	1.00
Soil loss (SL)										
Unburned	Observed	-	0.001	0.000	0.002	0.001	-	-	-	-
	Predicted	Default	0.000	0.000	0.000	0.000	-1.37	1.00	0.001	0.32
		Modified	0.001	0.000	0.001	0.001	0.79	0.28	0.000	0.93
Burned and Mulched	Observed	-	0.012	0.001	0.031	0.012	-	-	-	-
	Predicted	Default	0.000	0.000	0.000	0.000	-0.07	1.00	0.016	0.04
		Modified	0.010	0.000	0.024	0.009	0.92	0.20	0.005	0.91
Burned and Non-mulched	Observed	-	0.031	0.003	0.079	0.031	-	-	-	-
	Predicted	Default	0.000	0.000	0.000	0.000	-0.03	1.00	0.042	0.82
		Modified	0.016	0.000	0.039	0.017	0.75	0.50	0.021	0.99

Table 3 - Comparison of MMF model evaluations after wildfire from literature studies.

Authors	Location	Climate type	Forest type	Fire severity	Soil type	Post-fire mitigation measure	Time scale	Modeling approach	Coeff. of Nash and Sutcliffe (1978) (E, -)	
									Runoff	Soil loss
Fernandez et al. (2010)	Galicia (NW Spain)	Humid Mediterranean + Oceanic	Pinus pinaster + Ulex europaeus	Moderate + severe	Alumi-umbric Regosol	Straw mulch, wood chip mulch, cut shrub barriers	Annual	Calibration + validation	n.a.	-0.69 to 0.74
Vieira et al. (2014)	North-central Portugal	Humid Mediterranean	Eucalyptus globulus Labill. + Pinus pinaster Ait.	Low + moderate + severe	Umbric Leptosol	Mulching + litter application	Annual + seasonal	Calibration + validation	-0.26 to 0.78	-10.00 to 0.93
Hosseini et al. (2018)	North-central Portugal	Humid Mediterranean	Pinus pinaster	Moderate	Humic Cambisols + epileptic Umbrisols	None	Annual + seasonal	Calibration + validation	-1.82 to -0.33	0.29 to 0.54
This study	Castilla La Mancha (SE Spain)	Semi-arid Mediterranean	Pinus halepensis M.	Severe	Inceptisols + Aridisols	Mulching with straw burned + none	Annual + seasonal	Verification	-0.08 to 0.98	-1.37 to 0.92

Note: n.a. = not available.

933 **FIGURE CAPTIONS**

934

935 Figure 1 - Location of the experimental plots (Liétor, Spain) (a) and scheme of the experimental
936 design (b).

937

938 Figure 2 - Surface runoff volumes (a) and soil loss (b) observed in the experimental plots (Liétor,
939 Spain) (mean and error bars; different letters indicate significantly statistical differences after t-test
940 at $p < 0.05$).

941

942 Figure 3 - Ground vegetal cover in the experimental plots (Liétor, Spain) (mean and error bars;
943 different letters indicate significantly statistical differences after t-test at $p < 0.05$).

944

945 Figure 4 - Scatter plots of observations vs. MMF (default model) predictions of surface runoff (a,
946 values in mm) and soil loss (b, values in kg/m^2) in the experimental plots (Liétor, Spain).

947

948 Figure 5 - Scatter plots of observations vs. MMF (modified model) predictions of surface runoff (a,
949 values in mm) and soil loss (b, values in kg/m^2) in the experimental plots (Liétor, Spain).

HIGHLIGHTS

- The use of MMF model in burned areas of Mediterranean forests is quite limited
- The MMF hydrological predictions in unburned/burned/mulched soils are improved
- The prediction capacity of MMF running with default parameters was basically poor
- After some changes, MMF was able to predict the seasonal runoff and soil losses
- MMF is useful for predicting the hydrological response of Mediterranean forests.

Location of the experimental plots (Liétor, Spain)

(b)

Scheme of the experimental design

Figure 2
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Figure 5
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Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: