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

Article Type: Research Paper

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

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

COVER LETTER

Reggio Calabria (Italy), 22/10/2018

Dear Editors,

The hydrological effects of wildfire (such as surface runoff and soil erosion) are pronounced in forest ecosystems of Mediterranean regions, leading to increased runoff and soil erosion rates and, hence, to land degradation. These problems require the assessment of the effects of various mitigation measures (as, for instance, mulching) before their practical implementation, in order to protect the delicate forest ecosystems. This need has created a strong demand for models for runoff and erosion prediction after fire. The use of semi-empirical models, such as MMF (Morgan-Morgan-Finney) model allows a basic representation of physical processes governing runoff and erosion phenomena typical of the process-based models, but maintains the ease of use and the limited requirements of input parameters of the empirical models.

However, in spite of large application in a wide range of environments, the use of MMF to predict runoff and soil erosion in burned areas of the Mediterranean ecosystem is quite limited, since the modelling experiences reported in eminent literature have been made at the annual scale and in humid areas (such as Portugal and Northern Spain).

For reliable hydrological predictions by MMF in the forest ecosystems of the semi-arid Mediterranean environment, it is important to take into account the temporal changes in the vegetal and soil input parameters in simulating the seasonal patterns of runoff and erosion. Thus, compared to the previous studies carried out in the Mediterranean areas, the prediction accuracy of the MMF model can be further optimised, changing some of the modellers' assumptions.

In order to fulfil this need, we propose for possible publication on "Catena" a paper, which tries to improve the hydrological prediction capacity of the MMF model in Mediterranean pine forests subjected to wildfire. More specifically, surface runoff and soil loss were firstly measured in (i) unburned plots (assumed as control); (ii) plots subjected to a wildfire and not rehabilitated with any post-fire measures; (iii) plots subjected to a wildfire and treated with mulching throughout one year. Based on these observations (aggregated at the seasonal scale), the model was run with default parameters and then modified to optimise simulations of water runoff and soil erosion under the peculiar climatic conditions and forest management practices.

The results of the study revealed poor performance of MMF, when the model run with default parameters (setup according to the original guidelines of the model’s developers). Conversely, after introducing some changes in input data in both the hydrological and erosive components of MMF (seasonal values of evapotranspiration, reduction of the soil hydrological depth, embedment of soil water repellency effects in burned soils, modelling of only erosive precipitation), MMF was able to predict the seasonal runoff volumes and soil losses with good reliability in all the experimented soil conditions.

Overall, the study has shown the potential applicability of the model as management tool for predicting and controlling the hydrogeological risk in Mediterranean forest ecosystems threatened by wildfire as well as for evaluating the efficiency of post-fire treatments.

We hope that the proposed paper will be of interest to the readers of "Catena", since we think that the results of this study (i) help to achieve a better comprehension of hydrology in burned and rehabilitated forests (which, as known, is extremely complex, depending on a combination of several factors), and (ii) could support landscape planners when adopting the strategic choices about soil conservation in the delicate forest ecosystems of the Mediterranean environment.

Finally, we thank You in advance for the attention You will pay to our paper.

Kind regards.

Demetrio Antonio Zema
(on behalf of co-authors)

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

Demetrio Antonio Zema (1,*), João Pedro Nunes(2), Manuel Esteban Lucas-Borja (3)

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Dear Editors,

we would like to thank You again for giving us the possibility to revise our manuscript. We would be very grateful if You could reconsider the revised MS for publication on Your valued journal. You will find in the resubmission the revision notes replying to each of the Reviewer's comments; moreover, all changes made are evidenced in the tracked MS (more specifically, text added in red underlined characters and text removed in blue crossed characters).

It continues in the following pages.

AUTHORS’ REPLIES TO COMMENTS OF THE REVIEWERS

Dear Sirs/Madams, thanks a lot for Your revision work that we have considered very useful to improve our MS. In the following table You will find our replies to all your comments. However, we address You to the file containing the revised paper and attached to the resubmission.

N.	***Reviewer’s comment***	***Authors’ reply***
	Reviewer n. 3	
-	This paper covers a very interesting topic. Clearly, much thought and effort has been put into the study's design, implementation, and analysis. I commend the authors on a valuable topic which appears to have been executed well.	Many thanks for Your opinion. We are glad that You consider the paper interesting and of appreciable quality.
	However, the paper itself seems to suffer from a little identity confusion. Is it a model-improvement paper, or a field research paper? The intention is clear from the title: "Improvement of… predictions by the MMF model…", and the majority of the paper follows this focus well. However, included in the paper are also results and discussion about the field trial itself and is trying to accomplish two goals: what was the outcome of the field trials, and how could the model be improved to mimic these results? It feels like two papers in one, and I feel that these goals should be separated into two distinct papers. As it is, the paper does not do justice to the results of the field trials. There are only two small sections devoted to this (3.1 and 4.1), and do not cover the subject adequately.	As the paper title says, it is a model adaptation for burned and treated soils under Mediterranean conditions. This adaptation required the model's testing in field conditions, for which it was necessary to collect observations about runoff and erosion by fieldwork. Yours is an interesting and useful advice, but we prefer to leave the paper as it is for two reasons: - in a study dealing with hydrological modelling the description of methods and results about observation is very important and common; - the outcomes of the field trials have been already published in an earlier paper (Lucas-Borja, M. E., González-Romero, J., Plaza-Álvarez, P. A., Sagra, J., Gómez, M. E., Moya, D., ... & de Las Heras, J. (2019). The impact of straw mulching and salvage logging on post-fire runoff and soil erosion generation under Mediterranean climate conditions. Science of The Total Environment, 654, 441-451), - not about hydrological modeling - therefore another paper would not be novel.
	For example, the results displayed in related figures (2 and 3) require statistical analysis and significance testing, such as "a", "b", "c" indicators above the bars to denote which results were statistically significant. Additionally, Figure 3 needs error bars too.	We have added the results of statistical significance tests in Figures 2 and 3 and error bars in Figure 3.

	However, this is out of the scope of this paper, as we're talking about how well the model mimics the collected data and how that can be improved, not how much more erosion and runoff there is on burned vs. unburned plots, and how effective straw mulch is as a countermeasure. Because the field trial is an important topic to cover with the same academic rigor as the modeling exercise, I recommend extracting this from the paper and giving it its own spotlight in a second article.	Please, refer to the comment above.
	Besides this major point, the article needs a substantial amount of cleanup and clarification, mostly related to the handling of the abbreviations within the text and some tightening of the English. But the substance of the article is sound otherwise, and I feel that with these changes it would make a valuable contribution to the scientific literature.	We have revised the text according to Your valuable suggestions.
	A list of specific items to address in the paper are included as an attachment.	Please see the comments below.
1	Throughout paper: abbreviation definitions (such as “ground cover (GC)”) should only appear once, the first time the term is used in the paper. Thereafter, only the abbreviation should be used. In this paper, almost all abbreviations are redefined at least once, and some multiple times.	Done everywhere in thee text.
2	Multiple lines: r2 should be capitalized: R2. Please make this change in the multiple places it appears, including in Table 2.	Changed everywhere in thee text.
3	Multiple lines: tables and figures should be numbered in the order they appear in the text. The tables look OK, but the figures are scrambled. Please change the figure numbers to be sequential to their first reference.	Done everywhere in thee text.
4	Figures: All figures need to be higher quality (resolution). Also, including a title with each would be helpful.	Done.
5	P. 1 line 22: replace “requirement” with “number”. I am assuming that the benefit of MMF is that there are fewer numbers of parameters, not that they are less required.	Replaced.
6	P. 2 first paragraph of Intro: In the US and other regions in the world, wildfire is actually a necessary element for forest	We have added more discussion about it (see lines 48-51 of the revised clean MS).

	health, where forests evolved with the regular occurrence of wildfires. I do not know the history of wildfire in the Mediterranean, but there will be many readers who will notice a tone of strong bias against wildfire in this region. This position either needs to be tempered with a balanced discussion of the benefits vs. challenges of wildfire based on scientific analysis, or supported from the same scientifically-informed perspective. For example, perhaps one helpful reference would be Pausas et al. 2009 “Are wildfires a disaster in the Mediterranean basin? A review.”	
7	P. 2 lines 34-38: Be careful about the extrapolation of your results, based on one site. Your conclusion points out that, while the results are promising, more research is needed in the same conditions. Please briefly incorporate this caveat into your Abstract.	Incorporated.
8	P. 2 line 47: change “threats for” to “threats to”	Changed.
9	P. 2 line 52: “Soil Water Repellency” should not be capitalized. Just say “soil water repellency” (though the abbreviation should stay capitalized).	Done.
10	P. 3 line 71: insert a space after the colon “used:simple”	Inserted.
11	P. 3 line 82: again, change “requirements” to “numbers”	Changed.
12	P. 3 line 85: insert a space after period “2018).Since”	Inserted.
13	P. 3 line 94: “exercises” would be a better word choice than “experiences”	Changed.
14	P. 3 line 96: remove comma after “environments,”	Removed.
15	P. 3 line 98: it would be helpful to explicitly state “the objective of this study was to…”	Corrected.
16	P. 3 line 98: you note that the study site is a “Mediterranean semi-arid pine forest”. Is it a plantation, or a wild habitat? It would be helpful to be explicit, perhaps explaining this in the P. 4 narrative.	We have clarified this explanation. All this research was developed in a natural pine forest located in the southern Spain. This information has been added to the text (see line 119).
17	P. 4 line 113: remove the comma and semicolon	Removed.
18	P. 4 line 116: “elevation” would be a better word choice than “altitude”	Changed.

19	P. 4 line 122: “logging was the main historic disturbance” Wildfire was not? How did logging favor forest stand growth? I’d like to see a short explanation, with a reference.	We have added more explanation about this comment. Forest management practices are designed to stimulate bole wood productivity. It is usually held that pines growing in managed stands show lower growth sensitivity to water availability and greater resilience and resistance to drought events than pines in unmanaged stands. This information has been added to the text (see lines 144-147).
20	P. 5 line 144: insert “burn” between “soil severity” -> “soil burn severity”	Inserted.
21	P. 5 line 149: insert “burned” between “between plots” -> “between burned plots”, for clarity	Inserted.
22	P. 5 line 167: “amount” would be a better word choice than “height”	Changed.
23	P. 6 lines 174-175: don’t capitalize words that aren’t proper nouns: “Total Dissolved Sediments” and “Suspended Sediments” should be lower case (though the abbreviation should stay capitalized)	Corrected.
24	P. 6 line 175: how were TDS and SS measured in the lab? Provide a reference.	Reference added.
25	P. 6 line 187: “particles” should be singular: “particle”	Changed.
26	P. 6 line 190: I don’t understand what “an exponential rainfall distribution” is. Please explain or reword.	We have added more details in the text (see lines 226-240) with the related equations.
27	P. 6 line 191: insert a comma after “assumed”	Inserted.
28	P. 6 line 191: “runoff is produced when daily rainfall exceeds soil water storage capacity” but not also the infiltration rate, which would produce runoff before soil becomes saturated? This sounds like a shortcoming of the model and should be briefly discussed (the Discussion section would be appropriate). I’m very surprised that the soil’s infiltration rate is not included in a hydrological model. It sounds like you have addressed this limitation by dividing the soil depth into two layers, which was obviously helpful, but perhaps could be improved with infiltration information.	This is an important consideration and we thank a lot the Reviewer. The comment refers to an intrinsic characteristics of the MMF model, which evidently simulates the runoff generation mechanism by "saturation excess" (therefore, runoff begins when daily rainfall exceeds soil water storage capacity) instead of "infiltration excess" (runoff begins when rainfall intensity exceeds soil infiltration rate). It can really be a shortcoming of the model, when it is applied in Mediterranean semi-arid soils, where the prevalent runoff generation mechanism is "infiltration excess". However, also other runoff models (e.g., the SCS-CN model) are based on the "saturation" mechanism, but widely applied also in

		the Mediterranean environment with a fair runoff prediction capacity. Overall, the suggestion given by the Reviewer could be very useful for further MMF improvements, which may take into account the "infiltration excess" mechanism by modifying the water phase sub-model. To valorise the suggestion of the Reviewer, we have added these considerations in the "Discussion" section (see lines 525-528).
29	P. 6 line 199: states there are 16 input parameters, but only 15 are listed in this paragraph and Table 1. Also, line 228 notes there are 15 inputs.	Corrected (15 parameters, it depends on assuming E0/Et as single or two parameter(s)).
30	P. 7 line 204: the word “parameters” is not need and should be deleted	Deleted.
31	P. 7 line 207: insert “evapotranspiration” after the potential abbreviation (“potential (E0)”	Inserted.
32	P. 7 line 220: insert space into “theguidelines”	Inserted.
33	P. 7 line 222-224: this sentence (“This approach…literature values.”) is awkwardly phrased and should be rewritten for clarity	We have rewritten this sentence.
34	P. 7 line 229: “in field” should be hyphenated: “in-field”	Corrected.
35	P. 7 line 230: “with some corrections” – what were the corrections? And how were they made? Please explain, including equations if applicable.	There was a correction in the MS parameter, explained in another section. However, we have added more information (see lines 284-291).
36	P. 7 line 231: please include references for the values that were estimated from literature	Done. Note that all the modifications applied to the input parameters were detailed also in the previous manuscript version in the subsequent sections. However, we have added more information in these occurrences (see lines 284-291).
37	P. 7 line 232: change “datasets” to just “sets”	Changed.
38	P. 7 line 234-236: the phrasing on these lines is awkward and should be rewritten for clarity	We have rewritten this sentence.
39	P. 8 lines 237-241: I think this paragraph would be better at the end of this section, to improve the flow and readability of the section	Moved.
40	P. 8 line 239: “USLE-C factor” – what is this? USLE-C looks	Done.

	like an abbreviation that hasn't been defined yet so needs explanation. Also, is this a parameter in the model? This is the first we've heard about it, and it is not included in the parameter list. If this paragraph is moved to the end of the section (as suggested above), this term could be explained in the line 262-266 paragraph, and no change would be needed in this one.	
41	P. 8 lines 262, 264: "USLE-P factor" also not listed in section 2.3.1. It sounds like a parameter in the model (line 264: "it was set to one"), but is not listed. Both the USLE P-factor and C-factor need more explanation as to their role in the model. If they are not parameters, then what are they? What role do they play in the model. Should the parameter list be 17, not 15? Or is C-factor the same as the cover management factor (C)? Please explain.	The role of the USLE-C and USLE-P factors are reported in the paper of Morgan (2001). Of course, following the suggestion of the Reviewer, we have added an explanation for both (see lines 256-259).
42	P. 9 line 275: remove "depth", not necessary	Done.
43	P. 9 line 286: "corrected by a coefficient" – please provide an equation, even if very simple	Done.
44	P. 9 line 286: change "decreasing" to "to decrease"	Done.
45	P. 9 line 293: "which cannot be neglected neither after a wildfire" – the meaning of this is unclear. Please reword for clarity.	We have rewritten this sentence.
46	P. 9 line 299: "release seeds over soil" – I'm not sure what this is communicating. Is this indicating that part of the treatment is the inadvertent reseeding of the plot due to grass seed brought to the site in the straw, resulting in grass growing on the site? Please explain.	Thanks for the comment. The reviewer is right since straw usually contains seeds that can germinate and emerge after mulching application, resulting in herbal layer growing on the site. This information has been added to the text (see lines 359-361).
47	P. 9 line 301: "need of continuous control and adjustment of soil moisture" – in what context? In the model, or on the ground? I assume the latter, but please be clarify.	In the model. Information added.
48	P. 10 line 311: "scatter-plots" – remove quotes and hyphen. It's a well-known term.	Done.
49	P. 10 line 324: RMSE measures the standard deviation (SD) of the squared errors between observations and predictions, not	Corrected.

	their average, despite how it's explained by Fernandez et al., which is incorrect. MSE is the statistic which just measures the mean, or average.	
50	P. 10 line 325: change "closest" to "close"	Corrected.
51	P. 10 line 325: "RMSE is considered poor…" This is a misinterpretation of Singh et al. As just stated the sentence before, "RMSE should be as close as possible to zero". Why then, would an RMSE less than half of the SD indicate a "poor" score? Singh et al. state on their page 6 that as close to zero is a good thing, and if it's less than half the SD, this can be considered a low (i.e. "good") value. So if you're going to use Singh's interpretation of the RMSE, "poor" should be changed to "good" in this line.	Corrected. It was simply a typo.
52	P. 11 section 3.1: There are some edits needed in this paragraph, but my suggestion is to remove this section entirely, along with figures 2 and 3, as they should be reserved for a second paper.	Please see our reply to Your previous comment.
53	P. 11 line 362: change "The model was instead successful…" to "However, the model was successful…"	Changed.
54	P. 12 line 374-375: RMSE is evaluated against the SD of the data. However, the evaluation noted earlier is to compare RMSE to half of the SD, and the results show this happens much of the time. Have the discussion of the results follow the stated criteria.	Done.
55	P. 12 line 375: "residual" isn't a great word choice here and should simply be removed	Removed.
56	P. 12 line 385-386: again, the RMSE is compared to the SD, but not half the SD as stated in the criteria	Done.
57	P. 13 section 4.1: There are some edits needed in this paragraph, but my suggestion is to remove this section entirely, along with figure 2, as it should be reserved for a second paper.	Please see our reply to Your previous comment.
58	P. 14 line 449: Since evapotranspiration is already included as a parameter, including measurements over estimates will not	Corrected.

	improve the model itself, but rather addresses the accuracy of its predictions. Therefore, change “further model improvements” to “further improvements in model predictions”.	
59	P. 15 line 468: change “however” to “still”	Changed.
60	P. 15 line 469: remove “s” from “effects” -> “effect”	Removed.
61	P. 15 line 484: change “on “ to “by” (“influenced on” to “influenced by”)	Changed.
62	P. 15 line 488: need an additional closing parenthesis, to match the open parenthesis from the previous line -> “Vieira et al. (2014).” to “Vieira et al. (2014)).”	Done.
63	P. 15 line 496: change “precipitations” to “precipitation” or “precipitation events”	Changed.
64	P. 16 line 503: “amounts” would be a better word choice than “depth”	Changed.
65	P. 16 line 506: remove “also” – not needed	Removed.
66	P. 16 line 508: “shows a high sensitivity” – what is the evidence of this? Was a sensitivity analysis performed on this model? Provide information to support this, or at least a reference.	We have not carried out a sensitivity analysis, therefore the word "sensitivity" may be misleading, as rightly observed by the Reviewer. We have modified the sentence, removing the reference to "sensitivity".
67	P. 16 line 512: “correlated” would be a better word choice than “well related”	Changed.
68	P. 16 line 514-516: You’ll want to be careful about emotional statements such as “soil losses drastically improved”. Your results support this conclusion in my own opinion, but your supporting evidence is based on simple observation of points on a graph, which isn’t strong support. The “drastic” improvement is based on the fact that the default model didn’t predict any soil loss to begin with, then the model improvements resulted in acceptable values based on the results of the statistical analysis. These details (hard evidence) should be used to support your assertion that the change was substantial.	We agree with Your suggestion, thus we simply have removed the word "drastically" from the sentence.
69	P. 16 line 516: remove “residual” – not a good word choice	Removed.

70	P. 18 line 578: include “a” after “promising as” -> “promising as a”	Included.
71	P. 18 line 592: please alphabetize the abbreviations	Done.
72	Table 1, part c: explain in the table caption why same parameters are italicized.	It was a mistake. Italics removed.
Reviewer n. 4		
1	Introduction does not provide enough information about the content of the articles cited and the relationship between the methodology used there and the methodology used in the present work.	We have added more information about the cited literature of the Introduction section (see lines 96-112 of the revised clean MS).
2	The MMF model should be shortly presented (give the equations) in introduction.	It is not usual to introduce equations in the Introduction, but we did it in the section 2.3.1.
3	Line 250: Please explain why in the water phase an exponential rainfall distribution is assumed and what happens if it is not exponentially distributes (that is possible, point of view of hydrology).	This is the hydrological sub-model structure adopted and tested by the MMF developers (Morgan et al.). Therefore, there is not any particular reason. However, to address the Reviewer's requirement, we have added more information about the rainfall distribution, drawn by the original paper of Morgan et al., 2001 (see lines 226-240).
4	Lines 361-372. Please explain more clear. The linear estimation is correct point of view if statistics? Why linear, and why you didn't consdider a multiple linear model or another type of multiple model if there are other correlations as well.	We believe that this question results from a lack of clarity of the text. Trying to interpret the meaning of "linear estimation", we have used, as explained in the "Methods" section, a set of indexes commonly used in literature, such as R2, E, RMSE and CRM and compared the couples of observation/prediction of runoff and erosion with the identity line (1:1). If the model simulated exactly the observed variable, each couple was overlaid on the identity line. The other indexes used in this work do not hypothesise - except for R^2 - a linear estimation, but are based on the squared errors between observations and predictions (e.g., E and RMSE). Therefore, we have not assumed a linear estimation, as the Reviewer has understood from the text. We hope that this discussion has clarified this issue, and we have added some more details in the text to make this clear (see lines 379-381).

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

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ABSTRACT

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

This modelling experiment has shown the capacity of the MMF model to simulate the seasonal hydrological and erosion response of the experimental ~~of both~~ unburned and burned soils of~~in~~ Mediterranean semi-arid forests. Although more research is needed to validate the model's prediction capacity in these conditions, ~~Therefore,~~ the use of MMF as a management tool may be~~is~~ 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~~for~~ 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 ~~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~~requirements~~ 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-Gonzàlez 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 (Fernàndez et al., 2010)~~Portugal (Vieira et al., 2014; 2018; Hosseini et al., 2018)~~ and

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

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

2. MATERIALS AND METHODS

2.1 Study area

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

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

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

2.2 Hydro~~lo~~logical 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 x 1 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~~height~~ and intensity during the study period.

2.2.3 Hydrological data collection

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

2.3 Hydrological modelling

2.3.1 Outline of the MMF model

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

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

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

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

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

being:

$$R_c = 1000 \cdot MS \cdot BD \cdot EHD \cdot \frac{E_t}{E_0} \tag{2}$$

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

The sediment phase estimates soil particle detachment as the sum of raindrop splash (F, kg/m^2, calculated from kinetic energy, KE, J/m^2, and erodibility of the soil, K, g/J~~ canopy cover of vegetation~~) and runoff detachment (H, kg/m^2, calculated from ~~runoff volume,~~ Q, ~~plot slope,~~ S, ~~vegetation ground cover,~~ GC, and soil resistance, Z):

$$F = K \cdot KE \cdot 10^{3} \tag{3}$$

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

being:

$$Z = \cdot \frac{1}{0.5 \cdot COH} \tag{5}$$

and

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

Sediment transport capacity due to runoff (TC, kg/m^2) is calculated from ~~its volume,~~ Q, ~~slope,~~ S, and a crop or plant ~~vegetation~~ 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:~~.~~

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

Soil ~~E~~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).

~~The revised MMF model requires 16 input parameters, classified into four groups. A first group comprises rainfall parameters as annual rainfall (R, mm), number of rain days per year in the season (R_n, -) and the typical value for intensity of erosive rain (I, mm/h). The second group is related to soil characteristics, as soil moisture content at field capacity (MS, % w/w), bulk density of the top soil layer (BD, Mg/m^3), effective hydrological depth of soil (EHD, m), soil detachability index (K, g/J) and cohesion of the surface soil (COH, kPa) parameters. The third group is related with landform, and only includes slope steepness (S, °). The fourth group includes land cover parameters, as the proportion of the rainfall intercepted by the vegetation or crop cover (A, -), ratio (E_t/E_0, -) of actual (E_t) to potential (E_0), crop cover management factor (C, -), percentage canopy cover (CC, %), percentage ground cover (GC, %) and plant height (PH, m) to the ground surface.~~

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. ~~This approach tested the situation, which is typical for emergency post-fire stabilization operations, w~~When measuring input parameters is not possible or very expensive and time consuming, users of MMF~~ and modellers~~ are forced to adopt ~~the suggested ~~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 ~~in-field, five were derived from the guidelines of Morgan et al. (1984), Morgan (2001) and Morgan and Duzant (2008) with a~~some~~ correction for MS, according to Vieira et al. (2014) and Nunes et al. (2016)~~s~~, while the remaining three values had to be estimated from literature (Doorenbos and Kassam, 1986; Wischmeier and Smith, 1978; Fernàndez et al., 2010; Vieira et al., 2014; Nunes et al., 2016). More details about the model parameterisation are reported in the following section.

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

~~According to Vieira et al. (2014), the seasonal modelling approach involved the input of the seasonal values of soil moisture at field capacity (MS), corrected by changes in SWR (except for unburned plots), evapotranspiration (E_t/E_0), ground cover (GC) and USLE-C factor. Conversely, under the annual modelling approach the annual mean values over the full post-treatment period were provided to the model.~~

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

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

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

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

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

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

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 ~~depth ~~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 Fernàndez 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~~ing~~ with increasing fire severity (from 0.8 for extreme repellency to 1.1 under wettable conditions; Vieira et al., 2014) (Table 1)~~.~~, as follows:

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

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), ~~the effective hydrological depth of the soil (~~EHD~~)~~ must be properly modified to improve MMF results. The seasonal values of EHD were estimated by these authors as a linear function of ~~ground cover (~~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~~which cannot be neglected neither after a wildfire~~. 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 this surface layer, EHDs of "bare soil without surface crust" and "grass/pasture" were adopted for the burned and non-mulched plots and burned and mulched plots, respectively. This latter value of EHD was chosen, since ~~soil treatments with straw release seeds over soil and maintain higher moisture, enhancing vegetation cover recovery~~ straw usually contains seeds that can germinate and emerge after mulching application, resulting in herbal layer growing on the site (Lucas-Borja et al., 2018) (Table 1). If this choice is successful, the need of continuous control and adjustment of soil moisture in the model (as suggested by Vieira et al., 2014) can be overcome.

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

2.3.4 Model evaluation

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

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

To summarise:

- R^2~~r^2~~ ranges from 0 (no agreement between model and data variance) to 1 (perfect agreement); values over 0.5 are acceptable (Santhi et al., 2001; Van Liew et al., 2003; Vieira et al., 2018);
- E (Nash and Sutcliffe, 1970) is the most common measure of model accuracy and ranges from $-\infty$ to 1; the model accuracy is "good" if $E \geq 0.75$, "satisfactory" if $0.36 \leq E \leq 0.75$ and "unsatisfactory" if $E \leq 0.36$ (Van Liew and Garbrecht, 2003);
- RMSE, which measures the standard deviation ~~average error~~ between observations and predictions, should be as close~~st~~ as possible to zero (Fernandez et al., 2010); RMSE is considered good~~poor~~ if it predicted value is lower than 0.5 of the observed~~measured~~ 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/m^2). 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/m^2 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, ~~T~~the model was ~~instead~~ 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~~r^2~~ = 0.85-0.99; see also the proximity to the identity line) compared to the default model performance (R^2~~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 ~~residual~~ 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).

3.2.2 Soil erosion

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 ~~and Table 2~~). 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 simulations by hydrological models are normally not expected (e.g., Nearing, 1998). Vice versa, in soils such as burned and non-treated plots with a natural aptitude to produce more runoff compared to unburned as well as burned and mulched plots, this model's tendency to over-estimate infiltration is reduced; thus, the simulated runoff volumes are closer to the corresponding observations.

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

First, the role of vegetation cover (which varies throughout the year) cannot be neglected when the model must be implemented at the seasonal scale (Eekhout et al., 2018), since evapotranspiration is not constant in time (as it was assumed for the default model). Replacing the constant value of the input parameter E_t/E_0 (0.95 for the default model) with variable values considering the actual crop cover of each season, MMF increased the runoff production in all the soil conditions and the simulated seasonal means were closer to the corresponding observations (with difference not higher than 28%) (Table 2~~ and Figure 5a~~). The noticeable seasonal differences of ~~evapo-transpiration~~ ~~(~~E_t/E_0~~)~~ reduced (in the warm season) or increased (during the humid period) the water availability to generate surface runoff. These results were already observed in burned areas by Vieira et al. (2014) and Hosseini et al. (2018). Since the errors in predicting runoff by MMF may be caused by the inaccuracy of evapo-transpiration estimations (Fernandez et al., 2010), the use of observed values of evapo-transpiration may be suggested for further ~~model ~~improvements in model predictions.

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

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

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

4.2.2 Soil erosion

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

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

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

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

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

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

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

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

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

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

5. CONCLUSIONS

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

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

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

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LIST OF ABBREVIATIONS

A	Proportion (between 0 and 1) of the rainfall intercepted by the vegetation or crop cover

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	~~Seasonal r~~rainfall (mm)
R_0	Daily rainfall (mm)
R_c	Soil water storage capacity (mm)
R_n	Number of rain days~~ per season~~
S	Slope steepness (°)
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})
~~I~~	~~Typical value for intensity of erosive rain (mm/h)~~
~~MS~~	~~Soil moisture content at field capacity or 1/3 bar tension (% w/w)~~

~~BD~~	~~Bulk density of the topsoil layer (Mg/m^3)~~
~~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~~
~~K~~	~~Soil detachability index (g/J) defined as the weight of soil detached from the soil mass per unit of rainfall energy~~
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~~S~~	~~Slope steepness (º)~~
~~A~~	~~Proportion (between 0 and 1) of the rainfall intercepted by the vegetation or crop cover~~
~~E_t/E_0~~	~~Ratio of actual (E_t) to potential (E_0) evapo-transpiration~~
~~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~~
~~GC~~	~~Percentage ground cover, expressed as a proportion between 0 and 1~~
~~PH~~	~~Plant height (m), representing the height from which raindrops fall from the crop or vegetation cover to the ground surface~~

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TABLES

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

(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_t/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**	**Year**	**Autumn**	**Winter**	**Spring**	**Summer**
	Unburned					Burned and Mulched					Burned and Non-mulched				
R	266.2	85.8	91.1	62.3	13.5	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	12	3	6	2	1
I	25														
MS	0.28					0.28	0.252	0.252	0.308	0.308	0.28	0.252	0.252	0.308	0.308
BD	1.2														
EHD	0.200					0.160					0.145				
K	0.7														
COH	2														
S	6														
A	0.06														
E_t/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
C	0.046	0.051	0.058	0.023	0.065	0.116	0.156	0.111	0.09	0.116	0.238	0.293	0.23	0.207	0.238
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	0.13	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

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~~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.

FIGURE CAPTIONS

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

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

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

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

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

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

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ABSTRACT

The negative hydrological effects of wildfire are very difficult to predict in Mediterranean forest ecosystems, due the intrinsic climate and soil characteristics of these areas. Among the hydrological models simulating surface runoff and soil erosion in these environmental contexts, the semi-empirical Morgan-Morgan-Finney (MMF) model can ensure the representation of the main physical processes, while offering ease of use and limiting the number of input parameters. However, literature reports very few modelling studies using MMF in burned areas of the Mediterranean environment with or without post-fire rehabilitation measures. To fill this gap, the capacity of the MMF model to predict the seasonal surface runoff and soil loss in a Mediterranean forest was verified and improved for unburned plots and areas affected by a wildfire, with and without post-fire straw mulch treatment. The application of MMF with default input parameters (set up according to the original guidelines of the model's developers) led to poor performance. Conversely, after introducing some changes in input data for both the hydrological and erosive components (seasonal values of evapotranspiration, reduction of the soil hydrological depth, including soil water repellency effects in burned soils, and modelling erosive precipitation only), MMF was able to predict seasonal runoff volumes and soil loss with good reliability in all the experimented 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-Gonzàlez 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 (Fernàndez et al., 2010) and Portugal (Vieira et al., 2014; 2018; Hosseini et al., 2018). In two burned forest areas in NW of Spain with different levels of fire severity, Fernàndez et al. (2010) reported that for the first year following fire the MMF model presented reasonable accuracy in the predictions of soil erosion after three rehabilitation treatments. Vieira et al. (2014) introduced simple model enhancements in MMF, which performed well in simulating soil losses in recently burned pine and eucalypt forested areas in north-central Portugal, subjected to post-wildfire rehabilitation treatments. In the same environment, again Vieira et al. (2018) applied MMF to predict the effectiveness of different mulching techniques in reducing post-fire runoff and erosion at plot scale and found that the model was reasonably able to reproduce the hydrological and erosive processes occurring in these burned forest areas. Hosseini et al. (2018) found more accurate predictions of erosion than that of runoff, using MMF - adapted for burnt areas by implementing seasonal changes in model parameters - in microplots of recently burned maritime pine plantations of north-central Portugal with contrasting fire regimes.

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

2. MATERIALS AND METHODS

2.1 Study area

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

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

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

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 x 1 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.

2.2.3 Hydrological data collection

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

2.3 Hydrological modelling

2.3.1 Outline of the MMF model

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

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

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

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

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

being:

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

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

The sediment phase estimates soil particle detachment as the sum of raindrop splash (F, kg/m^2, calculated from kinetic energy, KE, J/m^2, and erodibility of the soil, K, g/J) and runoff detachment (H, kg/m^2, calculated from Q, S, GC, and soil resistance, Z):

$$F = K \cdot KE \cdot 10^3 \qquad (3)$$

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

being:

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

and

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

Sediment transport capacity due to runoff (TC, kg/m^2) is calculated from Q, S, and a crop or plant 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; Fernàndez et al., 2010; Vieira et al., 2014; Nunes et al., 2016). More details about the model parameterisation are reported in the following section.

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

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

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

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

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

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

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

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 Fernàndez 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:

$$MS_c = c \cdot MS \tag{7}$$

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

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

2.3.4 Model evaluation

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

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

To summarise:

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

3.2.2 Soil erosion

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

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

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

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

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

Third, the above-mentioned corrections were still not sufficient to optimise the MMF capacity of predicting runoff for burned soil (both mulched and non-mulched), since the SWR effect was not taken into account. Decreasing the MS parameter from the fire date throughout the year after burning in the model by SWR corrections allowed an increase of the runoff generation capacity of recently burned soils, and to progressively decrease it in the following seasons. Thanks to this correction, the burned soil was able to store less water just after the fire (due to the higher SWR) and gradually to increase this storage capacity after some months, when the effects of soil repellency become negligible. A similar mechanism to address SWR has been proposed by Vieira et al. (2014), although the authors took into account the seasonal recovery of SWR in their study sites.

After these changes, runoff predictions provided by the MMF model were adequate for all the studied soil conditions, as confirmed by both the visual comparisons between the observed and simulated values and the quantitative evaluation criteria.

4.2.2 Soil erosion

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

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

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

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

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

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

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

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

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

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

5. CONCLUSIONS

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

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

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

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LIST OF ABBREVIATIONS

A	Proportion (between 0 and 1) of the rainfall intercepted by the vegetation or crop cover

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 (º)
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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TABLES

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

(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_t/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**	**Year**	**Autumn**	**Winter**	**Spring**	**Summer**
	Unburned					Burned and Mulched					Burned and Non-mulched				
R	266.2	85.8	91.1	62.3	13.5	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	12	3	6	2	1
I	25														
MS	0.28					0.28	0.252	0.252	0.308	0.308	0.28	0.252	0.252	0.308	0.308
BD	1.2														
EHD	0.200					0.160					0.145				
K	0.7														
COH	2														
S	6														
A	0.06														
E_t/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
C	0.046	0.051	0.058	0.023	0.065	0.116	0.156	0.111	0.09	0.116	0.238	0.293	0.23	0.207	0.238
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	0.13	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

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.

FIGURE CAPTIONS

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

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

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

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

Figure 5 - Scatter plots of observations vs. MMF (modified model) predictions of surface runoff (a, 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

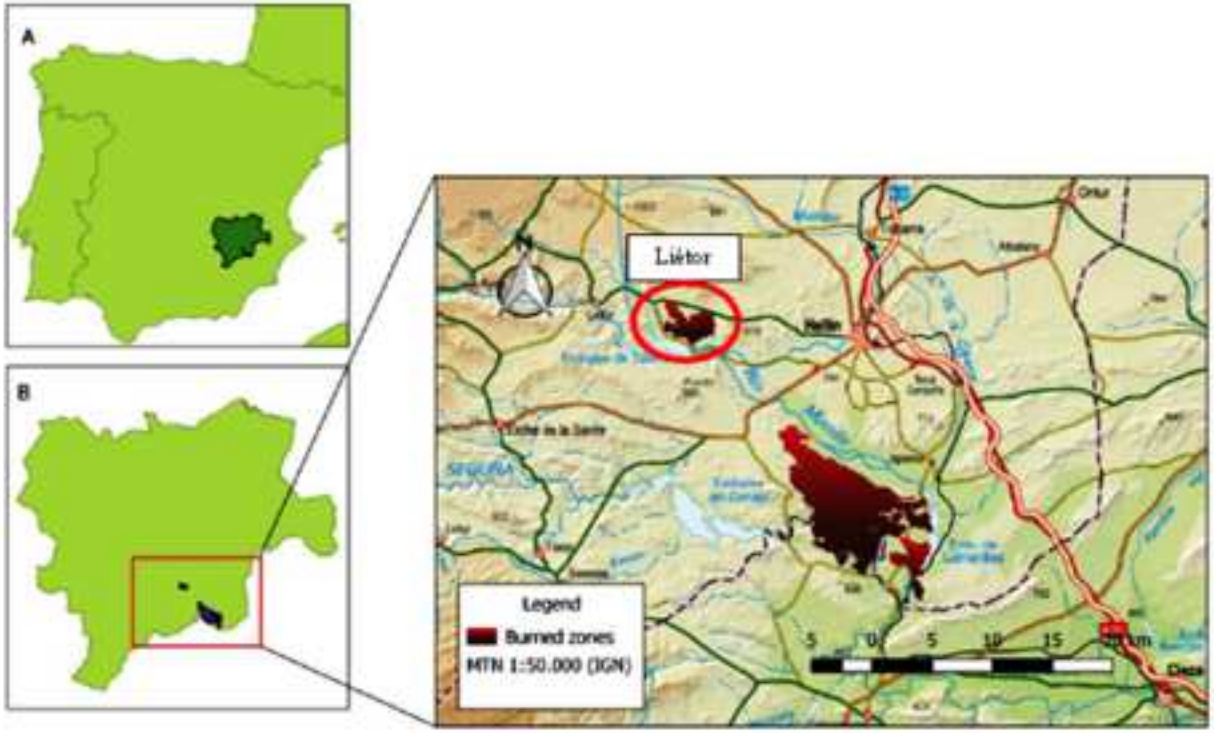
- The MMF hydrological predictions in unburned/burned/mulched soils are improved

- The prediction capacity of MMF running with default parameters wabasically 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.

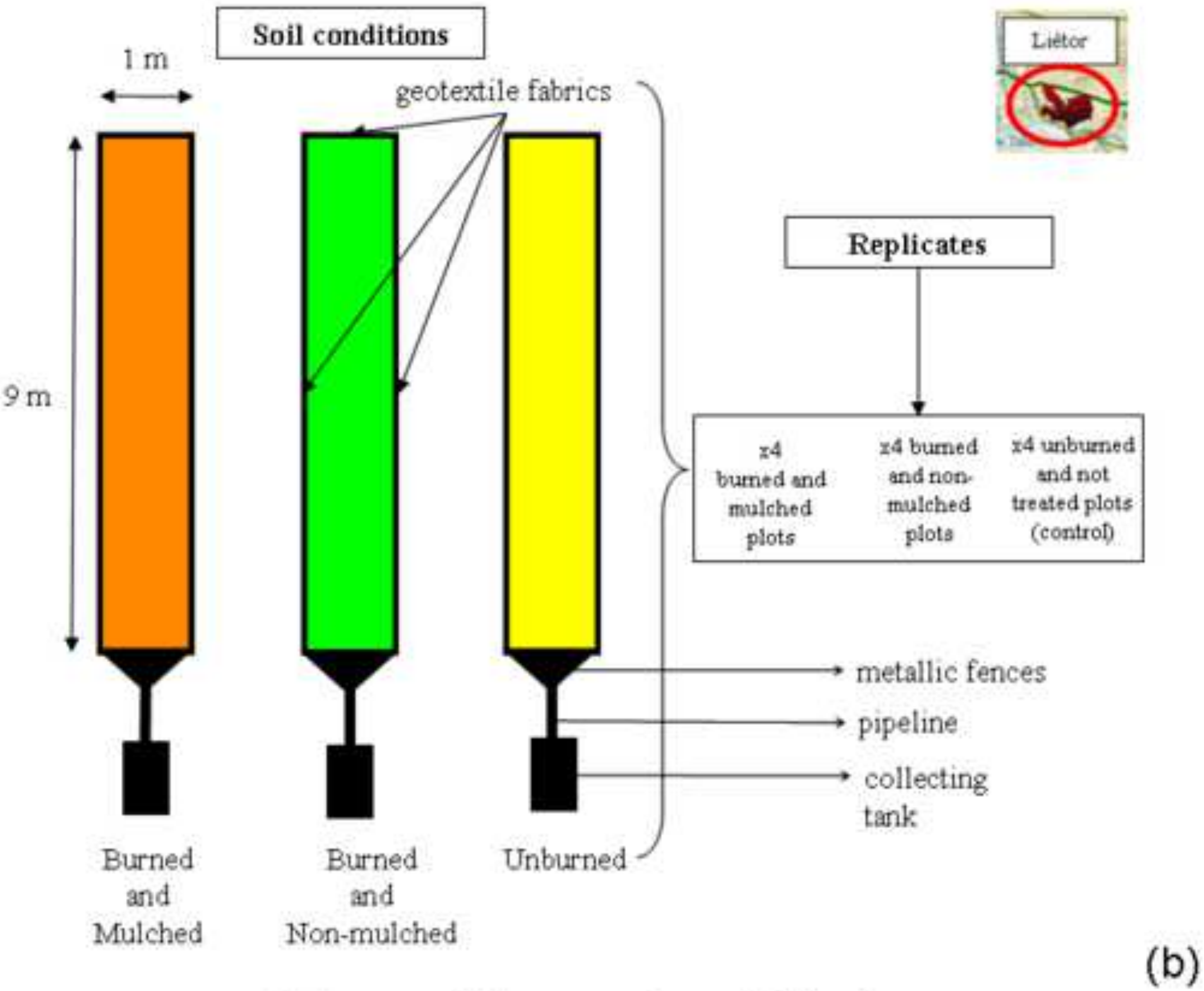
Figure 1 a



(a)

Location of the experimental plots (Liétor, Spain)

Figure 1 b



Scheme of the experimental design

Figure 2

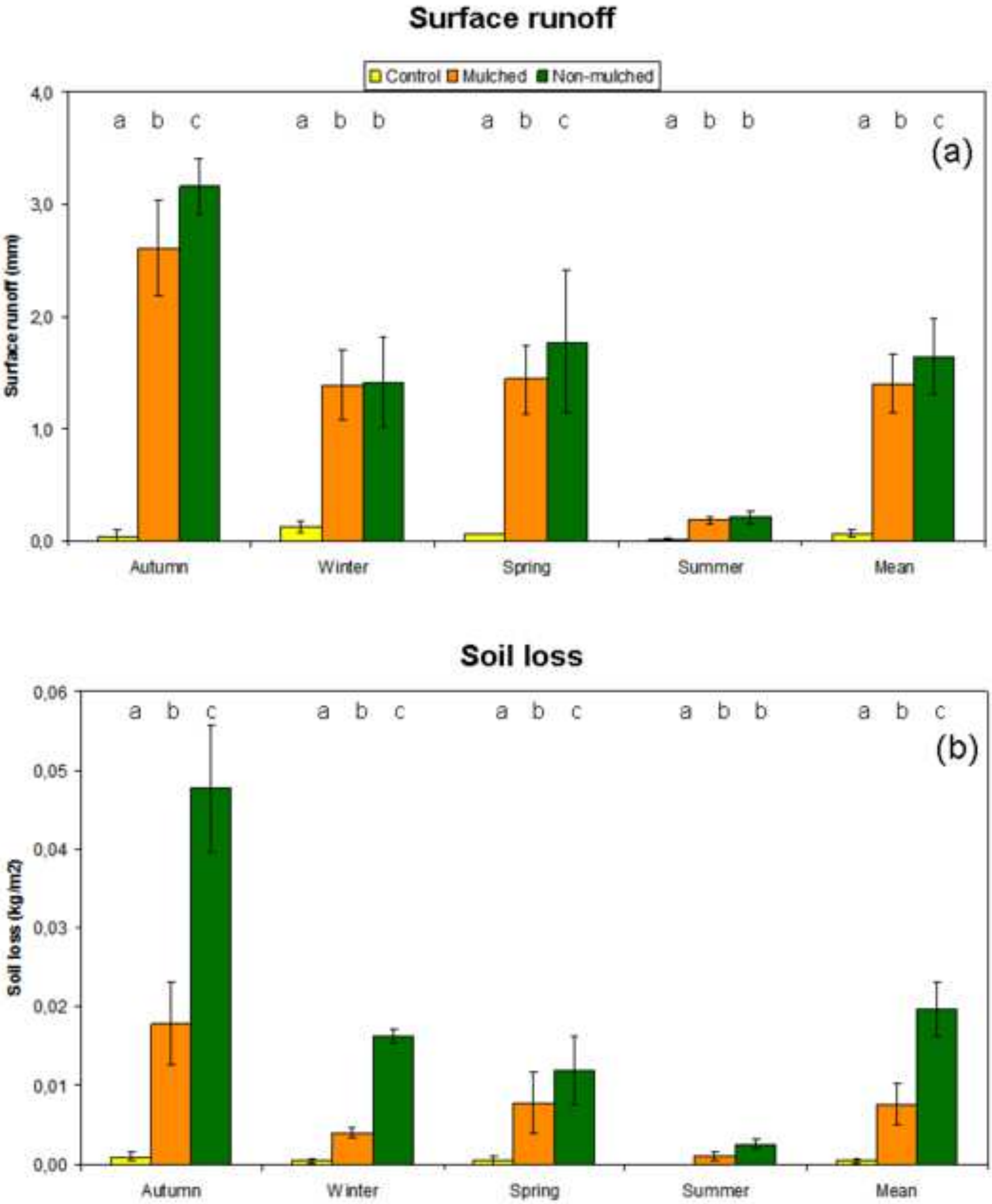

Surface runoff
🟨 Control 🟧 Mulched 🟩 Non-mulched
Surface runoff (mm)
4,0
3,0
2,0
1,0
0,0
a b c
a b b
a b c
a b b
a b c
(a)
Autumn
Winter
Spring
Summer
Mean
Soil loss
Soil loss (kg/m2)
0,06
0,05
0,04
0,03
0,02
0,01
0,00
a b c
a b c
a b c
a b b
a b c
(b)
Autumn
Winter
Spring
Summer
Mean

Figure 3

Click here to download high resolution image

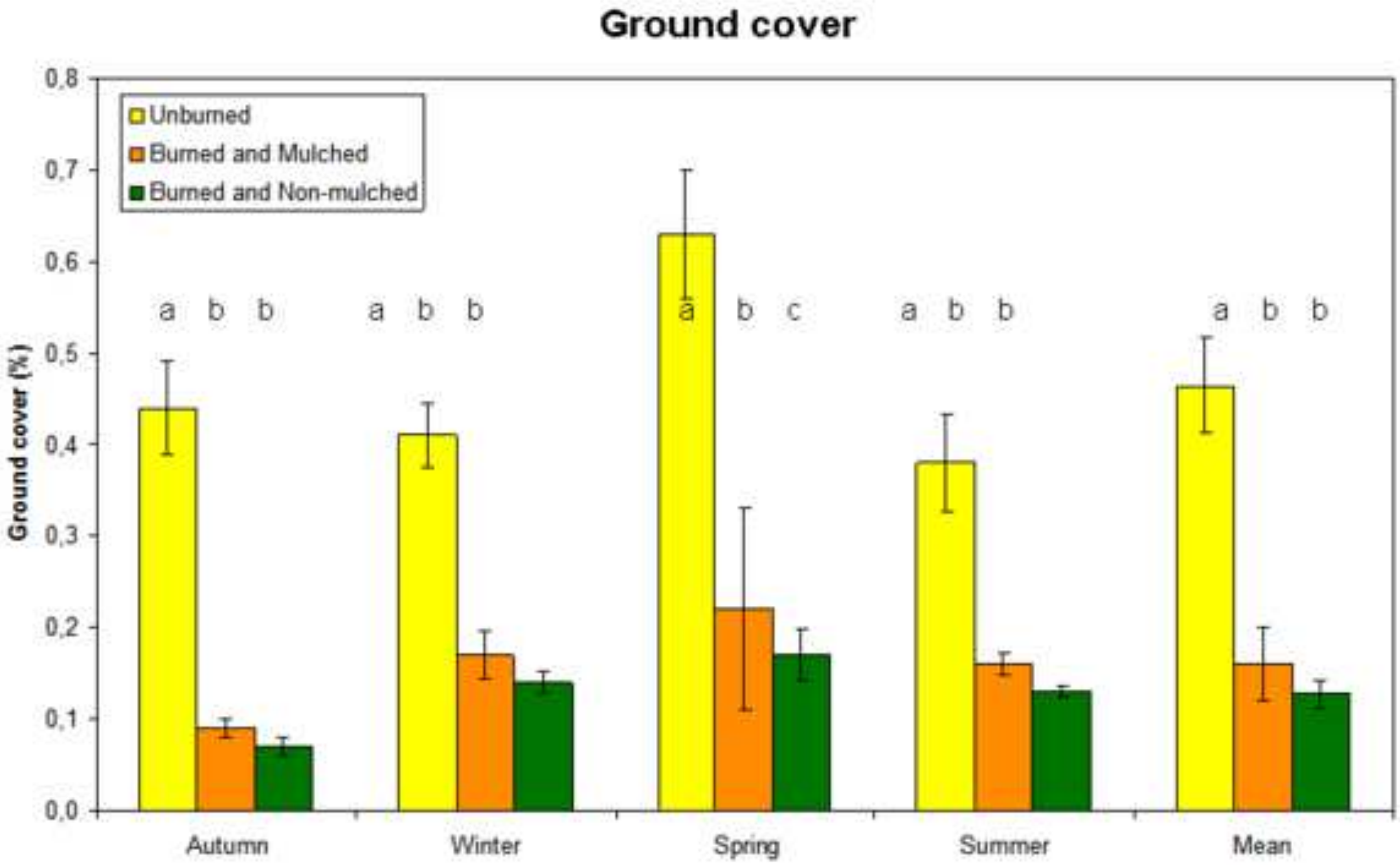


Figure 4

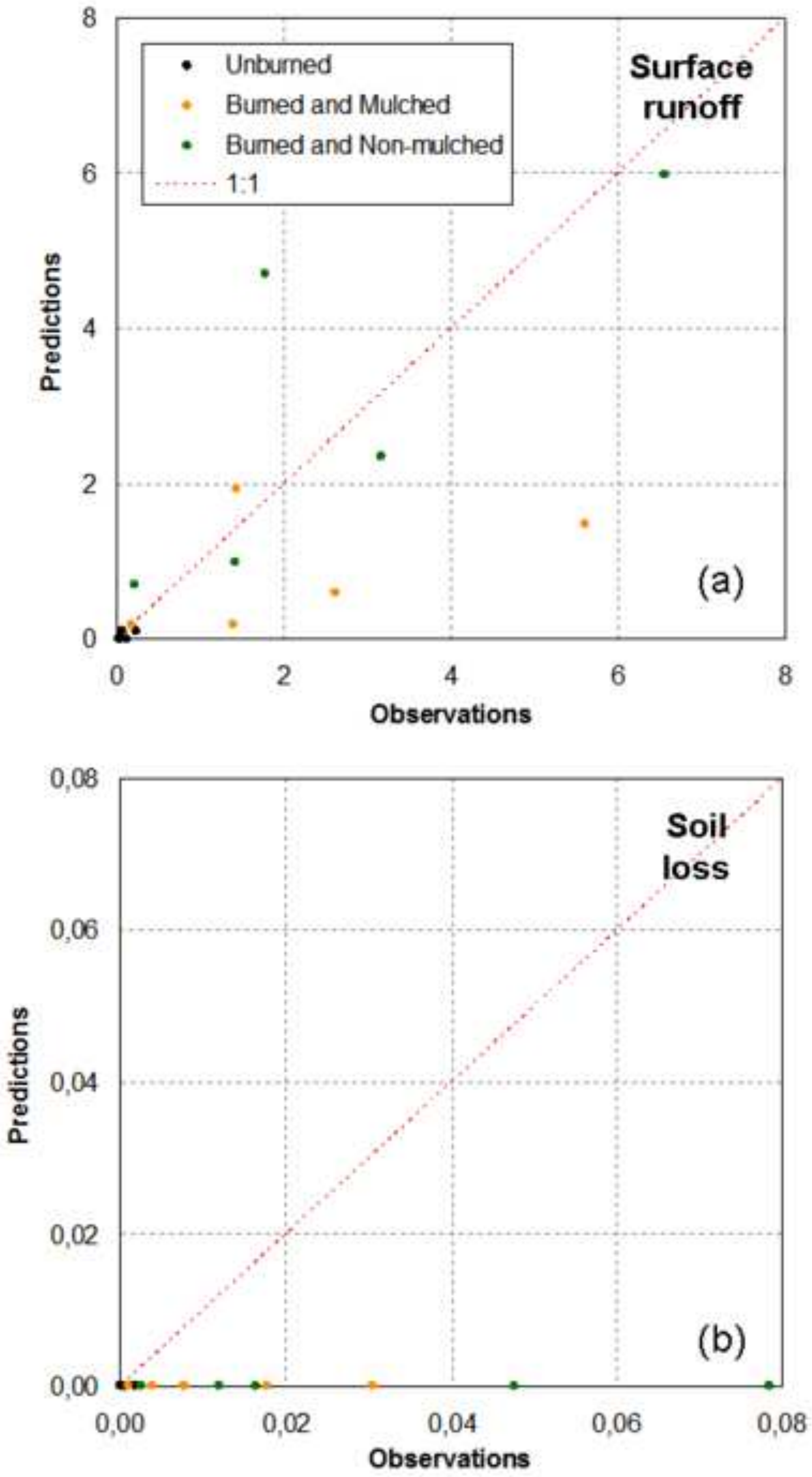

Unburned
Burned and Mulched
Burned and Non-mulched
1:1
Surface runoff
(a)
Predictions
Observations
0
2
4
6
8
0
2
4
6
8
Soil loss
(b)
Predictions
Observations
0,00
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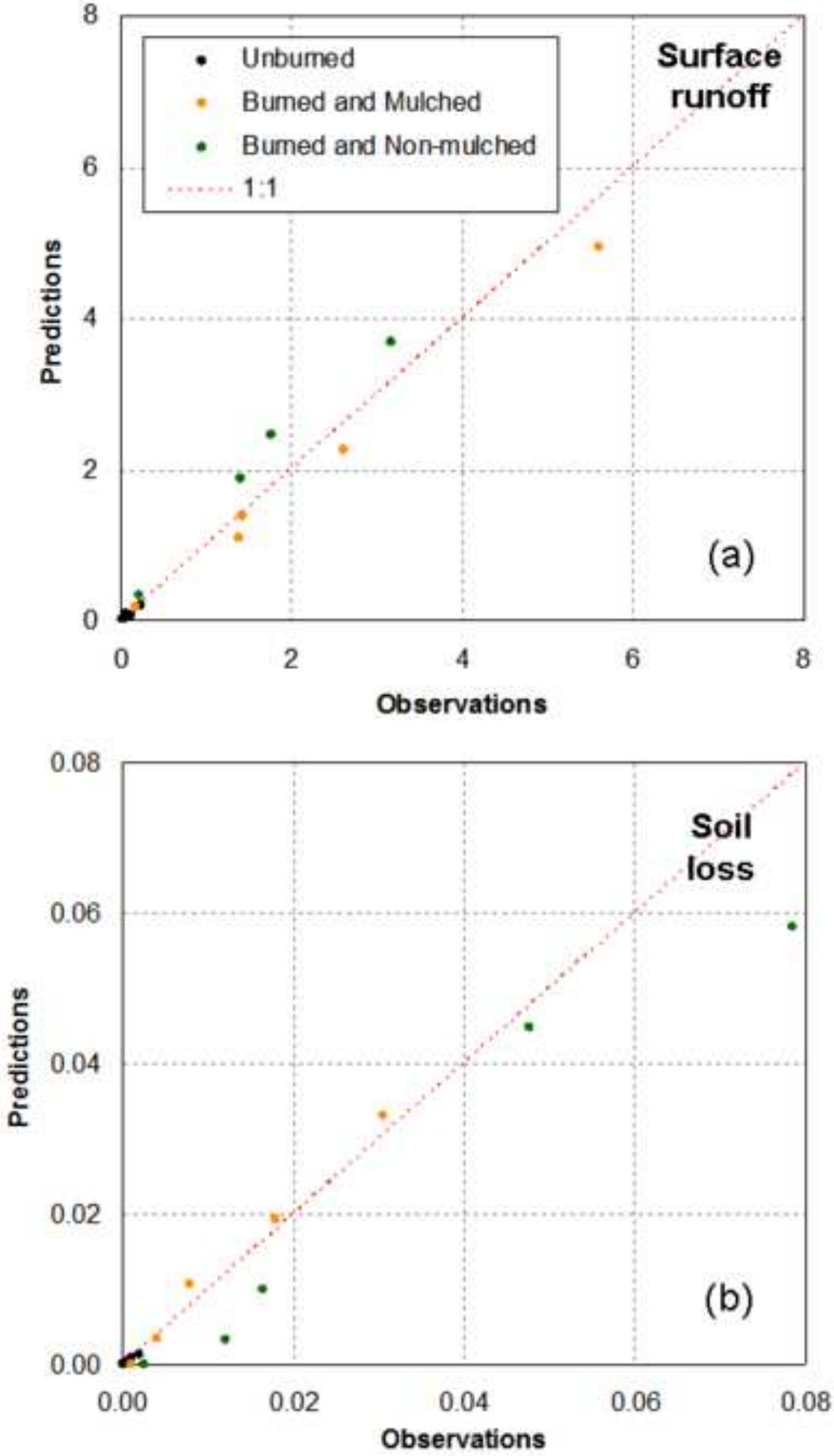
Figure 5


8
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Predictions
Unburned
Burned and Mulched
Burned and Non-mulched
1:1
Surface runoff
(a)
0
2
4
6
8
Observations
0.08
0.06
0.04
0.02
0.00
Predictions
Soil loss
(b)
0.00
0.02
0.04
0.06
0.08
Observations

***Declaration of Interest Statement**

Declaration of interests

Χ 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: