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Title: Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, soil erosion and water quality of runoff.

Article Type: Research Paper

Keywords: Prescribed fire; runoff; water quality; soil erosion; pine plantations.

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Order of Authors: Manuel Esteban Lucas-Borja, Ph.D.; Pedro Antonio Plaza-Álvarez; Javier González-Romero; Javier Sagra; Raquel Alfaro-Sánchez, Dr; Demetrio Zema, Dr; Daniel Moya, Dr; Jorge De las Heras

Abstract: Fires are a complex phenomenon that may generate a chain of responses and processes that affect each part of the ecosystem. Thus, it is important to understand the magnitude of the impacts of fire on soil properties and the response of plants to this disturbance. For the moment, few studies have examined the effects of prescribed fire on large plots in afforested pine plantations in Mediterranean ecosystems. To fill this gap, the effects of a prescribed fire on runoff, soil erosion, and water quality for approximately one year after burning have been evaluated in pine plantations in south-eastern Spain. We constructed six erosion plots in the control area and six erosion plots in the burned area that were 4 m long and 2 m wide, immediately after the prescribed fire. Runoff, soil erosion and runoff water quality were studied after each rainy event in all plots. Our results reveal that prescribed fire did not significantly affect runoff and soil erosion when low intensity precipitations occur at pine plantations. In relation to water quality, water turbidity, salinity, pH, organic matter content and ionic substances concentrations increased immediately after prescribed burn, nevertheless these changes disappeared over time. We can conclude that prescribed fire can be a useful tool for fuel reduction in Mediterranean pine plantations without wide and long-term impacts to soil losses, or water quality.

Response to Reviewers: 1   This study presents the results of an experiment whereby various soil and runoff parameters are compared among control and prescribed burned areas in a forested area in Spain. The aim was to investigate the short-term impacts of prescribed burns (low severity burns) in the analyzed parameters. The results indicate that low intensity prescribed burns seem not to affect runoff generation and soil erosion when low intensity precipitation occurs. Runoff water quality parameters were only slightly affected when comparing burned and control plots at the end of the experiment.

The experimental design with 12 plots (six in the control and six in the prescribed burned areas) was well conceived and is well described. The language is Ok. The number and quality of figures and tables are adequate. Overall, my recommendation is to accept the paper with minor revisions focused on improving the Introduction section. Many thanks for Your opinion, which makes us glad about our paper.

POINTS TO ADDRESS

2 (INTRODUCTION)

1) Lines 39-41: "The more severe the fire, … susceptibility to surface runoff and erosion". Another important factor, which is barely discussed, is the recurrence of fires. The recurrence of wildfires is a key variable in the planning and management of water bodies within a fire-prone watershed, namely as regards the conservation of riverine ecosystems or the public supply of drinking water, because the consequences of wildfires on water quality (eutrophication) become periodic instead of occasional. This has been noted by Santos et al. (2015) and could be acknowledged in the revised version.

Reference

Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes R.M.V., Pacheco F.A.L. (2015). Water resources planning for a river basin with recurrent wildfires. Science of the Total Environment, v. 526, p. 1-13.

Thanks for the suggestion, which we have embedded in the text with the related reference.

3 2) Lines 41-44: "Key casual factors … loss of soil organic matter". A very important casual factor enhancing soil loss and runoff is the inadequate land use (called conflict), meaning a use that is not conforming with the soil's capability (natural use), as demonstrated in Pacheco et al. (2014).

Reference

Pacheco, F.A.L., Varandas, S.G.P., Sanches Fernandes, L.F., & Valle Junior, R.F. (2014). Soil losses in rural watersheds with environmental land use conflicts. Science of the Total Environment, v. 485- 486C, p. 110-120. We have valorised also this suggestion in the revised text.

4 3) Lines 58-60: Catchment-scale studies often report minimal impacts … substantial impacts". Well, some studies at catchment scale have involving the evaluation of wildfires on stream water quality and aquatic biodiversity have alerted for the harmful impacts of wildfires. For example, Santos et al. (2015) alerted that An important consequence of wildfires is the increase of soil erosion with the accompanying transport of suspended fine sediments and dissolved nutrients downhill. The siltation and compaction of the substrate with reduction of the interstitial water oxygen levels are one of the most important reasons for M.margaritifera decline. Fine silts also clog the bivalve gills decreasing respiration rates. Pacheco et al. (2015), while using a multivariate statistical analysis, have associated 15% of water quality variance (nitrate) in catchments in Portugal to wildfires. Santos et al. (2015) explicitly related major peaks of phosphorus yields in stream water of various catchments to the simultaneous action of wildfires and rainfall intensity. These impacts downstream result from increasing runoff and soil erosion upstream and therefore could be acknowledged as contributions for the evaluation of wildfire impacts at catchment scale.

References

Santos, R.M.B., Sanches Fernandes, L.F., Varandas, S.G.P., Pereira, M.G., Sousa, R., Teixeira, A., Lopes-Lima, M., Cortes R.M.V., Pacheco F.A.L. (2015). Impacts of climate change and land-use scenarios on Margaritifera margaritifera, an environmental indicator and endangered species. Science of the Total Environment, v. 511, p. 477-488.

Pacheco F.A.L., Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes R.M.V. (2015). Controls and forecasts of nitrate fluxes in forested watersheds: a view over mainland Portugal. Science of the Total Environment, v. 537, p. 421-440.
Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes R.M.V., Pacheco F.A.L. (2015). A framework model for investigating the export of phosphorus to surface waters in forested watersheds: implications to management. Science of the Total Environment, v. 536, p. 295-305. All of these considerations are interesting, thus we have them to the revised text.

Reviewer n. 2

1 The paper by Lucas-Borja with title: "Short-term effects of prescribed burning in Mediterranean pine plantations on runoff, surface erosion and water quality" provides an interest work regarding the impacts of burning in run-off. The article is well written and interest. It could be used, beyond statistical analysis, other approaches to provide higher novelty and interest to the reader. I have some moderate recommendations. Thanks a lot for Your positive opinion. We think that Your suggestion targeted to further approaches to the present study beyond statistical analysis may be a valuable proposal for a secondo paper, in which we should apply multivariate statistical or learning machine techniques.

2 Graphical abstract: need revisions, provide a clip art with less text Done.

3 Presentation: Include photos of the process, it would be very interest to the reader. Done.

4 Methodology: Maybe a simulation process could advance the existing methodology and results, or in the future. Suggestion embedded in the revised text of the conclusions (see lines the conclusion section please).

5 Monitoring: Was it possible to check groundwater quality? Are there nearby springs? Or downstream? Unfortunately, we did not plan to monitor groundwater (due to the fact that no withdrawn is made from the aquifer in this area).

Reviewer n. 3

- In this work the authors aim to assess the effects of a prescribed fire in pine plantations in south-eastern Spain on the runoff, soil erosion and water quality for approximately one year after burning. This is an interesting scientific research at international level.
- However, in my opinion the ms is written like a technical report and many issues have not been covered.
- For example, regarding water quality, the study of polycycling aromatic hydrocarbons is important.
- Moreover, the authors have not given information for the methodologies used for the physico-chemical analysis.
- QC/QA of the methods was not provided. The information and data presented on this interest scientific subject are limited.
- In my opinion this ms does not meet the high standards of STOTEN and should not be published in STOTEN its present form. - Thanks for Your general positive opinion about the MS.
- As regards the fact that You consider the paper as a “technical report”, we do not completely agree about this, since we have discussed the results of an original experiment by a scientific approach, as highlighted in the Discussion section. Moreover, we do not see what further issues we should have covered (if You could be more specific and detailed, we could do our best to integrate the MS).
- The analysis of polycycling aromatic hydrocarbons is really important, as the Reviewer observes, but mainly in areas with

anthropogenic activities, since these compounds derive from coal and oil (not used in the analysed pine forests).
- The information about the methodologies used for the physico-chemical analysis are reported in Lucas-Borja et al. (2012).
- QC/QA of the methods was not provided, since the analysis were carried out by an external independent laboratory, whose analytical protocols are scientific, but they can not be controlled from an external subject.
- We hope that these replies are successful in order to convince the Reviewer about the MS merit to be published in STOTEN.

Reviewer n. 4

Line 27 Please provide full text of initials at their first use Done.
Line 30 affections refers to emotions. I would rather use the term impacts. We have replaced "affections" with "impacts".
Lines 35-36 This is a repetition of the first abstract line. Please try to omit it. We have removed this sentence.
Line 48 of bare Corrected.
Lines 77-78 Again another repetition from the abstract. Rephrased.
Line 78 Here authors should provide some highlights of their new findings and the originality of their work What is the new and original contribution of their work compared to the few (as stated by authors) previous studies? We have justified the novelty of our paper (Please see this section on the manuscript).
Line 99 From the geological point of view,..... Corrected.
Line 106 ? Corrected.
Line 110 Is there a specific reason for this orientation? Please provide some more details here. No, we were looking for comparable plots in terms of orientation and in order to avoid noise on the results.
Line 142 Can you please add it on Figure 1? Done.
Line 145 Does not make any sense. Please rephrase. Rephrased and referenced.
Line 157 5 storm events x 3 samples in each plot X 2 plots =30. Is 60 correct? Yes, we have changed it. Done
Lines 167-168 I think you only refer to chemical constituents and not to physiochemical properties like pH. EC, SAR, etc I think it needs some rephrasing here. We do not understand this observation, since the sentence relates to chemical constituents and not to physiochemical properties.
Line 186 needs rephrasing Rephrased.
Line 202 So they are not storms but rainfall events Corrected.
Line 214 Significantly higher Corrected.
Line 219 I think you should add a Table with those results. Thanks for this suggestion. We would prefer to maintain the same number of tables since we consider this part of the text add valuable information to this section of the ms.
Lines 266-272 I think you should omit this part of your work. What is the conclusion of the high correlation of Cl and HCO3? Does it contribute anything to your conclusions? Is it related to the fire event? We have omitted this part and Table 4.
Line 334 Find Corrected.
Line 334 effect/impact Corrected.
Line 337 compared to what? Compared to the control. Information added.
Line 343 in accordance perhaps? Corrected.
Lines 345-346 Cannot make out the meaning. Please rephrase. Rephrased.
Line 351 . Corrected.
Line 357 Find Corrected.
Line 358 meaningful or significant? Corrected.

Line 360 Conclusions section is rather poor. It needs careful rewriting adding also the limitations of the present methodology. We have modified and enlarged this section.
Line 361 Delete Deleted.
Table 3 Line 11 where do those errors refer to. Are there modeled values? We meant “standard deviation”. We have corrected.
Table 3 Line 12 at between? Corrected.
Table 3 Line 12 Please describe the methodology you used to estimate significant differences. The number of samples is low to allow estimate significant differences. On the other hand the aim of this study is to estimate whether prescribed fires do alter water quality. Therefore authors should have estimated difference in means between control and burnt plot, but also for this case five samples only do not guarantee a safe outcome. We have added information about the methodology. In more detail, the letters indicate the differences between the mean values of each analysed parameter deriving from the five sampled runoff volumes.
Table 4 line 19 I do not think that this table contributes to your work. Perhaps it would be better to omit it. Table removed.

Dear Prof. Barcelò,

We would like to thank you for giving us the possibility to revise our manuscript. We have appreciated the work of the Reviewers very much, since it helps to improve our paper a lot. All their requests have been duly considered and included in the text. We would be very grateful if you could reconsider the revised MS for publication on the STOTEN journal. You will find in the resubmission the revision notes replying to each of the Reviewers' comments; moreover, all changes made to the MS are evidenced in tracked changes.

Thank you very much for your time,
Sincerely.

Manuel Esteban Lucas-Borja
Castilla La Mancha University

Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, soil erosion and water quality of runoff

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[a] Higher Technical School of Agricultural and Forestry Engineering, Castilla-La Mancha University, Campus Universitario s/n, 02071 Albacete, Spain.

[b] Centre de Recerca Ecològica i Aplicacions Forestals (CREAF), Barcelona, Spain.

[c] Department AGRARIA, Mediterranean University of Reggio Calabria, Reggio Calabria, Italy.

*Email: ManuelEsteban.Lucas@uclm.es

***Responses to Reviewers Comments**

Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, surface erosion and water quality of runoff

Lucas-Borja, M.E.[a,*], Plaza-Álvarez, P.A.[a], Gonzalez-Romero[a], J., Sagra, J.[a], Alfaro-Sánchez, R.[b], Zema, D.A.[c], Moya, D.[a], de las Heras, J.[a]

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Castilla La Mancha University

Our response to reviewers continues in the following pages.

AUTHORS’ REPLY TO THE 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.

Number	***Reviewer’s comment***	***Authors’ reply***
	Reviewer n. 1	
1	This study presents the results of an experiment whereby various soil and runoff parameters are compared among control and prescribed burned areas in a forested area in Spain. The aim was to investigate the short-term impacts of prescribed burns (low severity burns) in the analyzed parameters. The results indicate that low intensity prescribed burns seem not to affect runoff generation and soil erosion when low intensity precipitation occurs. Runoff water quality parameters were only slightly affected when comparing burned and control plots at the end of the experiment. The experimental design with 12 plots (six in the control and six in the prescribed burned areas) was well conceived and is well described. The language is Ok. The number and quality of figures and tables are adequate. Overall, my recommendation is to accept the paper with minor revisions focused on improving the Introduction section.	Many thanks for Your opinion, which makes us glad about our paper.
	POINTS TO ADDRESS	
2	(INTRODUCTION) 1) Lines 39-41: "The more severe the fire, … susceptibility to surface runoff and erosion". Another important factor, which is barely discussed, is the recurrence of fires. The recurrence of wildfires is a key variable in the planning and management of water bodies within a fire-prone watershed, namely as regards the conservation of riverine ecosystems or the public supply of drinking water, because the consequences of wildfires on water quality (eutrophication) become periodic instead of	Thanks for the suggestion, which we have embedded in the text with the related reference.

	occasional. This has been noted by Santos et al. (2015) and could be acknowledged in the revised version. Reference Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes R.M.V., Pacheco F.A.L. (2015). Water resources planning for a river basin with recurrent wildfires. Science of the Total Environment, v. 526, p. 1-13.	
3	2) Lines 41-44: "Key casual factors … loss of soil organic matter". A very important casual factor enhancing soil loss and runoff is the inadequate land use (called conflict), meaning a use that is not conforming with the soil's capability (natural use), as demonstrated in Pacheco et al. (2014). Reference Pacheco, F.A.L., Varandas, S.G.P., Sanches Fernandes, L.F., & Valle Junior, R.F. (2014). Soil losses in rural watersheds with environmental land use conflicts. Science of the Total Environment, v. 485- 486C, p. 110-120.	We have valorised also this suggestion in the revised text.
4	3) Lines 58-60: Catchment-scale studies often report minimal impacts … substantial impacts". Well, some studies at catchment scale have involving the evaluation of wildfires on stream water quality and aquatic biodiversity have alerted for the harmful impacts of wildfires. For example, Santos et al. (2015) alerted that An important consequence of wildfires is the increase of soil erosion with the accompanying transport of suspended fine sediments and dissolved nutrients downhill. The siltation and compaction of the substrate with reduction of the interstitial water oxygen levels are one of the most important reasons for M.margaritifera decline. Fine silts also clog the bivalve gills decreasing respiration rates. Pacheco et al. (2015), while using a multivariate statistical analysis, have associated 15% of water quality variance (nitrate) in catchments in Portugal to wildfires. Santos et al. (2015) explicitly related major peaks of phosphorus yields in stream water of various catchments to the simultaneous action of	All of these considerations are interesting, thus we have them to the revised text.

	wildfires and rainfall intensity. These impacts downstream result from increasing runoff and soil erosion upstream and therefore could be acknowledged as contributions for the evaluation of wildfire impacts at catchment scale. References Santos, R.M.B., Sanches Fernandes, L.F., Varandas, S.G.P., Pereira, M.G., Sousa, R., Teixeira, A., Lopes-Lima, M., Cortes R.M.V., Pacheco F.A.L. (2015). Impacts of climate change and land-use scenarios on Margaritifera margaritifera, an environmental indicator and endangered species. Science of the Total Environment, v. 511, p. 477-488. Pacheco F.A.L., Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes R.M.V. (2015). Controls and forecasts of nitrate fluxes in forested watersheds: a view over mainland Portugal. Science of the Total Environment, v. 537, p. 421-440. Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes R.M.V., Pacheco F.A.L. (2015). A framework model for investigating the export of phosphorus to surface waters in forested watersheds: implications to management. Science of the Total Environment, v. 536, p. 295-305.	
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2	Graphical abstract: need revisions, provide a clip art with less text	Done.
3	Presentation: Include photos of the process, it would be very interest to the reader.	Done.
4	Methodology: Maybe a simulation process could advance the	Suggestion embedded in the revised text of the conclusions (see

	existing methodology and results, or in the future.	lines the conclusion section please).
5	Monitoring: Was it possible to check groundwater quality? Are there nearby springs? Or downstream?	Unfortunately, we did not plan to monitor groundwater (due to the fact that no withdrawn is made from the aquifer in this area).
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	- In this work the authors aim to assess the effects of a prescribed fire in pine plantations in south-eastern Spain on the runoff, soil erosion and water quality for approximately one year after burning. This is an interesting scientific research at international level. - However, in my opinion the ms is written like a technical report and many issues have not been covered. - For example, regarding water quality, the study of polycycling aromatic hydrocarbons is important. - Moreover, the authors have not given information for the methodologies used for the physico-chemical analysis. - QC/QA of the methods was not provided. The information and data presented on this interest scientific subject are limited. - In my opinion this ms does not meet the high standards of STOTEN and should not be published in STOTEN its present form.	- Thanks for Your general positive opinion about the MS. - As regards the fact that You consider the paper as a “technical report”, we do not completely agree about this, since we have discussed the results of an original experiment by a scientific approach, as highlighted in the Discussion section. Moreover, we do not see what further issues we should have covered (if You could be more specific and detailed, we could do our best to integrate the MS). - The analysis of polycycling aromatic hydrocarbons is really important, as the Reviewer observes, but mainly in areas with anthropogenic activities, since these compounds derive from coal and oil (not used in the analysed pine forests). - The information about the methodologies used for the physico-chemical analysis are reported in Lucas-Borja et al. (2012). - QC/QA of the methods was not provided, since the analysis were carried out by an external independent laboratory, whose analytical protocols are scientific, but they can not be controlled from an external subject. - We hope that these replies are successful in order to convince the Reviewer about the MS merit to be published in STOTEN.
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Line 27	Please provide full text of initials at their first use	Done.
Line 30	affections refers to emotions. I would rather use the term impacts.	We have replaced “affections” with “impacts”.
Lines 35-36	This is a repetition of the first abstract line. Please try to omit it.	We have removed this sentence.

Line 48	of bare	Corrected.
Lines 77-78	Again another repetition from the abstract.	Rephrased.
Line 78	Here authors should provide some highlights of their new findings and the originality of their work What is the new and original contribution of their work compared to the few (as stated by authors) previous studies?	We have justified the novelty of our paper (Please see this section on the manuscript).
Line 99	From the geological point of view,.....	Corrected.
Line 106	?	Corrected.
Line 110	Is there a specific reason for this orientation? Please provide some more details here.	No, we were looking for comparable plots in terms of orientation and in order to avoid noise on the results.
Line 142	Can you please add it on Figure 1?	Done.
Line 145	Does not make any sense. Please rephrase.	Rephrased and referenced.
Line 157	5 storm events x 3 samples in each plot X 2 plots =30. Is 60 correct?	Yes, we have changed it. Done
Lines 167-168	I think you only refer to chemical constituents and not to physiochemical properties like pH. EC, SAR, etc I think it needs some rephrasing here.	We do not understand this observation, since the sentence relates to chemical constituents and not to physiochemical properties.
Line 186	needs rephrasing	Rephrased.
Line 202	So they are not storms but rainfall events	Corrected.
Line 214	Significantly higher	Corrected.
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Line 334	Find	Corrected.
Line 334	effect/impact	Corrected.
Line 337	compared to what?	Compared to the control. Information added.
Line 343	in accordance perhaps?	Corrected.
Lines 345-346	Cannot make out the meaning. Please rephrase.	Rephrased.

Line 351	.	Corrected.
Line 357	Find	Corrected.
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Line 360	Conclusions section is rather poor. It needs careful rewriting adding also the limitations of the present methodology.	We have modified and enlarged this section.
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Table 4 line 19	I do not think that this table contributes to your work. Perhaps it would be better to omit it.	Table removed.

Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, ~~surface~~ soil erosion and water quality of runoff.

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[c] Department ~~of Agricultural Science (~~AGRARIA~~)~~, Mediterranean University of Reggio Calabria, Reggio Calabria, Italy.

*Email: ManuelEsteban.Lucas@uclm.es

Abstract

Fires are a complex phenomenon that may generate a chain of responses and processes that affect each part of the ecosystem. Thus, it is important to understand the magnitude of the impacts of fire on soil properties and the response of plants to this disturbance. For the moment, few studies have examined the effects of prescribed fire on large plots in afforested pine plantations in Mediterranean ecosystems. To fill this gap, ~~We aim to evaluate~~ the effects of a prescribed fire on runoff, soil erosion, and water quality for approximately one year after burning have been evaluated in pine plantations in south-eastern Spain. We constructed six erosion plots in the control area and six erosion plots in the burned area that were 4 m long and 2 m wide, immediately after the prescribed fire. ~~Following our research purposes, r~~Runoff, soil erosion and runoff water quality were studied after each rainy event in all plots. Our results reveal that prescribed fire did not significantly affect runoff and soil erosion when low intensity precipitations occur at pine plantations. In relation to water quality, water turbidity, salinity, pH, ~~OM~~ organic matter content and ionic substances concentrations increased immediately after prescribed burn, nevertheless~~,~~ these changes disappeared over time. We can conclude that prescribed fire can be a~~n~~ useful tool for fuel reduction in Mediterranean pine plantations without wide and long-term ~~affections~~ impacts to soil losses, or water quality.

Keywords: Prescribed fire; runoff; water quality; soil erosion; pine plantations.

1. Introduction

~~Forest fires are a complex phenomenon that may generate a chain of responses and processes that affect each part of the ecosystem.~~ Post-fire runoff and erosion are strongly and positively related to fire severity, which is due, in large part, to changes in soil physical and chemical conditions (Morales et al., 2000; Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2007). The more severe the fire, the greater the amount of fuel consumed, ash deposited, nutrients released, bare soil exposed and greater susceptibility to surface runoff and erosion. Also the recurrence of wildfires and the inadequate land use are important variables to be considered in the planning and management of land and water body conservation, because on one hand the consequences of wildfires become periodic instead of occasional (Santos et al., 2015a) and on the other hand a conflicting land use may enhance runoff and soil erosion rates (Pacheco et al., 2014; Lucas-Borja et al., 2019). Key casual factors enhancing soil losses and runoff are the reduction in infiltration and some combination of sealing, soil water repellency, loss of surface cover, and disaggregation due to loss of soil organic matter (Jiménez-Pinilla et al., 2015; Larsen et al., 2009; Neary et al., 2005; Lucas-Borja et al., 2018; Plaza-Alvarez et al., 2019). Changes in soil physical and chemical properties can then lead to large and potentially adverse changes in runoff, erosion and water quality (Neary et al., 2005). Low severity fires generally have fewer effects on vegetation, soils, runoff and erosion because the litter is not completely consumed, percentage of bare soil is typically less than about 30%, and soil organic matter is largely unchanged (Keeley et al., 2009; Pereira et al., 2018).

Land managers conduct prescribed fires to reduce fuel loading or modify fuel structure intending to reduce the potential risk and severity of subsequent fires (Fernandes, 2015).

Prescribed fires also are used to facilitate the germination and growth of desired forest species (Neary et al., 1999; Tolhurst and Cheney, 1999; Ferreira et al., 2005; Bird et al., 2008). Hence prescribed fires are typically planned to burn at low to moderate severity rather than high severity, and they are correspondingly quite patchy in space.

Catchment-scale studies often report minimal impacts of prescribed fires on runoff and soil erosion, although plot and hillslope-scale studies have sometimes detected more substantial impacts (Morales et al., 2000; Robichaud, 2000; Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2007). With respect to soil erosion, a recent review concluded that the impact of prescribed burns on soil cover is minimal and soil heating is negligible (Pereira et al., 2018). In such cases one would expect greatly reduced overland flow and soil erosion compared to high severity wildfires. Benavides-Solorio and MacDonald (2001;~~,~~ 2005) found that sediment production rates from plots and hillslopes burned at low and moderate severity were generally much lower than for areas burned at high severity. Vega et al.~~,~~ (2005) and Fernandez et al.~~,~~ (2008) also detected only minor soil erosion rates at the plot scale after low severity fires, as much of the displaced soil was captured in the surface organic layer.

Wild and prescribed fires also may impact surface water quality, particularly pH, nutrients, dissolved organic carbon, and turbidity (DeBano et al., 1998). As regards the wildfires, some studies at catchment scale have evaluated their effects on stream water quality and aquatic biodiversity, alerting for their harmful impacts.

For example, an important consequence of wildfires is the increase of soil erosion with simultaneous transport of suspended fine sediments and dissolved nutrients downstream (Santos et al., 2015b). Pacheco et al. (2015) have associated 15% of water quality variance (especially nitrate) to wildfires in catchments of Portugal. Santos et al. (2015c) have found a direct link of peaks of phosphorus yields in stream water to the simultaneous action of wildfires in some catchments.

Prescribed fires in mixed-conifer forest and riparian forest in California~~,~~ were found to have only a small effect on water quality that persisted for just 3 to 12 months (Bêche et al., 2005; Stephens et al., 2004). However, multiple prescribed fires within the same catchment can cause larger and longer-term effects (Cawson et al., 2012). ~~Few studies have examined the effects of prescribed fire on larger plots in afforested pine plantations in Mediterranean ecosystems.~~ These latter authors have proposed a comprehensive review of surface runoff and erosion after prescribed burning in forests. This review shows that, according to a high proportion of the available studies, the hydrological effects of prescribed burning are quite contrasting. Moreover, from this and other literature studies, it is evident that the changes in soil hydrology and water quality generated by prescribed fire have been little studied in the Mediterranean forest ecosystems. In particular, no comprehensive studies at plot scale have been carried out in afforested plantations of the Iberian Peninsula. Hence the objective of this study was to assess the effects of a prescribed fire in pine plantations in south-eastern Spain on the runoff, soil erosion, and water quality for approximately one year after burning.

2. Material and methods

2.1. Study site

The study was conducted in a relatively hilly area in the province of Albacete, Castilla-La Mancha region, Spain (Figure 1). The study site corresponds to ~~with~~ a zone, whose ~~which~~ potential vegetation is primarily *Quercus ilex* subsp. *rotundifolia*, while the current vegetation was ~~a~~ 45-50 year old planted stand of mixed Aleppo and

Mediterranean maritime pine (*Pinus halepensis* and *Pinus pinaster*, respectively). The understory was dominated by *Quercus faginea* Lam., L, *Quercus ilex* subsp. *ballota, Quercus coccifera,* L., *Juniperus oxycedrus, Brachypodium retusum* P. and *Thymus* sp.~~.~~ The control and burned plots also had very similar tree densities (~~at~~ about 500 trees/ha) and mean diameters (~~of~~ 30 cm) (Table 1).

Elevations in the study area range from about 1010 to 1040 m a.s.l. The climate is classified as hot dry Mediterranean (Allué, 1990) with a mean annual temperature of is 13.5 °C. The mean minimum temperature of the coldest month is −0.9 °C and the mean maximum temperature of the hottest month is nearly 32 °C. Mean annual precipitation is about 450 mm (Spanish National Meteorological Agency, 1950-2016). ~~Respect~~ From the geological point of view the ~~geology~~ pliocene tertiary materials formed by very rounded quartzite ridges of variable size and reddish-clay matrix appear on Mesozoic "lías", which are carbonated in nature: a lower calico-dolomitic, a mean clay-loam media, to finish with an episode of limestone, mainly oolitic. Soils are brown, stony, and clayey in texture (Rivas Martínez et al., 1987). The mean slope is around of 15 %.

2.2. *Experimental design*

The Regional Forest Service conducted a prescribed fire ~~about~~ in the area of the selected plots on 30th March 2016. Prior to the fire we identified the locations for our study plots, and immediately after the fire we constructed six erosion plots in the control area and six erosion plots in the burned area, all of which ~~that~~ were 4 m long and 2 m wide (Figure 1). Plots were placed on north- to northeast aspects, with mean slope of the six control plots equal to 15.0% (±4.4), while the mean slope of the six burned plots was 14.5% (±2.6) (Table 1). The plot boundaries were ~~constructed from~~made of 0.5 m wide geotextile fabric that was ~~0.5 m wide~~ inserted up to 0.4 m below the ground surface. The entire perimeter was closed with geotextile that was tightly fastened to 0.8-m long and~~,~~ 20-mm in diameter iron rods, ~~that were~~ pounded into the ground at 15 cm of depth to prevent the flow of surface water. At the bottom of the plot the geotextile narrowed to ~~direct~~convey the runoff and sediment into a pipe that led to a 25-litre container. The area where the plot narrowed was protected from rain by a plastic cover, and the ground surface also was covered by plastic secured to the ground by nails, to ensure that ~~all~~ the entire runoff and all sediments were~~as~~ delivered to the collection point and then~~ce~~ to the storage container (Figure 1).

The meteorological conditions for the burning were the following: wind of 14 km/h ~~speed~~ with southeast direction, ambient temperature of 14 ºC and relative humidity of 63 %. Soil and air temperatures during the prescribed fire were monitored by three HOBO thermocouple type K (0–1250 ◦C (±4.0 ◦C)) with insulated 30-AWG wire (diameter <0.2 cm), assembled in Data Loggers UX120-014M (Onset Corp., Bourne (MA), Australia). They were placed in each burned plot ~~at~~ 25 cm above the ground, for monitoring the soil surface, and 2~~two~~ cm below the mineral soil surface, respectively. The slope and aspect of each plot were derived directly from measurements~~ing~~ by ~~with~~ a horizontal ~~on~~ graduated bar. We counted and identified each tree and estimated the percentage of burned canopy. All the planted pine trees were 58 years old, since the study area was planted in 1960. We also measured the diameter of each tree at breast height, percent shrub cover, percent bare soil, and percent area mulched by pine- needle and of and leaf litter (Table 1).

To minimize disturbance, we measured surface cover in three adjacent 400-~~-~~m^2 plots in the control and burned area, respectively. The area~~amount~~ of bare soil, shrub, grass/herb, and litter cover were measured along three longitudinal transects. In each plot one soil sample was collected at a depth of 5-10 cm and analysed for soil texture, pH, organic matter content, electrical conductivity, and carbon: nitrogen (C:N) ratio, following Lucas-Borja et al.~~,~~ (2012).

A weather station (WatchDog 2000 Series model) with a tipping bucket rain gauge was set up 50 m outside the afforested area, and this was used to characterize ~~gross~~ precipitation, storm duration, and rainfall intensity. In the hourly rainfall series of the experimental database, two consecutive events were considered separate, if no rainfall was recorded for 6 h or more (Wischmeier and Smith, 1978; Zema et al., 2017).~~ Storms were defined by six hours with no rain, and m~~ Mean rainfall intensity was the total rainfall divided by the ~~length of the ~~storm duration. A funnel to collect and measure rainfall was installed about one meter away from the top of each plot, and a comparison of the mean rainfall from these to the rain gauge in the open air was used to determine the mean rainfall interception for the control and burned plots, respectively. Percent and absolute interception in the control and burned plots were compared and tested for their correlation to total rainfall, rainfall intensity, and storm duration.

After each storm the volume of runoff was measured~~ and converted to millimetres~~. Runoff coefficients were calculated as the ratio of runoff to rainfall. Runoff water samples were collected after the storms which occurred on days 5, 37, 49, 203 and 394 after the fire by actively mixing the runoff and taking three successive samples totalling about 0.5 litres. The samples (n=3~~6~~0) were analysed in the laboratory for the weight~~mass~~ of solid sediments (“suspended sediment” or SS in g/L), total dissolved solids (TDS), and a set~~uite~~ of water quality parameters. The weight~~mass~~ of eroded soil was calculated by multiplying the SS and TDS values by the volume of runoff and summing these two values. The water quality parameters were measured following standard procedures, and these included electrical conductivity (EC), pH, sodium adsorption ratio (SAR), residual sodium carbonates (RSC), water hardness (WH), total salt content (TSC), organic matter (OM), inorganic nitrates (NO^{3-}), bicarbonates (HCO_3^{+}), chlorine (Cl^{-}), potassium (K^{+}), sodium (Na^{+}), magnesium (Mg^{2+}), calcium (Ca^{2+}), and phosphates (PO_4^{-3}). Carbonates (CO_3^{-2}), sulphates (SO_4^{2-}), ammonium (NH_4^{+}) and boron (B) were also analysed, but the concentrations of these components were negligible in almost all the samples, so these data are not presented here. Budget limitations precluded the analysis of water quality for the other six storms that generated runoff.

2.3. *Statistical analyses*

The dependent variables (~~amount of~~ runoff volume, runoff coefficient, soil loss~~erosion~~, and water quality parameters) were normally distributed, allowing the use of a multifactor ANOVA analyses to evaluate the effect of prescribed burning (burned versus unburned) and days after fire (DAF). The multifactor ANOVA analyses and Tukey–Kramer’s honestly significant difference (HSD) test were used to determine if there were significant differences in any of the dependent variables between the control and burned plots. ~~Pearson correlation coefficients were calculated to evaluate whether runoff was related to total rainfall or days after the fire.~~ All significance levels were set at $p<0.05$. Statistical analyses were conducted using R software (R Development Core Team, 2016).

3. Results

3.1. Plot Characteristics Before and After Burning

Prior to burning the mean shrub/herb cover also was very similar and close ~~at slightly around the~~to 50%~~ in~~, while in the burned plots after the fire it was reduced to 10%. Prior to burning ~~percent~~ bare soil averaged only 5% and post-fire it ~~was incremented~~raised up to 11%.

The temperatures during the prescribed fire was determined in ~~(~~Plaza-Álvarez et al.~~,~~ (2018). At 25 cm above the surface, the mean temperature of burning was 94 °C (±15 °C). Mean ~~soil surface~~ temperatures of soil surface ~~only~~ reached 43°C (±4 °C)~~.~~ only. The mean duration of surface temperatures above 60 °C was only 16 seconds, and the mean maximum temperatures ~~at two~~2 cm below the surface were only 20 °C (±3 °C). Thus, this fire monitoring ~~we~~ confirmed ~~with this fire monitoring~~ the low intensity target of these burns. Hence, the fire had little effect on the soil, but did kill an estimated 18% of the tree canopy, mostly towards the lower part of the canopy. One week after burning the scorched needles began falling and increased the mean litter cover from 44% (±7%), before the burning, to 79% (±6%), throughout ~~over~~ the ~~following~~ six months following ~~after~~ burning.

3.2. Rainfall and Runoff

Total rainfall over the study period was 408.4 mm in 20 storms. Total precipitation for the 11 ~~storms~~ rainfall events that generated runoff was 314.2 mm. Net rainfall for the control and burned plots was relatively similar (~~at~~ 252 and 241 mm, respectively), indicating net interception rates of 20% and 24%, respectively. On a ~~storm basis~~event

Field Code Changed

scale interception ~~rates~~ sometimes exceeded 50%, and the highest ~~interception~~ rates were generally associated with rainfall intensities of less than 4 mm/h (Table 2). For the combined data, rainfall interception was found to be significantly related to storm rainfall (R^2=0.59).

Eleven of the 20 storms produced runoff, with no runoff being generated with ~~hen there was~~ less than three mm~~illimetres~~ of rainfall or a mean intensity of less than 4 mm/h. The ~~M~~mean ~~of total~~ runoff from these 11 storms for the control plots was 8.57 mm with a ~~range~~ variability of 0.17 to 1.5 mm compared to 9.98 mm for the burned plots and a vaariability~~range~~ of 0.15 to 2.27 mm. The difference in mean runoff was not significant between treatments (control versus prescrib~~v~~ed fire), however two storms generated ~~runoff being~~ significantly higher runoff in the burned plots. In the highest~~r~~ storm, whose~~ich~~ intensity was 12 mm/h, on 268 DAF the runoff was 50% higher than control plots (Figure 2). This storm also generated more runoff than any other storms: 2.27 mm in burned plots and 1.5 mm in control plots.

The results of the ANOVA ~~analyses~~ showed that burning and days after the fire ~~each~~ had both ~~a~~ significant effects on runoff volumes~~quantity~~ and ~~the~~ runoff coefficients ~~respectively)~~. The interaction between burning and days after the fire was also significant (F-ratio=3.7). For burned plots, runoff collected in the reservoirs varied between 1.2 and 18~~-~~litres with an average of 7.3 litres,~~.~~ ~~W~~whereas, for control plots, the collected runoff varied between 1.3 and 12 litres, with an average of 5.65 litres. Few events were large~~big~~ enough to generate appreciable ~~meaningful~~ runoff (Fig. 2).

3.3. Soil Erosion

Almost all ~~Near of~~ the total soil loss~~erosion~~ was collected as mineral sediment, the remaining, less 1-%, was sediment dissolved in runoff water. Results indicated that TDS were not significantly higher in burned than in control plots for each water quality analysis. SS only was~~showed to be meaningfully~~ significantly higher in burned plots at 394 DAF. For that analysis, SS value was significantly lower than in previous analysis carried out in~~at~~ control plots (Table 3).

3.4. Water quality

~~With regard to water quality, only consistent~~ Appreciable trends amongst all storms was higher amount of OM, either equal or higher HCO_3^-, higher K^+, and higher Ca^{2+}. The ~~F~~first storm on day 5 was not particularly remarkable, but produced runoff~~had~~ with significantly higher EC, pH, SAR, TSC, K^+, Mg^{2+}, and Ca^{2+} (n=7). The s~~S~~econd storm on day 37 was similar, but generally did not give~~no~~ significant differences among the studied parameters comparing burned and control plots~~-~~. The third storm on day 49 was of small and low intensity with no significant differences among the studied parameters comparing burned and control plots. The ~~F~~fourth storm on day 203 was of low intensity with higher EC, SAR, RSC, OM, HCO_3^-, Cl^-, K^+, Na^+ (n=8). The ~~L~~last storm on day 394 ~~was again with~~ showed higher SS, EC, pH, WH, Na^+, Ca^{2+}, NO_3^- (n=7). Common ~~increases~~ observations were the increase in EC (~~all~~ three storms), pH (storms 1 and 5), SAR (storms 1 and 4), K^+ (storms 1 and 4), Na^+ (storms 4 and 5), Ca^{2+} (storms 1 and 5) (n=6).

For each of the five sampled storms the burned plots always had a higher mean concentration of organic matter (OM) than the control plots (Table 3). ~~T~~ For the first and last runoff samples the burned plots had substantially higher pH, ~~electrical conductivity~~

~~(~~EC~~)~~, WH~~water hardness~~ and~~ total salt content~~TSC. The differences in EC and ~~total salt content~~TSC were primarily due to the higher Cl^- K^+, and Na^+~~chloride, potassium, and sodium~~ values. ~~With regard to nitrates (NO_3^-), bicarbonates (HCO_3) and phosphates ($PO4^{-3}$).~~ For NO_3^- no differences were founded, as well as with PO_4^{-3}. ~~Bicarbonates~~ HCO_3^-showed ~~meaningful~~ significant differences at 203 DAF. Regarding ~~Sodium Adsorption Ratio (~~SAR~~)~~, differences were founded at 5 DAF and 203 DAF, with a higher value for control plots in the first case and higher for burned plots in the other one. ~~Residual Sodium Carbonates (~~RSC~~)~~ showed differences only for the fourth analysis (203 DAF), ~~appearing~~ burned samples showing ~~larger~~ higher values ~~at burned samples~~.

To sum up, one year after the prescribed fire, our results showed that pH, carbonates, bicarbonates, total dissolved solids and organic matter content were significantly higher in the runoff coming from burned plots. However, electrical conductivity and concentration of some elements (calcium, sodium, chloride and magnesium) of the collected runoff were not affected by the prescribed fire. Runoff quality was highly modified in the burned areas ~~just~~ immediately after the prescribed fire (5 days after) (Table 3). Those differences mainly became non-significant in later dates.

~~Concerning correlations between water quality parameters (Table 4), OM had positively meaningful correlation with EC, anions like Cl^-, HCO_3^- and cations like K^+ and Mg^{2+}, also with SS, RSC, WH and TSC. Electrical conductivity was highly correlated with Total salt content (TSC), WH or TD. Ionic substances were also significantly correlated with EC and between them. The pH value was correlated with EC, $Ca^{+,}$ WH and TSC,~~

~~on the other hand negatively correlated with SAR or RSC. SAR was positively correlated with Na^+ and RSC and negatively with Ca^+ or WH.~~

4. Discussion

4.1. Rain interception~~.~~

Tree canopies can protect soil surface from falling rain drops depending on fall height and drop size (Styczen and Morgan, 1995). In lower intensity storms water dripping from the tree canopy can increase drop size and kinetic energy (Geißler et al., 2012; Nanko et al., 2004; Vis, 1986). In our study we did not find any difference in net rainfall between the control and the burned plots due to the relatively small amount of the tree canopy that was burned, so the main effect of the tree canopy in the burned plots was the rapid post-fire litterfall and the associated increase in surface cover. On the other hand, the fire did greatly reduce the amount of shrub cover, and this~~e~~ loss ~~of this cover~~ is~~would be~~ expected to increase the kinetic energy of the rainfall as well as the water dripping from the forest canopy. This ~~would be expected to~~ increases rainsplash and soil erosion in the burned plots.

4.2. Runoff

The prescribed burning effects on soils of Mediterranean ecosystems depend~~s~~ on the rainfall characteristics such as ~~magnitude~~ depth and intensity, and the vegetation recovery rate (Inbar et al., 1998). High intensity rainfalls accelerate runoff and erosion (Neary et al., 2005). In this particular case, barely few medium-high magnitude events took place. Consequently, no high runoff peaks took place till 247, 268 and 318 days after fire (DAF). Only these events generated significant~~meaningful~~ ($p<0.05$) runoff differences between burned and control plots. These differences can be explained due to the higher shrub and herb cover at the control plots (Table 1) that was more efficient ~~performed better~~ than the litter in~~ order to stop~~reducing runoff generation. This reduction~~fact~~ can be explained as a result of to the complex system of vegetation patches in control plots, which is highly disconnected (Ruiz-Sinoga et al., 2010);~~,~~ this~~at~~ influence of semiarid Mediterranean vegetation on runoff generation has been widely reported in previous studies (Romero Díaz et al., 1999; Dunjó et al., 2004).

On the other hand, the lack of any differences in total generated runoff between burned and control plots for low intensity events~~,~~ showed ~~us~~ that pine needles ~~effect~~ could replace to some extent the previous vegetation cover effect on~~ver~~ runoff generation. This is in line with Pannkuk and Robichaud (2003), Vega et al.~~,~~ (2004) and~~or~~ Prats et al.~~,~~ (2011), who found pine needle litter to be effective minimizing post-fire runoff generation. Also Keestra et al.~~,~~ (2014) found that pine needles falling and covering soil surface immediately after a prescribed fire is an efficient and natural mulching, avoiding runoff and erosion in the immediate post-fire period.

4.3. Soil Erosion

In northwestern Spain prescribed fires in shrublands more than doubled soil losses compared to unburned areas for light burns (Vega et al., 2005). In absolute terms the soil losses measured in this study were ~~towards~~ close to the lower range of values reported in other experiments (see for example Malmot et al., 2007 and Alexandrov et al., 2003). These low soil losses can be attributed to the prescribed fire~~s~~ characteristics (i.e. ~~in terms of~~ fire intensity) and the low area~~amount~~ of bare soil due to the fall of the scorched needles. Previous studies have~~d~~ pointed that the organic layer covering ~~which~~

~~cover~~ the soil protects it against erosion (Fernandez et al., 2008). Other studies also reported few or no~~n-existent~~ erosion for low intensity fires (Van Lear & Danielovich, 1988;~~,~~ Shahlee et al., 1991;~~,~~ Eliott & Vose, 2005). Soil loss was only due to~~by~~ suspended and dissolved sediments (Table 3), as no sediment was captured in the reception equipment (Figure 1). ~~With regard to the lack of significant differences between burnt and control plots when it comes to SS or TDS, different authors have already reported that for light-moderate burns in the United States (Eliott & Vose, 2005).~~ The lack of significant differences of soil loss between burnt and control, plots when it comes to SS or TDS, have been already reported for light-moderate burns in the United States (Eliott & Vose, 2005). Even though these results must be considered with caution, due to the absence of more large or intense rainfall events during the first year after fire, it would seem ~~to suggest~~ that prescribed burning in reforested areas could be used with an acceptable level of soil loss.

4.4. *Water quality*

~~With regard to Organic Matter (OM), i~~In light of our results, OM seems to be significantly higher after fire, at least for the first year. These results do not agree with previous studies that did not~~'t found~~ find any ~~affection~~ impact of prescribed burning on OM (see ~~like~~ Covington et al., ~~(~~1984;~~),~~ Hatten et al., ~~(~~2008~~)~~and ~~or~~ Gareth et al.~~,~~ (2008). Concerning water salinity, measured as ~~Electrical Conductivity (~~EC~~)~~, ~~Total Salt Content (~~TSC~~)~~, these values were significantly higher for burned plots immediately after burning in comparison to control (unburned) plots, and this increase~~which~~ could be explained as the~~a~~ result of inorganic ions being released from combusted organic matter (Nadiu and Srivasuki, 1994). Similar results were obtained by Pereira et al.~~,~~ (2011). After prescribed fire, pH increased due to ashes, which ~~this~~ is in accordance with other studies (~~like~~like.g., Ulery et al., ~~(~~1993;~~),~~ Williams et al., ~~(~~1997;~~),~~ Plumlee et al., ~~(~~2007~~)~~ and~~or~~ Pereira et al., ~~(~~2010). After the initial months, pH differences between control and burned plots disappeared, that is in accordance ~~suitable~~ with the results of Úbeda et al.~~,~~ (2005)~~ results~~, who founded that one year after fire pH and total carbon soil values returned to pre-fire levels. This increase after prescribed burn may be due ~~affects~~ to the presence of certain water-soluble elements in runoff after fire~~, by inhibiting or enhancing the presence of several elements~~ (Williams et al., 1997).

~~When it comes to~~ With regard to Ca^{2+}, Mg^{2+}, Na^{+},~~ or~~ K^{+}, Cl^{-} ~~or~~ and NO_3^{-}, ~~as said before,~~ significant differences were founded immediately after fire, but chemical concentrations t~~r~~end to equalise with time. This was also observed by Adams and Boyle (1980), who founded that after 3 months the differences ~~were~~ almost totally disappeared gone. Kutiel and Inbar (1993) and Williams et al.~~,~~ (1997) also indicated that after burning Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} concentrations increased in the overland flow. Belillas et al.~~,~~ (1993) founded that runoff from burnt slopes~~,~~ ~~presented~~ showed higher concentrations for NO_3^{-}, K^{+} or Ca^{2+}, ~~mean~~while Na^{+} did not~~n't~~ showed any differences. Nevertheless, those ~~showed~~ differences were not~~n't~~ significant ($p>0.05$). Carbonates~~,~~ resist to high temperatures, and due to that are not likely to be affected by fire (Rabenhorst, 1988). Eliott & Vose (2005) did not~~n't founded~~ find any ~~meaningful~~ significant differences for PO_4^{-3} after burning.

5. Conclusions

Since changes in soil hydrology and water quality generated by prescribed fire have been little studied in the Mediterranean forest ecosystems, this investigation evaluates at the plot scale the effects of a prescribed fire in pine plantations in south-eastern Spain on the runoff, soil erosion, and water quality for approximately one year after burning. ~~To sum up, l~~Low intensity prescribed burns seem not to affect ~~to~~ runoff generation and soil erosion, when low intensity precipitations occurs at pine plantations. Runoff water quality ~~parameters~~ ~~were~~ was also slightly affected, when comparing burned and control plots at the end of the experiment. ~~It can be also said that~~Also water turbidity, salinity, pH, OM content and ~~ionic substances~~ion concentrations increased immediately after prescribed burn, nevertheless these changes disappeared over time. In light of these results, it can be assumed that low intensity prescribed burns can be a useful tool for fuel reduction in Mediterranean pine plantations without wide and long-term affections to soil losses, or water quality. A modeling approach targeted to simulate surface runoff, soil erosion and water quality in runoff as the effects of prescribed fire may be welcome to provide an important hydrological tool for forest management and conservation.

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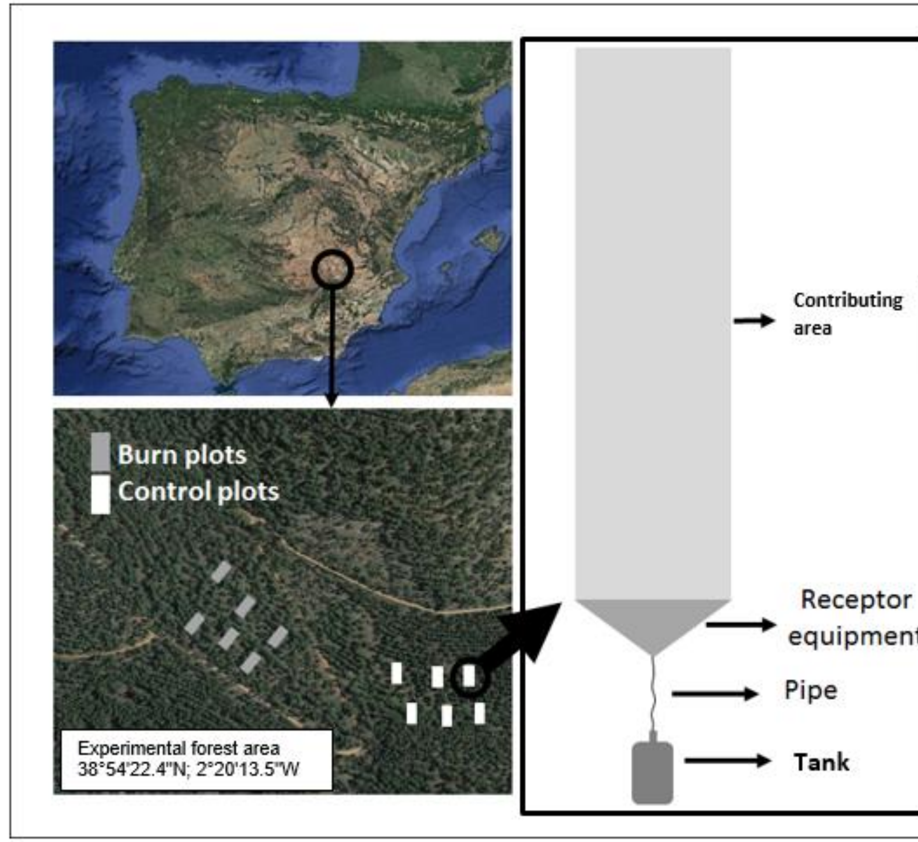
*Graphical Abstract

Prescribed fires in
Mediterranean Pine plantations



- No significant increase of surface runoff comparing burned and control plots
- No effects on soil erosion comparing burned and control plots
- Slight changes in water quality of runoff comparing burned and control plots

***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Highlights

- Prescribed fires do not significantly affect runoff at pine plantations.
- Low intensity prescribed burns seems not to affect soil erosion at pine plantations.
- Runoff water quality parameters were slightly affected by prescribed fire.
- Rain intensity may modulate runoff generation and erosion at pine plantations.

Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, soil erosion and water quality of runoff.

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Abstract

Fires are a complex phenomenon that may generate a chain of responses and processes that affect each part of the ecosystem. Thus, it is important to understand the magnitude of the impacts of fire on soil properties and the response of plants to this disturbance. For the moment, few studies have examined the effects of prescribed fire on large plots in afforested pine plantations in Mediterranean ecosystems. To fill this gap, the effects of a prescribed fire on runoff, soil erosion, and water quality for approximately one year after burning have been evaluated in pine plantations in south-eastern Spain. We constructed six erosion plots in the control area and six erosion plots in the burned area that were 4 m long and 2 m wide, immediately after the prescribed fire. Runoff, soil erosion and runoff water quality were studied after each rainy event in all plots. Our results reveal that prescribed fire did not significantly affect runoff and soil erosion when low intensity precipitations occur at pine plantations. In relation to water quality, water turbidity, salinity, pH, organic matter content and ionic substances concentrations increased immediately after prescribed burn, nevertheless these changes disappeared over time. We can conclude that prescribed fire can be a useful tool for fuel reduction in Mediterranean pine plantations without wide and long-term impacts to soil losses, or water quality.

Keywords: Prescribed fire; runoff; water quality; soil erosion; pine plantations.

1. Introduction

Post-fire runoff and erosion are strongly and positively related to fire severity, which is due, in large part, to changes in soil physical and chemical conditions (Morales et al., 2000; Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2007). The more severe the fire, the greater the amount of fuel consumed, ash deposited, nutrients released, bare soil exposed and greater susceptibility to surface runoff and erosion. Also the recurrence of wildfires and the inadequate land use are important variables to be considered in the planning and management of land and water body conservation, because on one hand the consequences of wildfires become periodic instead of occasional (Santos et al., 2015a) and on the other hand a conflicting land use may enhance runoff and soil erosion rates (Pacheco et al., 2014; Lucas-Borja et al., 2019). Key casual factors enhancing soil losses and runoff are the reduction in infiltration and some combination of sealing, soil water repellency, loss of surface cover, and disaggregation due to loss of soil organic matter (Jiménez-Pinilla et al., 2015; Larsen et al., 2009; Neary et al., 2005; Lucas-Borja et al., 2018; Plaza-Alvarez et al., 2019). Changes in soil physical and chemical properties can then lead to large and potentially adverse changes in runoff, erosion and water quality (Neary et al., 2005). Low severity fires generally have fewer effects on vegetation, soils, runoff and erosion because the litter is not completely consumed, percentage of bare soil is typically less than about 30%, and soil organic matter is largely unchanged (Keeley et al., 2009; Pereira et al., 2018).

Land managers conduct prescribed fires to reduce fuel loading or modify fuel structure intending to reduce the potential risk and severity of subsequent fires (Fernandes, 2015). Prescribed fires also are used to facilitate the germination and growth of desired forest species (Neary et al., 1999; Tolhurst and Cheney, 1999; Ferreira et al., 2005; Bird et al., 2008). Hence prescribed fires are typically planned to burn at low to moderate severity rather than high severity, and they are correspondingly quite patchy in space.

Catchment-scale studies often report minimal impacts of prescribed fires on runoff and soil erosion, although plot and hillslope-scale studies have sometimes detected more substantial impacts (Morales et al., 2000; Robichaud, 2000; Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2007). With respect to soil erosion, a recent review concluded that the impact of prescribed burns on soil cover is minimal and soil heating is negligible (Pereira et al., 2018). In such cases one would expect greatly reduced overland flow and soil erosion compared to high severity wildfires. Benavides-Solorio and MacDonald (2001; 2005) found that sediment production rates from plots and hillslopes burned at low and moderate severity were generally much lower than for areas burned at high severity. Vega et al. (2005) and Fernandez et al. (2008) also detected only minor soil erosion rates at the plot scale after low severity fires, as much of the displaced soil was captured in the surface organic layer.

Wild and prescribed fires also may impact surface water quality, particularly pH, nutrients, dissolved organic carbon, and turbidity (DeBano et al., 1998). As regards the wildfires, some studies at catchment scale have evaluated their effects on stream water quality and aquatic biodiversity, alerting for their harmful impacts. For example, an important consequence of wildfires is the increase of soil erosion with simultaneous transport of suspended fine sediments and dissolved nutrients downstream (Santos et al., 2015b). Pacheco et al. (2015) have associated 15% of water quality variance (especially nitrate) to wildfires in catchments of Portugal. Santos et al. (2015c) have found a direct link of peaks of phosphorus yields in stream water to the simultaneous action of wildfires in some catchments.

Prescribed fires in mixed-conifer forest and riparian forest in California were found to have only a small effect on water quality that persisted for just 3 to 12 months (Bêche et al., 2005; Stephens et al., 2004). However, multiple prescribed fires within the same catchment can cause larger and longer-term effects (Cawson et al., 2012). These latter authors have proposed a comprehensive review of surface runoff and erosion after prescribed burning in forests. This review shows that, according to a high proportion of the available studies, the hydrological effects of prescribed burning are quite contrasting. Moreover, from this and other literature studies, it is evident that the changes in soil hydrology and water quality generated by prescribed fire have been little studied in the Mediterranean forest ecosystems. In particular, no comprehensive studies at plot scale have been carried out in afforested plantations of the Iberian Peninsula. Hence the objective of this study was to assess the effects of a prescribed fire in pine plantations in south-eastern Spain on the runoff, soil erosion, and water quality for approximately one year after burning.

2. Material and methods

2.1. Study site

The study was conducted in a relatively hilly area in the province of Albacete, Castilla-La Mancha region, Spain (Figure 1). The study site corresponds to a zone, whose potential vegetation is primarily *Quercus ilex* subsp. *rotundifolia*, while the current vegetation was 45-50 year old planted stand of mixed Aleppo and Mediterranean maritime pine (*Pinus halepensis* and *Pinus pinaster*, respectively). The understory was dominated by *Quercus faginea* Lam., L, *Quercus ilex* subsp. *ballota, Quercus coccifera,* L., *Juniperus oxycedrus, Brachypodium retusum* P. and *Thymus* sp. The control and burned plots also had very similar tree densities (about 500 trees/ha) and mean diameters (30 cm) (Table 1).

Elevations in the study area range from about 1010 to 1040 m a.s.l. The climate is classified as hot dry Mediterranean (Allué, 1990) with a mean annual temperature of is 13.5 °C. The mean minimum temperature of the coldest month is −0.9 °C and the mean maximum temperature of the hottest month is nearly 32 °C. Mean annual precipitation is about 450 mm (Spanish National Meteorological Agency, 1950-2016). From the geological point of view the pliocene tertiary materials formed by very rounded quartzite ridges of variable size and reddish-clay matrix appear on Mesozoic "lías", which are carbonated in nature: a lower calico-dolomitic, a mean clay-loam media, to finish with an episode of limestone, mainly oolitic. Soils are brown, stony, and clayey in texture (Rivas Martínez et al., 1987). The mean slope is around of 15%.

2.2. Experimental design

The Regional Forest Service conducted a prescribed fire in the area of the selected plots on 30th March 2016. Prior to the fire we identified the locations for our study plots, and immediately after the fire we constructed six erosion plots in the control area and six erosion plots in the burned area, all of which were 4-m long and 2-m wide (Figure 1). Plots were placed on north- to northeast aspects, with mean slope of the six control plots equal to 15.0% (±4.4), while the mean slope of the six burned plots was 14.5% (±2.6) (Table 1). The plot boundaries were made of 0.5 m wide geotextile fabric that was inserted up to 0.4 m below the ground surface. The entire perimeter was closed with geotextile that was tightly fastened to 0.8-m long and 20-mm in diameter iron rods, pounded into the ground at 15 cm of depth to prevent the flow of surface water. At the bottom of the plot the geotextile narrowed to convey the runoff and sediment into a pipe that led to a 25-litre container. The area where the plot narrowed was protected from rain by a plastic cover, and the ground surface also was covered by plastic secured to the ground by nails, to ensure that the entire runoff and all sediments were delivered to the collection point and then to the storage container (Figure 1).

The meteorological conditions for the burning were the following: wind of 14 km/h with southeast direction, ambient temperature of 14 ºC and relative humidity of 63%. Soil and air temperatures during the prescribed fire were monitored by three HOBO thermocouple type K (0–1250 ◦C (±4.0 ◦C)) with insulated 30-AWG wire (diameter <0.2 cm), assembled in Data Loggers UX120-014M (Onset Corp., Bourne (MA), Australia). They were placed in each burned plot 25 cm above the ground, for monitoring the soil surface, and 2 cm below the mineral soil surface, respectively. The slope and aspect of each plot were derived directly from measurements by a horizontal graduated bar. We counted and identified each tree and estimated the percentage of burned canopy. All the planted pine trees were 58 years old, since the study area was planted in 1960. We also measured the diameter of each tree at breast height, percent shrub cover, percent bare soil, and percent area mulched by pine- needle and of and leaf litter (Table 1).

To minimize disturbance, we measured surface cover in three adjacent 400-m^2 plots in the control and burned area, respectively. The area of bare soil, shrub, grass/herb, and litter cover were measured along three longitudinal transects. In each plot one soil sample was collected at a depth of 5-10 cm and analysed for soil texture, pH, organic matter content, electrical conductivity, and carbon: nitrogen (C:N) ratio, following Lucas-Borja et al. (2012).

A weather station (WatchDog 2000 Series model) with a tipping bucket rain gauge was set up 50 m outside the afforested area, and this was used to characterize precipitation, storm duration, and rainfall intensity. In the hourly rainfall series of the experimental database, two consecutive events were considered separate, if no rainfall was recorded for 6 h or more (Wischmeier and Smith, 1978; Zema et al., 2017). Mean rainfall intensity was the total rainfall divided by the storm duration. A funnel to collect and measure rainfall was installed about one meter away from the top of each plot, and a comparison of the mean rainfall from these to the rain gauge in the open air was used to determine the mean rainfall interception for the control and burned plots, respectively. Percent and absolute interception in the control and burned plots were compared and tested for their correlation to total rainfall, rainfall intensity, and storm duration.

After each storm the volume of runoff was measured. Runoff coefficients were calculated as the ratio of runoff to rainfall. Runoff water samples were collected after the storms which occurred on days 5, 37, 49, 203 and 394 after the fire by actively mixing the runoff and taking three successive samples totalling about 0.5 litres. The samples (n=30) were analysed in the laboratory for the weight of solid sediments ("suspended sediment" or SS in g/L), total dissolved solids (TDS), and a set of water quality parameters. The weight of eroded soil was calculated by multiplying the SS and TDS values by the volume of runoff and summing these two values. The water quality parameters were measured following standard procedures, and these included electrical conductivity (EC), pH, sodium adsorption ratio (SAR), residual sodium carbonates (RSC), water hardness (WH), total salt content (TSC), organic matter (OM), inorganic nitrates (NO^{3-}), bicarbonates (HCO_3^{+}), chlorine (Cl^{-}), potassium (K^{+}), sodium (Na^{+}), magnesium (Mg^{2+}), calcium (Ca^{2+}), and phosphates (PO_4^{-3}). Carbonates (CO_3^{-2}), sulphates (SO_4^{2-}), ammonium (NH_4^{+}) and boron (B) were also analysed, but the concentrations of these components were negligible in almost all the samples, so these data are not presented here. Budget limitations precluded the analysis of water quality for the other six storms that generated runoff.

2.3. Statistical analyses

The dependent variables (runoff volume, runoff coefficient, soil loss, and water quality parameters) were normally distributed, allowing the use of a multifactor ANOVA analyses to evaluate the effect of prescribed burning (burned versus unburned) and days after fire (DAF). The multifactor ANOVA analyses and Tukey–Kramer's honestly significant difference (HSD) test were used to determine if there were significant differences in any of the dependent variables between the control and burned plots. All significance levels were set at $p<0.05$. Statistical analyses were conducted using R software (R Development Core Team, 2016).

3. Results

3.1. Plot Characteristics Before and After Burning

Prior to burning the mean shrub/herb cover also was very similar and close to 50%, while in the burned plots after the fire it was reduced to 10%. Prior to burning bare soil averaged only 5% and post-fire it raised up to 11%.

The temperatures during the prescribed fire was determined in Plaza-Álvarez et al. (2018). At 25 cm above the surface, the mean temperature of burning was 94 ^{o}C (±15 ^{o}C). Mean temperatures of soil surface reached 43^{o}C (±4 ^{o}C)only. The mean duration of surface temperatures above 60 ^{o}C was only 16 seconds, and the mean maximum temperatures 2 cm below the surface were only 20 ^{o}C (±3 ^{o}C). Thus, this fire monitoring confirmed the low intensity target of these burns. Hence, the fire had little effect on the soil, but did kill an estimated 18% of the tree canopy, mostly towards the lower part of the canopy. One week after burning the scorched needles began falling and increased the mean litter cover from 44% (±7%), before the burning, to 79% (±6%), throughout the six months following burning.

3.2. Rainfall and Runoff

Total rainfall over the study period was 408.4 mm in 20 storms. Total precipitation for the 11 rainfall events that generated runoff was 314.2 mm. Net rainfall for the control and burned plots was relatively similar (252 and 241 mm, respectively), indicating net interception rates of 20% and 24%, respectively. On a event scale interception sometimes exceeded 50%, and the highest rates were generally associated with rainfall intensities of less than 4 mm/h (Table 2). For the combined data, rainfall interception was found to be significantly related to storm rainfall (R^2=0.59).

Eleven of the 20 storms produced runoff, with no runoff being generated with less than three mm of rainfall or a mean intensity of less than 4 mm/h. The mean runoff from these 11 storms for the control plots was 8.57 mm with a variability of 0.17 to 1.5 mm compared to 9.98 mm for the burned plots and a vaariability of 0.15 to 2.27 mm. The difference in mean runoff was not significant between treatments (control versus prescribed fire), however two storms generated significantly higher runoff in the burned plots. In the highest storm, whose intensity was 12 mm/h, on 268 DAF the runoff was 50% higher than control plots (Figure 2). This storm also generated more runoff than any other storms: 2.27 mm in burned plots and 1.5 mm in control plots.

The results of the ANOVA showed that burning and days after the fire had both significant effects on runoff volumesand runoff coefficients. The interaction between burning and days after the fire was also significant (F-ratio=3.7). For burned plots, runoff collected in the reservoirs varied between 1.2 and 18litres with an average of 7.3 litres, whereas, for control plots, the collected runoff varied between 1.3 and 12 litres, with an average of 5.65 litres. Few events were large enough to generate appreciable runoff (Fig. 2).

3.3. Soil Erosion

Almost all the total soil loss was collected as mineral sediment, the remaining, less 1%, was sediment dissolved in runoff water. Results indicated that TDS were not significantly higher in burned than in control plots for each water quality analysis. SS only was significantly higher in burned plots at 394 DAF. For that analysis, SS value was significantly lower than in previous analysis carried out in control plots (Table 3).

3.4. Water quality

Appreciable trends amongst all storms was higher amount of OM, either equal or higher HCO_3^-, higher K^+, and higher Ca^{2+}. The first storm on day 5 was not particularly remarkable, but produced runoff with significantly higher EC, pH, SAR, TSC, K^+, Mg^{2+}, and Ca^{2+} (n=7). The second storm on day 37 was similar, but generally did not give significant differences among the studied parameters comparing burned and control plots. The third storm on day 49 was of small and low intensity with no significant differences among the studied parameters comparing burned and control plots. The fourth storm on day 203 was of low intensity with higher EC, SAR, RSC, OM, HCO_3^-, Cl^-, K^+, Na^+ (n=8). The last storm on day 394 showed higher SS, EC, pH, WH, Na^+, Ca^{2+}, NO^-_3 (n=7). Common observations were the increase in EC (three storms), pH (storms 1 and 5), SAR (storms 1 and 4), K^+ (storms 1 and 4), Na^+ (storms 4 and 5), Ca^{2+} (storms 1 and 5) (n=6).

For each of the five sampled storms the burned plots always had a higher mean concentration of organic matter (OM) than the control plots (Table 3). For the first and last runoff samples the burned plots had substantially higher pH, EC, WHandTSC. The differences in EC and TSC were primarily due to the higher Cl^- K^+, and Na^+ values. For NO_3^- no differences were founded, as well as with PO_4^{-3}. HCO_3^-showed significant differences at 203 DAF. RegardingSAR, differences were founded at 5 DAF and 203 DAF, with a higher value for control plots in the first case and higher for burned plots in the other one. RSC showed differences only for the fourth analysis (203 DAF), burned samples showing higher values .

To sum up, one year after the prescribed fire, our results showed that pH, carbonates, bicarbonates, total dissolved solids and organic matter content were significantly higher in the runoff coming from burned plots. However, electrical conductivity and concentration of some elements (calcium, sodium, chloride and magnesium) of the collected runoff were not affected by the prescribed fire. Runoff quality was highly modified in the burned areas immediately after the prescribed fire (5 days after) (Table 3). Those differences mainly became non-significant in later dates.

4. Discussion

4.1. Rain interception

Tree canopies can protect soil surface from falling rain drops depending on fall height and drop size (Styczen and Morgan, 1995). In lower intensity storms water dripping from the tree canopy can increase drop size and kinetic energy (Geißler et al., 2012; Nanko et al., 2004; Vis, 1986). In our study we did not find any difference in net rainfall between the control and the burned plots due to the relatively small amount of the tree canopy that was burned, so the main effect of the tree canopy in the burned plots was the rapid post-fire litterfall and the associated increase in surface cover. On the other hand, the fire did greatly reduce the amount of shrub cover, and this loss is expected to increase the kinetic energy of the rainfall as well as the water dripping from the forest canopy. This increases rainsplash and soil erosion in the burned plots.

4.2. Runoff

The prescribed burning effects on soils of Mediterranean ecosystems depend on the rainfall characteristics such as depth and intensity, and the vegetation recovery rate (Inbar et al., 1998). High intensity rainfalls accelerate runoff and erosion (Neary et al., 2005). In this particular case, barely few medium-high magnitude events took place. Consequently, no high runoff peaks took place till 247, 268 and 318 days after fire (DAF). Only these events generated significant ($p<0.05$) runoff differences between burned and control plots. These differences can be explained due to the higher shrub and herb cover at the control plots (Table 1) that was more efficient than the litter inreducing runoff generation. This reduction can be explained as a result of to the complex system of vegetation patches in control plots, which is highly disconnected (Ruiz-Sinoga et al., 2010); this influence of semiarid Mediterranean vegetation on runoff generation has been widely reported in previous studies (Romero Díaz et al., 1999; Dunjó et al., 2004).

On the other hand, the lack of any differences in total generated runoff between burned and control plots for low intensity events showed that pine needles could replace to some extent the previous vegetation cover effect on runoff generation. This is in line with Pannkuk and Robichaud (2003), Vega et al. (2004) and Prats et al. (2011), who found pine needle litter to be effective minimizing post-fire runoff generation. Also Keestra et al. (2014) found that pine needles falling and covering soil surface immediately after a prescribed fire is an efficient and natural mulching, avoiding runoff and erosion in the immediate post-fire period.

4.3. Soil Erosion

In northwestern Spain prescribed fires in shrublands more than doubled soil losses compared to unburned areas for light burns (Vega et al., 2005). In absolute terms the soil losses measured in this study were close to the lower range of values reported in other experiments (see for example Malmot et al., 2007 and Alexandrov et al., 2003). These low soil losses can be attributed to the prescribed fire characteristics (i.e. fire intensity) and the low area of bare soil due to the fall of the scorched needles. Previous studies have pointed that the organic layer covering the soil protects it against erosion (Fernandez et al., 2008). Other studies also reported few or no erosion for low intensity fires (Van Lear & Danielovich, 1988; Shahlee et al., 1991; Eliott & Vose, 2005). Soil loss was only due to suspended and dissolved sediments (Table 3), as no sediment was captured in the reception equipment (Figure 1). The lack of significant differences of soil loss between burnt and control, plots when it comes to SS or TDS, have been already reported for light-moderate burns in the United States (Eliott & Vose, 2005). Even though these results must be considered with caution, due to the absence of more large or intense rainfall events during the first year after fire, it would seem that prescribed burning in reforested areas could be used with an acceptable level of soil loss.

4.4. Water quality

In light of our results, OM seems to be significantly higher after fire, at least for the first year. These results do not agree with previous studies that did notfind any impact of prescribed burning on OM (see Covington et al., 1984; Hatten et al., 2008and Gareth et al. (2008). Concerning water salinity, measured as EC, TSC, these values were significantly higher for burned plots immediately after burning in comparison to control (unburned) plots, and this increase could be explained as the result of inorganic ions being released from combusted organic matter (Nadiu and Srivasuki, 1994). Similar results were obtained by Pereira et al. (2011). After prescribed fire, pH increased due to ashes, which is in accordance with other studies (like.g., Ulery et al., 1993; Williams et al., 1997; Plumlee et al., 2007 and Pereira et al., 2010). After the initial months, pH differences between control and burned plots disappeared, that is in accordance with the results of Úbeda et al. (2005), who founded that one year after fire pH and total carbon soil values returned to pre-fire levels. This increase after prescribed burn may be due to the presence of certain water-soluble elements in runoff after fire(Williams et al., 1997).

With regard to Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-} and NO_3^{-}, significant differences were founded immediately after fire, but chemical concentrations tend to equalise with time. This was also observed by Adams and Boyle (1980), who founded that after 3 months the differences almost totally disappeared gone. Kutiel and Inbar (1993) and Williams et al. (1997) also indicated that after burning Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} concentrations increased in the overland flow. Belillas et al. (1993) founded that runoff from burnt slopes showed higher concentrations for NO_3^{-}, K^{+} or Ca^{2+}, while Na^{+} did not showed any differences. Nevertheless, thosedifferences were not significant ($p>0.05$). Carbonates resist to high temperatures, and due to that are not likely to be affected by fire (Rabenhorst, 1988). Eliott & Vose (2005) did notfind any significant differences for PO_4^{-3} after burning.

5. Conclusions

Since changes in soil hydrology and water quality generated by prescribed fire have been little studied in the Mediterranean forest ecosystems, this investigation evaluates at the plot scale the effects of a prescribed fire in pine plantations in south-eastern Spain on the runoff, soil erosion, and water quality for approximately one year after burning. Low intensity prescribed burns seem not to affect runoff generation and soil erosion, when low intensity precipitations occur at pine plantations. Runoff water quality was also slightly affected, when comparing burned and control plots at the end of the experiment. In addition, water turbidity, salinity, pH, OM content and ion concentrations increased immediately after prescribed burnt, nevertheless these changes disappeared over time. In light of these results, it can be assumed that low intensity prescribed burns can be a useful tool for fuel reduction in Mediterranean pine plantations without wide and long-term affections to soil losses, or water quality. A modeling approach targeted to simulate surface runoff, soil erosion and water quality in runoff as the effects of prescribed fire may be welcome to provide an important hydrological tool for forest management and conservation.

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Tables

Table 1. Number and type of study plots with the mean (± standard deviation) slope, aspect, tree density and diameter, dominant tree species, shrub cover, percent bare soil, percent litter, and percent of the canopy scorched.

Plots	Control plots	Burned plots
n	6	6
Slope (%)	15 (±4,4)	14,5 (±2,6)
Aspect	N	N-NE
Tree density (n ha)	477 (±33)	529 (±60)
Tree diameter (cm)	27 (±7)	32 (±6)
Tree species composition	*P. pinaster* Ait., *P. halepensis* M.	*P. pinaster* Ait., *P. halepensis* M., *Q. ilex* L.
Shrub/herb species	*Quercus coccifera* L., *Brachypodium retusum* P., *Thymus vulgaris* L., *Dactylis glomerata* L.	*Qercus coccifera* L., *Brachypodium retusum* P., *Thymus vulgaris* L., *Sanguisorba minor* S.
Canopy consumed (%)	-	18 (±5)
Shrub/herb cover (%)		
Pre-fire	56 (±9)	51 (±7)
Post-fire	59 (±5)	10 (±3)
Litter (%)		
Pre-fire	40 (±8)	44 (±7)
Post-fire	38 (±9)	79 (±6)
Bare soil (%)		
Pre-fire	4 (±1)	5 (±1)
Post-fire	3 (±1)	11 (±3)

Table 2. List of storms by date and days after fire (DAF) with total rainfall and maximum rainfall intensity in the open, and mean storm precipitation and percent interception for the control and burned plots, respectively. Values in parentheses are standard errors, and the storms underlined were analysed for sediment and water quality.

				Outside forest plantation		**Inside forest plantation**	
	Major storm number	**Date**	**Days after fire**	**Storm rainfall (mm)**	**Maximum intensity ($mm \cdot h^{-1}$)**	**Mean rainfall (mm)**	**Rainfall interception (%)**
Control	1	5	04 Apr 2016	20.0	8.8	18.2 (3.7)	11.3
Burned						17.7 (4.4)	9.1
Control	2	37	06 May 2016	20.1	8.4	16.8 (6.3)	22.9
Burned						15.4 (5.6)	15.9
Control	3	49	18 May 2016	10.2	4.3	4.4 (2.1)	58.3
Burned						4.3 (2.2)	56.7
Control	4	196	12 Oct 2016	21.1	8.8	19.3 (6.7)	10.4
Burned						19.0 (4.9)	9.2
Control	5	203	19 Oct 2016	27.4	5.3	22.0 (7.1)	19.1
Burned						22.2 (6.2)	19.7
Control	6	223	08 Nov 2016	17.0	5.6	13.8 (6.8)	26.0
Burned						12.6 (5.1)	18.0
Control	7	247	02 Dec 2016	52.4	4.2	39.7 (5.4)	37.1
Burned						32.9 (8.2)	24.2
Control	8	268	23 Dec 2016	59.6	11.6	45.0 (6.4)	22.1
Burned						46.4 (7.7)	23.7
Control	9	318	11 Feb 2017	38.2	6.3	36.3 (1.9)	10.5
Burned						34.2 (3.3)	5.0
Control	10	377	04 Apr 2017	20.2	5.7	18.4 (3.7)	11.3
Burned						17.7 (2.9)	9.2
Control	11	394	28 Apr 2017	28.2	6.8	18.2 (3.6)	37.2
Burned						17.8 (2.8)	35.6

Table 3. Mean and standard deviation for the five sets of runoff that were analysed for the various physical and chemical water quality parameters. Asterisks indicate a significant difference between the control and burned plots for a given date and water quality parameter. Significant differences of the mean parameter values among the five runoff samples are indicated with uppercase letters for the control plots and with lowercase letters for the burned plots. Abbreviations: DAF, days after the prescribed fire; TDS, total dissolved sediment ($mg \cdot l^{-1}$); SS, suspended sediment ($mg \cdot l^{-1}$); EC, electrical conductivity ($mS \cdot cm^{-1}$); SAR, sodium adsorption ratio; RSC, residual sodium carbonates ($meq \cdot l^{-1}$); WH, water hardness (hydrometric French degrees); TSC, total salt content ($g \cdot l^{-1}$); OM, organic Matter ($mg \cdot l^{-1}$); NO_3^-, inorganic nitrates ($mg \cdot l^{-1}$); HCO_3^-, bicarbonates ($mg \cdot l^{-1}$); Cl^-, chlorine ($mg \cdot l^{-1}$); K^+,

DAF	Plots	TDS	SS	EC	pH	SAR	RSC	WH	TSC	OM
5	Control	0.17 (0.06)A		0.044 (0.006)	6.57 (0.04)A	0.74 (0.06) B	0.08 (0.06)	1.6 (0.3)	0.028 (0.004)	4.1 (1.1)
	Burned	0.18 (0.03)a		0.120 (0.03)*	7.22 (0.05)ab*	0.41 (0.03)a*	0.11 (0.09)	5.1 (1.6)	0.078 (0.021)*	12.0 (5)
37	Control	0.30 (0.09)A		0.210 (0.14)	7.41 (0.19)B	0.33 (0.011)A	0.90 (0.9)	10.0 (7)	0.130 (0.09)	6.7 (1.6)
	Burned	0.23 (0.04)a		0.108 (0.02)	7.31 (0.07)b	0.29 (0.019)a	0.10 (0.3)	4.9 (1)	0.069 (0.013)	13.0 (4)
49	Control	0.17 (0.09)B	93.18 (51)	0.087 (0.012)	6.82 (0.1)A	1.42 (0.11)C	0.38 (0.07)	2.8 (0.3)	0.057 (0.008)	5.3 (0.8)
	Burned	0.18 (0.027)b	154 (47)	0.100 (0.011)	6.91 (0.07)a	1.29 (0.18)b	0.42 (0.05)	3.7 (1.1)	0.063 (0.008)	13.0 (4)
203	Control	0.14 (0.02)A	147 (57)	0.074 (0.01)	7.45 (0.13)B	0.21 (0.03)A	0.11 (0.1)	3.7 (0.7)	0.048 (0.006)	8.8 (1.7)
	Burned	0.33 (0.12)a	100 (24)	0.190 (0.06)*	7.16 (0.12)ab	1.1 (0.08)b*	0.40 (0.06)*	6.0 (1.7)	0.120 (0.04)	19.0 (3)*
394	Control	-	24 (10)A	0.04 (0.005)	6.57 (0.09)A	0.28 (0.03)A	0.41 (0.12)	2.94 (0.53)	0.03 (0.003)	10.56 (1.7)
	Burned	-	174 (55)*	0.08 (0.01)*	7.00 (0.11)a*	0.30 (0.04)	0.21 (0.08)	5.60 (0.83)*	0.05 (0.01)	13.02 (2.12)

potassium ($mg \cdot l^{-1}$); Na^+, sodium ($mg \cdot l^{-1}$); Mg^{2+}, magnesium ($mg \cdot l^{-1}$); Ca^{2+}, calcium ($mg \cdot l^{-1}$); PO_4^{3-}, Phosphates ($mg \cdot l^{-1}$).

DAF	Plots	$N0_3^-$	HCO_3	Cl^-	K^+	Na^+	Mg^{2+}	Ca^{2+}	PO^{4}_{-3}
5	Control	1.4 (0.6)	24 (11)	11.1 (1.3)	0.8 (0.3)	6.6 (0.6)A	1.5 (0.8)	4 (0.8)	-
	Burned	1.1 (0.5)	55 (15)	22.0 (6)	5.0 (1.3)a*	6.1 (0.8)a	4.1 (1.2)*	14 (5)*	-
37	Control	2.4 (0.7)	59 (28)	20.0 (6)	2.6 (1.06)	6.4 (2.4)A	7.0 (4)	27 (20)	0.36 (0.19)
	Burned	1.1 (0.4)	65 (27)	22.2 (1.1)	6.4 (1.4)a	4.5 (0.4)a	4.2 (0.7)	13 (3)	0.56 (0.21)
49	Control	0.9 (0.3)	57 (5)	20.3 (1.1)	5.5 (1.5)	16.5 (0.8)B	3.0 (0.6)	6 (0.9)	0.00 (0.00)
	Burned	1.6 (0.9)	71 (13)	24.5 (2.1)	10.2 (2.5)ab	15.8 (0.8)b	4.3 (0.8)	8 (3)	0.23 (0.23)
203	Control	2.4 (1.7)	39 (4)	11.1 (2.4)	2.8 (0.8)	2.8 (0.3)A	2.3 (0.6)	11 (3)	0.36 (0.09)
	Burned	10.0 (9)	98 (19)*	20.0 (3)*	20 (5)*b	18.0 (3)*b	3.7 (0.7)	18 (7)	0.60 (0.4)
394	Control	1.37 (0.4)	61 (5)	20.68 (1.04)	2.22 (0.5)	3.27 (0.17)	4.54 (0.23)	4.27 (1.8)	0.61 (0.22)
	Burned	0 (0)*	81.33 (11)	21.05 (2.1)	3.29 (0.79)	5.07 (0.74)*	4.29 (0.64)	15.34 (3.5)*	0.01(0)

Table 4. Correlations between the various water quality parameters. Values in bold are significant at $p<0.05$*.

	EC	pH	NO_3^-	HCO_3	Cl^-	K^+	Na^+	Mg^{2+}	Ca^{2+}	OM	SS	TDS	SAR	RSC	WH
PH	**0.45**														
$N0_3^-$	0.11	-0.12													
HCO_3	**0.57**	0.04	-0.14												
Cl^-	**0.47**	-0.04	0.06	**0.95**											
K^+	**0.76**	0.23	0.04	**0.68**	**0.62**										
Na^+	**0.49**	-0.17	0.05	**0.42**	**0.36**	**0.58**									
Mg^{2+}	**0.39**	0.08	0.11	**0.65**	**0.45**	**0.33**	0.15								
Ca^{2+}	**0.70**	**0.48**	0.05	**0.49**	**0.31**	**0.49**	0.08	**0.27**							
OM	**0.50**	0.10	0.08	**0.68**	**0.51**	**0.66**	0.06	**0.42**	**0.54**						
SS	0.15	-0.01	**-0.30**	**0.41**	0.17	**0.38**	**0.24**	0.02	0.07	**0.27**					
TDS	**0.42**	0.00	0.14	0.08	0.23	**0.43**	**0.64**	0.01	-0.01	-0.12	0.11				
SAR	0.17	**-0.35**	0.04	0.13	0.16	**0.35**	**0.89**	-0.07	**-0.26**	-0.15	0.19	**0.60**			
RSC	-0.06	**-0.41**	**-0.26**	**0.51**	0.21	**0.31**	**0.34**	0.10	**-0.28**	**0.29**	**0.48**	0.14	**0.40**		
WH	**0.68**	**0.42**	0.05	**0.66**	**0.42**	**0.51**	0.04	**0.62**	**0.86**	**0.63**	0.12	-0.07	**-0.31**	-0.16	
TSC	**0.86**	**0.57**	0.07	**0.43**	0.23	**0.58**	0.24	**0.26**	**0.66**	**0.43**	0.26	**0.30**	-0.09	-0.17	**0.62**

* TDS, Total dissolved sediment ($mg \cdot l^{-1}$); SS, Suspended sediment ($mg \cdot l^{-1}$); EC, Electrical conductivity ($mS \cdot cm^{-1}$); SAR; Sodium adsorption ratio; RSC; Residual sodium carbonates ($meq \cdot l^{-1}$); WH, water hardness (hydrometric French degrees); TSC; Total salt content ($g \cdot l^{-1}$); OM, Organic Matter ($mg \cdot l^{-1}$); NO_3^-, Inorganic nitrates ($mg \cdot l^{-1}$); HCO_3^-, Bicarbonates ($mg \cdot l^{-1}$); Cl^-, Chlorine ($mg \cdot l^{-1}$); K^+, Potassium ($mg \cdot l^{-1}$); Na^+, Sodium ($mg \cdot l^{-1}$); Mg^{2+}, Magnesium ($mg \cdot l^{-1}$); Ca^{2+}, Calcium ($mg \cdot l^{-1}$); PO_4^{3-}, phosphates ($mg \cdot l^{-1}$).

Figures

Figure 1. Location and scheme of the study plots.

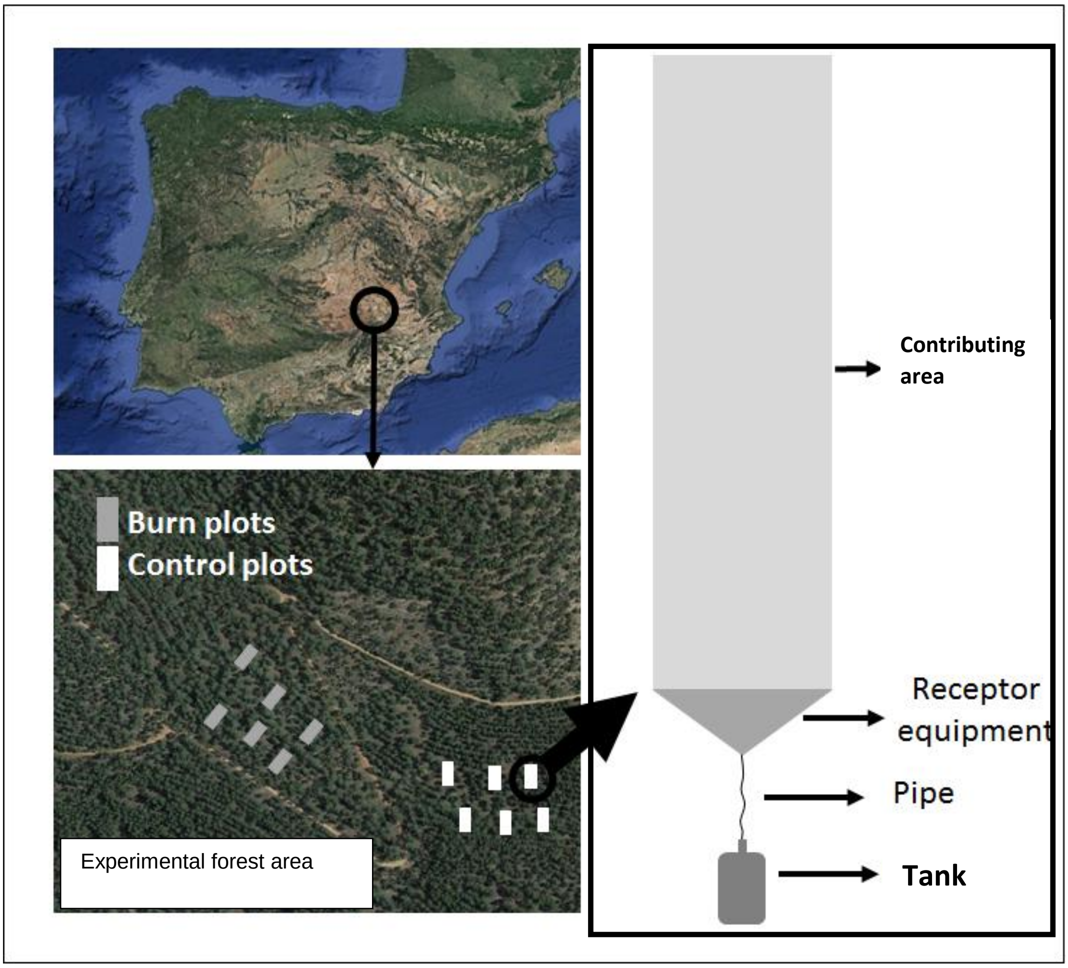
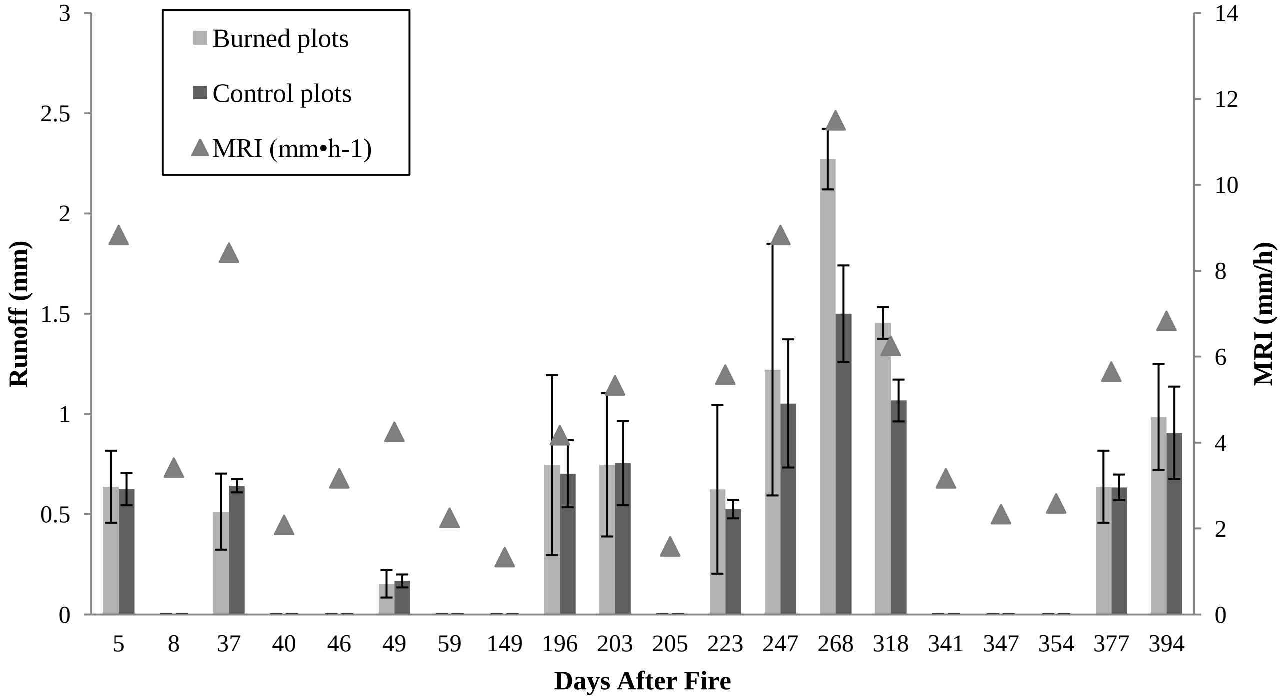


Figure 2. Mean runoff and associated error bars for the control and burned plots. Triangles indicate the maximum rain intensity (MRI) in the open. Daily rainfalls of less than three millimetres did not generate runoff and are not plotted here. X-axis is plotted by event rather than an arithmetic scale of days after burning.



Conflict of interest

Short-term effects of prescribed burning in Mediterranean pine plantations on surface runoff, soil erosion and water quality of runoff

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The authors declare no conflict of interest along this manuscript submission

Manuel Esteban Lucas-Borja, on behalf of the co-authors.