RESEARCH ARTICLE

Decision-making criteria to shape mulching techniques for fire-prone landscapes

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Abstract

Context Wildfires have severe impacts on landscapes' hydrological and sediment processes. They are linked to events such as flash floods and droughts, and high erosion rates which lead to loss of soil organic matter and detachment of seeds and seedlings. Mulching is an effective measure implemented directly after a fire to reduce soil erosion and increase soil water retention. However, its implementation has proved a challenge, mainly due to factors such as cost and public acceptance.

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Objectives This research aims to optimize the application of post-fire mulching by using decision-making criteria to select "how" and "where" the technique should be used. The specific objectives were to: (i) investigate the decision-making criteria on "how" to apply mulch by interviewing experts; (ii) define the cost-effectiveness relations of erosion modelling scenarios.

Methods The Monchique 2003 wildfire in Southern Portugal was used as a case study Experts' interviews and literature review were used to construct prioritization scenarios. Post-fire soil erosion was then modelled with the Revised Universal Soil Loss Equation (RUSLE) model and the Sediment Connectivity Index for the three resulting scenarios (the "Soil" scenario, considering the net potential erosion; the "Water" scenario, focusing on th1e protection of water bodies from sedimentation; and the "Road" scenario, focusing on road protection); and at two erosion thresholds (1 and 10 Mg ha^{-1} year^{-1}).

Results The interviews and the literature review highlighted the importance of socio-economic parameters when it comes to mulch application. Moreover, models showed that small interventions, aimed at areas nearby water bodies and road networks can be more cost-effective than large interventions.

Conclusions Models helped to create a hierarchy of scenarios, enabling land managers to assess decision making tools at the landscape level, linking their priorities with practical issues of emergency stabilization practices.

Introduction

The frequency and severity of wildfires are increasing worldwide (Jeuland et al. 2013), including in colder regions. Rural areas in Portugal are no exception. Wildfires have devastated the region, affecting around 988,000 ha between the years 2001 and 2017 (Beighley and Hyde 2018).

This phenomenon is caused by a combination of factors. Firstly, increasingly erratic seasonal climate variations and severe weather events increase wildfire occurrences (Turco et al. 2019; Calheiros et al. 2020). Other factors originate from land-use trends, such as land abandonment and afforestation with fire-prone trees has led to a landscape dominated by highly flammable forest or invasive shrubs (Marques et al. 2011; Prats et al. 2012; Beighley and Hyde 2018; Martins et al. 2020).

Wildfires have an undeniably devastating effect on nature and human society (Beighley and Hyde 2018). Furthermore, due to the loss of vegetation and subsequent changes in soil characteristics such as aggregate stability or water repellency, fire plays a detrimental role in a system's hydrological properties (Shakesby 2011). Soil infiltration and water retention capacity in burned areas are severely diminished, rendering the landscapes susceptible to excessive water run-off, soil erosion, and ash transport (Prats et al. 2018). Burnt areas are linked to events such as flash floods and droughts, while in local streams and reservoirs high concentrations of sediment and contaminants appear (Gould et al. 2016; Robinne et al. 2021). Moreover, erosion leads to loss of soil organic matter and detachment of seeds and seedlings, which hinders the affected area's recovery (Shakesby 2011).

Post-fire management practices can be defined as human endeavors to amend the ecological functions of a fire-affected landscape (López-Vicente et al. 2020). Those groups of practices can be categorized in various ways according to their temporal perspective (long-term or short-term) or their specific focus (e.g., protection of water quality, increasing biodiversity, etc.) (Robichaud et al. 2010). Emergency stabilization practices refer to measures implemented soon after the fire to minimize post-fire soil erosion or alleviate its off-site impacts. These practices aim to protect human health and safety and prevent pollution to water resources as well as further infrastructural damage (Robichaud et al. 2010; Nunes et al. 2020). Measures commonly applied are mulching, log erosion barriers, contour felled log debris, seeding of hillslopes with grass, and check-dams in the streams (Robichaud et al. 2010; González-Romero et al. 2021).

It is important to note, however, that most of the field experiments about the effectiveness of erosion mitigation treatments were conducted in plots ranging from 1 m^2 to 510 m^2. (Shakesby and Doerr 2006; Fernández et al. 2011; Shakesby et al. 2016; Wu et al. 2021). As a result, established methodologies linking plot to catchment scale are scarce and there is a lack of holistic system-level analysis (Girona-García et al. 2021). It is therefore evident that there is a knowledge gap on erosion mitigation at the landscape level.

Beyond scientific knowledge gaps, challenges remain in implementing appropriate measures quickly enough (before the first major precipitation event), because of stakeholders' lack of information about recent scientific advances; landowners and forest managers are often skeptical about the profitability and effectiveness of suggested measures (Girona-García et al. 2021). Furthermore, there are a lack of studies that calculate the cost-efficiency of different measures in relation to the hydrological services they provide. This knowledge gap is an obstacle to effective science-policy communication (Pastor et al. 2019). Moreover, mulching is rarely applied in fire-affected fields in Portugal since there is a lack of expertise on its application and costs (Lopes et al. 2020).

Multiple efforts have been made to address the arising complexities, but there is still a long way to go on priority area identification and examining the tradeoffs between alternative techniques (Gonçalves et al. 2011; Vogler et al. 2015; Vieira et al. 2018). It is therefore important to bridge the gaps between different kinds of knowledge and practice, and especially to investigate the socioeconomic aspect of mulching, e.g., how to address the public's perspective, apply local and expert knowledge, and nourish community engagement (USDA Forest Service 2006; Rodríguez-Carreras et al. 2020; Prats et al. 2022).

The aim of this research is twofold; (1) to investigate how multiple criteria can be combined to design effective post-fire interventions according to different viewpoints on emergency stabilization, and (2) to contribute towards the understanding of the differences and similarities between different potential spatial prioritization systems. This research focuses specifically on the practice of mulching as a soil stabilization technique since it has proved to be one of the most effective. The specific research questions are: (i) **Which** biophysical and socioeconomic **criteria** are appropriate to define **how and where** to implement mulching treatments? And (ii) What are the potential similarities and differences between the outcomes of different prioritization scenarios of deciding **where** to place mulching?

Materials and methods

The approach of this research consisted in a combination of interviews and spatial modelling (Fig. 1). These methods are described in "Interviews with experts". and "Building prioritization scenarios" sections.

Study area

The study area covers the region of the "Serra de Monchique" and its surroundings, situated in the West Algarve region of Southern Portugal. The climate can be characterized as Mediterranean, with mild winters and dry summers. Due to the Atlantic influence and the orography, the annual rainfall amount is large (850 mm year^{-1}) with occasional strong showers in the summer (Prats et al. 2021a, b). This climate creates a broad hydrographical network of surface torrential streams (Carvalho et al. 2018). The ecosystems are so unique, with heathlands being the most dominant habitat, that 'Serra de Monchique' has been designated as a Special Area of Conservation within the Natura 2000 network (Mitchell et al. 2009). In the last two decades, there were some major wildfire events in the area (ICNF 2018). Between August–September 2003, three wildfires devastated approximately 67,000 ha in Monchique and other surrounding municipalities. In 2018 another severe wildfire event burnt 27,000 ha of forest and shrubland (ICNF 2018).

Interviews with experts

Criteria tables

The interviews lasted 30 min to one hour, and a total of 16 experts were interviewed. We contacted participants that were knowledgeable in the field of post-fire management, but at the same time belonged to different disciplines and had different geographical expertise. Participants were identified through snowball sampling (Tongco 2007). Each interview script was unique, since the questions were adapted to the nature of the participant's experience (DeJonckheere and Vaughn 2019). Despite this high degree

Fig. 1 Conceptual roadmap of the research carried out. Dark green boxes correspond to methods, orange boxes correspond to research output content and blue boxes represent the final output regarding the research questions
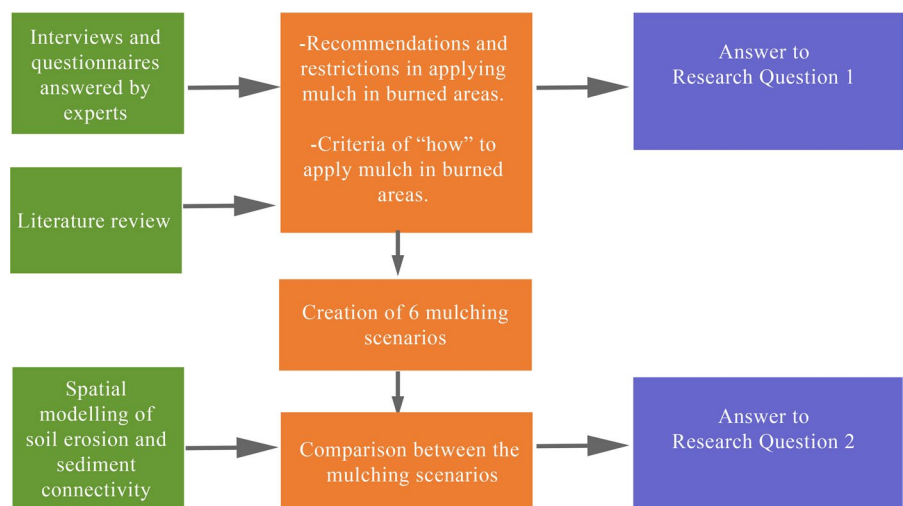
of flexibility, we prepared a sequence of topics, which served as a guide of open-ended questions about the differences between mulching and other emergency stabilization techniques:

Topic 1 Area prioritization issues. E.g., Which are the factors to be considered first/second/etc. when deciding which area requires intervention?

Topic 2 Conflicts that rise between stakeholders. E.g., How would the collection/processing/spreading of mulch material interfere with other economic activities?

Topic 3 The criteria to be taken under account when deciding "how" mulching technique could be applied. Further information can be found in the Supplementary material (Tables S1, S2).

When replies began to provide recurrent information we stopped the interviews and started data processing (DeJonckheere and Vaughn 2019). Data was processed in two steps: (1) systematize replies of each participant including the comments done while discussing criteria and indicators and (2) undertake thematic coding and complement the themes emerging from the interviews with a literature review. This resulted in a summary of the criteria that play a role in the decision-making process around mulching practices.

Comparison matrices

After introducing the participant to the function of a comparison matrix, we sent them the excel file that included Tables S1 and S2, alongside a comparison matrix (Table S3). Comparison matrices provide a template for pairwise comparisons, and it is a method widely used as a decision support tool (Diaz-Balteiro et al. 2009). Their purpose is to identify the relative importance of the criteria discussed during the previous steps The first row and first column of the matrix consist of the list of criteria. The participant was asked to fill in each cell with one option from a predefined, drop-down list which is explained as follows:

Equal: Two elements contribute equally to the objective of optimal

Left, or top moderately: I moderately favor the element written on the beginning of the row, or the beginning of a column as more important.

Left or top, strongly: I very strongly favor the element written on the beginning of the row, or the beginning of a column as more important.

The analysis of the pairwise comparisons was conducted according to the 'Analytical Hierarchy Process' (AHP), a method developed from Saaty (1980). Based on pairwise comparison inputs, weights are calculated by finding the dominant right eigenvector (Goepel 2018). The free, web based AHP version (Business Performance Management Singapore) was Used. AHP allowed the calculation of the aggregated weights of each criterion, the level of inconsistencies and group consensus as described in Goepel (2018). To calculate the weights of the criteria, we used the linear AHP judgement scale proposed by Saaty (1980).

The process of creating a final criteria table is the following: (i), the criteria that scored low in the comparison matrix as well as were discarded by literature were deleted; (ii), some criteria were merged or reformulated into one criterion; (iii), new criteria suggested by all the participants were added. The criteria were finally categorized as *Technical*, if they relate to the technical aspects of design and implementation; *Other environmental effects*, if they relate to the effects of mulching on natural ecosystem not directly linked to erosion reduction; or *Social* if they are connected to the social capacity to the design and implementation of the technique.

Out of the 16 interviewees, only ten experts completed the criteria tables, due to time and language limitations. For the same reasons, participants 9 to 13, 7 and 16 were interviewed without the use of a comparison matrix table (Table S4). In Table S4 one can find the relevant information about the interviewees: expertise, the type of institution that employees them and the country for which they are most professionally experienced.

Building prioritization scenarios

The three prioritization scenarios are based on the interviews and on literature review. According to Robichaud et al. (2000), the primary reasons for the application of emergency post-fire stabilization treatments, as defined in the Burned Area Emergency Response Handbook are: "(1) minimize the threat to life and property onsite or offsite; (2) reduce the loss

of soil and onsite productivity; (3) reduce the loss of control of water; and (4) reduce deterioration of water quality." The same study highlights that the most cited reasons for conducting stabilization projects were "property, water quality, and soil productivity". These reasons are still essential for post-fire management, as reflected in literature, technical reports, and assessments (Foltz et al. 2008; Shakesby et al. 2016; Sosa-Pérez and MacDonald 2017; Rego et al. 2019; USDA Forest Service 2022). Each of the scenarios described here focused on one of these central priorities: protection of soil, water quality, and road infrastructure.

The soil erosion **modelling** for the prioritization scenarios was carried out on the study case of Monchique, after the wildfire of 2003. Six large hydrological basins were affected by high fire severity, although one basin was not included due to its little burnt-affected surface (Fig. 2). Spatially distributed parameters such as soil attributes, geomorphology, land use types, etc., were used to calculate the prioritization areas for mulching application.

1st prioritization scenario- soil protection

The first scenario focuses on the protection of the soil from erosion, regardless of off-site parameters. The empirical model Revised Universal Soil Loss Equation (RUSLE) was used to estimate the post-fire soil erosion rates. It has been shown that RUSLE is able to estimate the post-fire erosive response with relative simplicity and low input requirements (Vieira et al. 2018). The soil erosion "A" of the RUSLE model is calculated as follows (Wischmeier & Smith 1978):

$$A = R * K * LS * C * P \; \left(Mg \; ha^{-1} yr^{-1}\right) \qquad (1)$$

where R is the rainfall erosivity (MJ mm h^{-1} ha^{-1} $year^{-1}$), K is the soil erodibility (Mg h MJ^{-1} mm^{-1}), and the non-dimensional factors LS, C and P represent the effect of topography (slope length and steepness), crop, and soil conservation practices respectively.

The P factor was not included in this study since no soil conservation practices are indicated. The spatial resolutions of the downloaded raster files for R and K were 500 m (Soil Erosion by Water (RUSLE2015)— ESDAC—European Commission 2015), resampled to 25 m resolution to match the resolution of the LS.

The C factor was assigned to each area according to its land use, and it is determined using various sources. The land use map of Portugal for the year 2007 was downloaded (Carta de Uso e Ocupação do Solo de Portugal Continental para 2007— (COS2007v2.0) and then a table was created to match each land use with a C-factor value. To do this, we used the recommendations from Panagos et al. (2015) and Parente et al. (2022), mixed with rational estimations based on cover and management implied by each land use. A summary of the C-factor values is presented in Table S5 and Annex 2. After creating a map with C-factor values for unburned conditions, we calculated the changed C-factor due to the wildfire. This was done by loading maps of the difference between the Normalized Burn Ratio (dNBR) values pre- and post- the 2003 fire event (López-Vicente et al. 2020; Robichaud et al. 2007a, b). NBR is a function of values derived from satellite imagery, were the highest dNBR values are indicative of greatest change on vegetation due to the fire. To use this
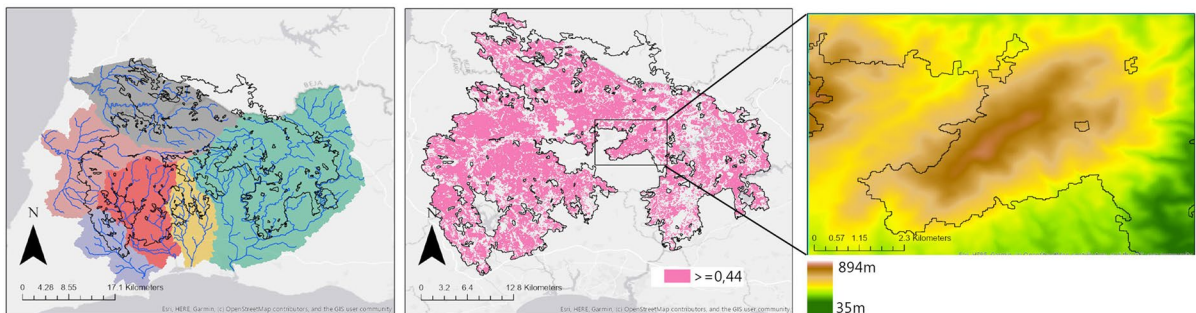

Fig. 2 Location of the Monchique 2003 wildfire, which burnt 67,000 ha in southern Portugal, the affected hydrological basins, the fire perimeter and fire severity, and zoom into the selected sub-area to assess the prioritization scenarios

indicator for area prioritization models, it is necessary to arrange classes that identify degree of burn severity (Table S6; based on Rozario et al. 2018; Wu et al. 2021). After that, the C-factor for burned conditions was calculated based on previous publications of modelling exercises (Martínez-Murillo and López-Vicente 2018; González-Romero et al. 2021; Parente et al. 2022) and is shown in Table S7. We made a distinction for the areas with coniferous vegetation, as they shed their needles after a low or medium intensity fire. The shed needles play the role of a "natural mulch", protecting the soil against erosion (Gonçalves et al. 2011).

Finally, the priority areas were delineated according to dNBR values higher than 0.44 (moderate-high severity burn). We targeted areas using their calculated annual erosion rate (A), using two thresholds: (i) Areas with $A > 1$ Mg ha^{-1} year^{-1} and (ii) areas with $A > 10$ Mg ha^{-1} year^{-1}, sub-dividing the main scenario into sub-scenarios Soil 1 and Soil10. These two thresholds were chosen because of the high uncertainty over what constitutes a "tolerable" erosion rate (Verheijen et al. 2009).

2nd prioritization scenario- water body protection

The literature review showed multiple publications that describe the environmental and economic consequences of water sedimentation due to fire affected soils (De Vente et al. 2013; Moody et al. 2013; Shakesby et al. 2016; Nunes et al. 2020). No distinction was made between streams of different sizes (e.g., by using Strahler stream order) nor the potential significance of the stream or reservoir (e.g., if it is used for fishing or for water consumption by humans). To assess this risk, we calculated the amount of eroded sediment from the burnt areas reaching the streams, using an approach based on the Sediment Connectivity Index (SCI; see Annex 3), calculated using the stream network as a target. "Connectivity" in geological sciences is used to support the comprehension of material flow, such as water or sediment flows, within a system (Baartman et al. 2020). The next step is to calculate the Sediment Delivery Ratio (SDR) to streams, which is the proportion of the eroded sediment in each area (each pixel in our case) that reaches the target (SDR 2022; based on Borselli et al. 2008; Sougnez et al. 2011; Vigiak et al. 2012). Briefly, the SDR is calculated as shown below:

$$SDR_i = \frac{SDR_{max}}{1 + \exp\left(\frac{IC_0 - IC_i}{k}\right)} \qquad (2)$$

where SDR_{max} is the maximum value for SDR, which by default is 0.8. IC_o and k are calibration parameters ($IC_o = 0.5$; $k = 2$) according to Jamshidi et al. (2014).

Sediment export to streams is calculated by multiplying the SDR by the sediment yield calculated with the RUSLE for the first scenario. The priority areas were delineated similarly to the first scenario: by selecting areas with a dNBR value higher than 0.44. According to the annual sediment export rates, two thresholds were also considered for comparability: Water1 and Water10, respectively higher than 1 and 10 Mg ha^{-1} year^{-1}.

3rd prioritization scenario- road protection

The third prioritization scenario uses the same approach as the second scenario, with one difference: the road networks are used as target for the Connectivity Index (and therefore for sediment yield) instead of the stream network. More specifically, the regional infrastructure that connects settlements with each other (Fig. S1). This scenario is based on some interviewees who argued that the accessibility to target areas will be an important information to select the target areas, because it will prioritize accessibility, and reduce the transportation costs. The literature review showed that some researchers were also focusing on the damage to infrastructure created by water and sediment flow (Sosa-Pérez and MacDonald 2017; Kalantari et al. 2017). The priority areas were mapped as for the first and second scenarios, and also divided according to sediment yield thresholds into sub-scenarios Roads1 and Roads10.

Cost comparison for the prioritization scenarios

Finally, the scenarios were compared in terms of their costs per hectare, the total cost, and the cost per Mg of erosion avoided. We used available values in the literature to calculate the application costs and hand-applied straw mulch erosion (Prats et al. 2014; Fernandez and Vega 2014); and included a penalty factor per meter of distance from roads to the selected area, to reflect the accessibility of mulching areas (1 €/m distance).

Results

Interviews with experts

The differences among the participants' answers were largely dependent on their field of expertise and their geographical location. For example, the two interviewees from the US were experienced with other types of resources, procedures, and priorities. However, they expressed many common opinions with their European colleagues, especially those that have experience with mulching in operational terms. One thing they commonly believed is that it is important to follow predefined protocols to target areas for application. The protocols include on-site factors (mainly soil burn severity indicators and slope degree), as well as off-site ones (protection of water reservoirs and vital road infrastructure were mentioned).

Results per criterion

The final arrangement of criteria is presented in Table 1. The importance of the **cost** criterion was not rated very high by the participants through the pairwise comparison process (Fig. 3), and the weights calculated from the comparison matrices gives only 7,7%.

All participants stressed the importance of **timely** application of mulch, as reflected by the criteria weighing (23,7%). Most of the interviewees specified that it is important that mulch is applied before the first major rainfall event after a wildfire to be effective at reducing erosion. The practical difficulties in achieving this were underlined by some participants; the material must be sourced, processed, and spread in time. Parameters that play an important role in the process are material type (weight, source proximity, volume), the structure of the operation (preparedness and workforce expertise), and legal procedures (permissions, financial aids).

All interviewees expressed the opinion that mulching is one of the most **effective** techniques for reducing erosion because its effectiveness (Fig. 3). Effectiveness weight (27,6%) is the highest among the criteria. They were generally in line with literature (Table 1) in the following points: (i) the effectiveness of mulching largely relies on the proportion of ground that is covered, and therefore, the main parameters in the erosion reduction process are the mulch application rate and decomposition rate; (ii) the duration in which the mulch provides the necessary cover is related to its decomposition rate and its capacity to remain on-site, i.e. its longevity.

The **longevity** criterion for most interviewees is embedded within effectiveness (Table 1), and its weight was 6.8% (Fig. 3). The experts that had a high level of technical knowledge reaffirmed the literature on this topic. Mulch materials can be removed by wind if the material is very light, as in the case of the straw, or can be removed by concentrated surface runoff. The shape and weight of the material are important parameters in this regard, and straw, wood-residue mulches or needles have different advantages. For example, Participant 2 stressed that needles from coniferous trees are resistant against transport by water because of their shape. But overall, mulch is mainly removed because of its natural decomposition, which relates to the climatic conditions and the chemical properties of the mulch material.

All participants agreed that when machinery is used to collect or spread material the risk of **compaction** must be considered. Some participants mentioned some ways to alleviate the risk: (i) use light machinery, (ii) apply mulch on skid trails after the machine passes on forest soils, (iii) limit the compacted area by designing the paths used by the machine beforehand. Since there are ways to alleviate the risk of compaction, and the score on the matrix is very low (4,9%) the criterion is subtracted from the final list (Table 1).

Post-fire mulch is not often linked to **carbon storage**. Participant 12, spoke with emphasis on the importance of Carbon to Nitrogen ratio (C:N) and the mulch material decomposition time for the communities of soil biota. According to literature (Table 1), response of the communities of soil biota is very complex, but species have developed traits and behaviors for increased fire resilience. Despite the varied responses, restoring soil biota and soil organic matter levels are important tasks in the field of forest restoration. Participant 3 emphasized the importance of the soil carbon storage levels. Since the weight of this criterion is not very low (11.9%), and there is an ongoing debate amongst the experts, it remains on the list. However, its name is changed to "Effects to soil organic matter" to include all aspects related to the carbon and nutrient content of the soil.

Table 1 Criteria selected for the mulching techniques, indicators and related references supporting the selection of the criteria by the experts

Selection criteria for the mulching techniques		Indicators	References
Technical	Cost	Cost of material	MacDonald and Larsen (2009), Prats et al. (2014), Fernandez and Vega (2014)
		Cost of labor	
		Cost of transport	
		Cost of equipment	
	Time needed for implementation	Accesibility of material	
		Accessibility of experienced workers	
		Accessibility of equipment	
		Time needed for application	
	Effectiveness in reducing erosion	Ground cover (Short-term effect)	Prats et al. (2014), Robichaud et al. (2013a, b, c)
		Longevity (Long-term effect)	Fernández et al. (2011), Girona-García et al. (2021), Fernández et al. (2016), Robichaud et al. (2013a, b, c), Robichaud et al. (2010)
		Compaction (EXCLUDED)	Prats et al. (2019b; 2021b)
Other environmental effects	Effects on soil organic matter (SOM)	Soil disturbance levels	Barreiro and Díaz-Raviña (2021), Barreiro et al. (2016), Lopes et al. (2020)
		Protection of SOM from erosion	
		Accelerating/ decelerating restoration of previous population-diversity levels of soil biota	
	Enhancing growth of invasive vegetation	Spread of exotic or invasive seeds	Hunter et al. (2006), Kruse et al. (2004), Robichaud et al. (2013a, b, c); Fernández and Vega (2014)
	Supress vegetation growth (EXCLUDED)		Kruse et al., (2004), Dodson and Peterson, (2010), Prats et al. (2022)
Social	Institutional facilitation	Funding opportunities	Lichterman (2009), Prats et al. (2022), Ribeiro et al. (2020), Robichaud et al. (2000), Ryan et al. (2009)
		Facilitation by regulations	
	Social acceptance and willingness to participate	Communication between stakeholders and agency-community relations	
		Knowledge sharing between experts and public	
		Compatibility of technique with land use	
		Conflicts for the use of material	

The criteria that were discarded from the list, as well as the indicators and references were also shown, as it was the case of compaction and supress vegetation growth

Most of the experts experienced in an Iberian context expressed that the **risk of enhancing invasive vegetation** species is not of considerable importance. However, the interviewees with experience from the US stressed that this is an important matter when treating burned forests. For example, Participant 4 emphasized that some agricultural mulches may contain unwanted seeds, especially invasive grasses, that are bad quality forage and might unbalance the biodiversity in natural areas. Some studies conducted in the US (Table 1) agree with the interviewees that were concerned about this effect of mulching. Overall, this criterion is significant when an area targeted for mulching application has a biodiversity status that is considered vulnerable or protected. In that case the mulch material should be chosen carefully, for example it could be purchased with a certification that the material is free of weeds, pesticides etc. The weight

Fig. 3 Criteria weights as calculated from the comparison matrices. The consensus among the participants is 68.8%. According to the classification found at (Goepel 2018) that is a moderate consensus level
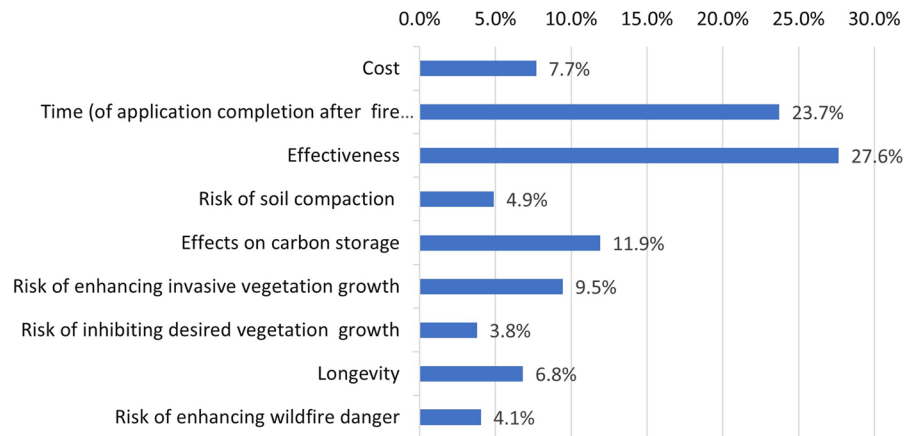
of this site-specific issue on the matrix is not very low (9.5%), and the criterion remains on the final table.

Although not stressed by any of the interviewees, there are some studies which argue that mulch can **suppress vegetation growth (**Table 1**).** Since the more recent and more numerous studies argue that there is no negative effect as long as the application rate is within certain levels (Dodson and Peterson 2010; Prats, Sierra-Abraín, et al., 2021), the criterion is subtracted from the list. That is in line with its low weigh on the matrix (3,8%; Fig. 3).

None of the interviewees confirmed that there is a **risk of enhancing wildfire danger** by mulching burned land. Furthermore, it seems that there is no published study relating to fuel increase through mulching. Taking this into consideration the criterion is subtracted from the final list. Its weight from the comparison process was 4,1%.

A common idea among the participants was that **knowledge sharing activities** are urgently required; the established views and practices cannot change until knowledge sharing occurs amongst experts, administrators, landowners, and other stakeholders. In the case of mulching, this is important because the concept of mulching challenges long-established land management practices. Also, erosion is not considered a priority issue in some areas, given other more direct and visible stressors faced by rural populations. Most of the participants mentioned **additional social criteria** such as (Table S7):

1. Institutional facilitation: the level in which governmental institutions facilitate the communities, landowners, associations, etc., to achieve a higher

societal and technical capacity for the optimal implementation of restoration measures. That includes funding opportunities, facilitation by regulations, legal frameworks etc.

2. Social acceptance and willingness to participate: the interest and willingness of people directly involved to take part in decision-making, planning, supervision, implementation, and monitoring of the measures. To achieve a great acceptance and willingness to participate, on- and off-site effects need to be understood, as well as the requirements of its application. It also involves the capacity to voice views and interests via organized groups such as associations, local initiative groups etc.

Building prioritization scenarios

Erosion rates on the soil, water, and road scenarios

The estimated soil erosion rates by the RUSLE model are shown in Fig. 4. Most of the landscape (95% of the case study) is estimated to have erosion rates below 1 Mg ha^{-1} year^{-1}, and only 3% of the landscape is estimated to have rates of erosion between 1 and 5 Mg ha^{-1} year^{-1} (Table 2). The most erosive classes correspond to a much smaller proportion, amounting up to approximately 800 hectares. In the case of sediment export to the stream network, 96% of the case study area is estimated to have sediment export rates lower than 1 Mg ha^{-1} year^{-1}, and still 98% when it comes to regional roads.

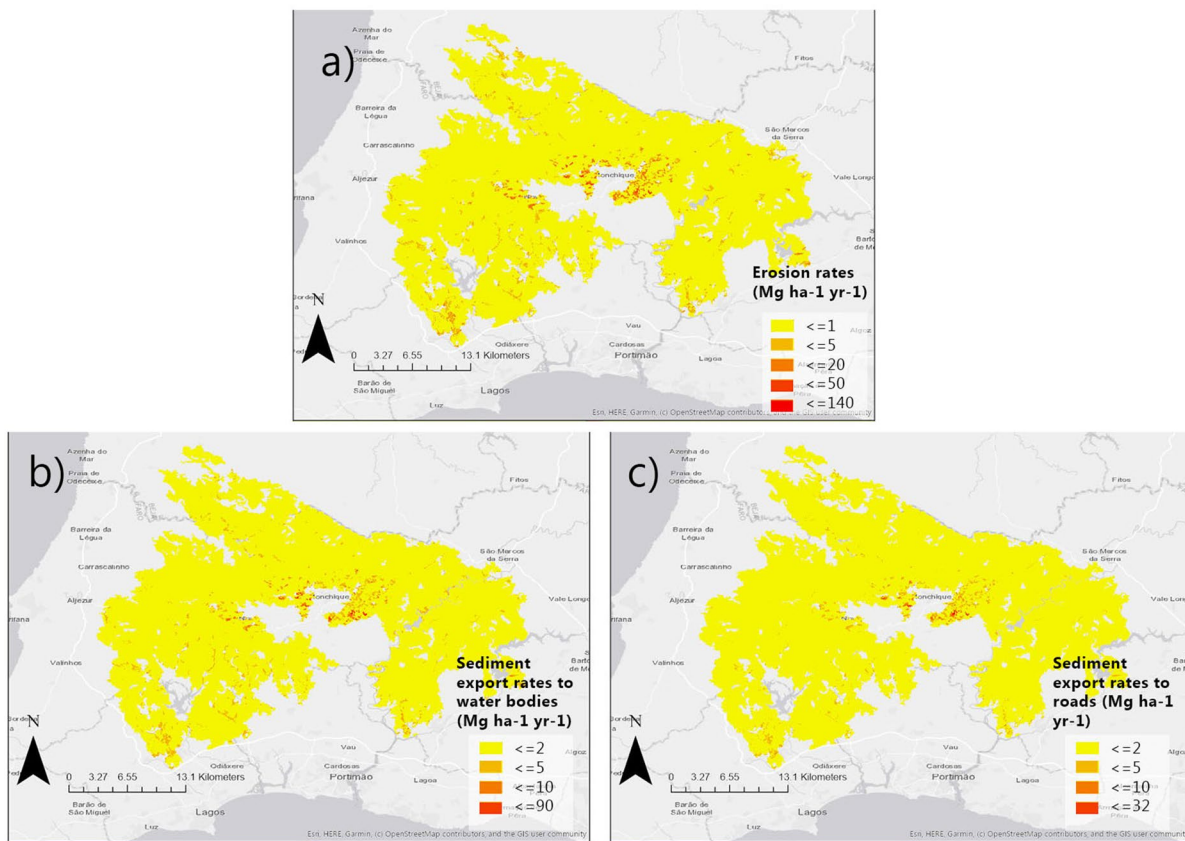**Fig. 4 a** Spatial distribution of soil erosion rates (Mg ha^{-1} year^{-1}) calculated using RUSLE in the Monchique landscape. **b** Spatial distribution of sediment export rates to water bodies calculated using IC. **c** Spatial distribution of sediment export rates to roads calculated using IC

Table 2 Size of the eroded area, in each of the five erosion classes (following a rounded Jenks natural breaks classification method) for the soil prioritization scenario (which shows soil erosion at the pixel scale) as well as for the Water and Roads prioritization scenarios (which shows sediment exportation to the water bodies and road network, respectively)

RUSLE soil erosion class (Mg ha^{-1} year^{-1})	Size of the eroded area (ha)				
	< 1 Mg ha^{-1} year^{-1}	1–5 Mg ha^{-1} year^{-1}	5–20 Mg ha^{-1} year^{-1}	20–50 Mg ha^{-1} year^{-1}	> 50 Mg ha^{-1} year^{-1}
Soil	59,545	1782	744	61	2
Water	59,852	1824	249	56	1
Roads	60,759	1064	130	27	6

Targeted areas

The erosion estimated for the prioritization scenario Soil1 was less than half the erosion of scenarios Water1 or Road10; and erosion in Soil10 was 65–63% lower than scenarios Water10 and Roads10 (Table 3). Consequently, the areas prioritized by the scenario Soil1 are approximately 3 times larger than those of Water1, and 5 times larger than those of Roads1 (Fig. 5). When the threshold increase to 10 Mg ha^{-1} year^{-1}, the median

Table 3 Median erosion rates, average size (ha) slope (%), distance from water bodies and distance from roads from each prioritization scenario

Prioritization scenarios	Median erosion ($Mg\ ha^{-1}\ year^{-1}$)	Size (ha)	Slope (%)	Distance from water bodies (m)	Distance from roads (m)
Soil1	4.0	1064.0	19	381	955
Soil10	13.6	134.8	31.7	445	355
Water1	8.1	379.8	26	348	510
Water10	38.7	4.5	43.5	209	316
Roads1	9.9	197.7	29.3	491	190
Roads10	37.0	4.4	48.1	642	139

erosion in Soil 1 increases by one order of magnitude as compared to Soil10, while the size sharply decrease, the Soil10 being 7 times smaller than Soil1, although 30 times larger than scenarios Water10 or Roads10.

Moreover, Fig. 5 shows some overlap between the areas with a low (Soil1, Water1, Road1) and a high threshold (Soil10, Water10, Roads10) and Soil10. This degree of spatial complementarity between targeted areas (i.e. their overlapping extent) was illustrated in the Venn diagrams of Fig. 6. The Water1 and Soil10 scenarios are almost entirely overlapping (127 ha), but the same is not true for Roads1 and Soil10 (only 97 ha, or 50% of the area on Roads1) and Water10 and Roads10 (only 1.3 ha, or 30% of the area on Water10).

Cost comparison

The least expensive prioritization scenarios, with estimated costs of only 3600–3000 €, were Water10 and Roads10, due to their smaller area of application, of only 4 ha (Table 4). However, these scenarios attained the highest cost-effective relations (only 23–19 € per Mg of soil not eroded), because they were the most erosive scenarios (38–37 $Mg\ ha^{-1}\ year^{-1}$) and the nearest to the road network (316–139 m; Table 3). The cost-effective relations for Roads1 and Soil 10 were intermediate (70 € per Mg of soil not eroded) and the least cost-effective were Water1 and Soil1 (139–404 € per Mg).

Discussion

Decision-making biophysical and socioeconomic criteria appropriate to define "optimal" mulching practices

There is a high level of agreement amongst the interviewees about the fundamental importance of **technical criteria,** which sum up to 60% (Fig. 3) and was composed by the **effectiveness** of the technique at reducing erosion, the **time** needed for application and its economic **cost**. The translation of the effectiveness criteria into the modelling exercises was carried out by prioritizing scenarios with (i) the best chance for effectiveness, which consisted of areas with fire severity above moderate-high (as low and moderate severity areas might receive a needle carpet from the unburned canopy), (ii) the strongest hydrological connection to water lines or roads, (c) the highest potential for erosion and sediment exports.

The interviewee responses resonated with the conclusions of previous studies: erosion rates are directly dependent on the soil cover, which means that the greatest losses happen in the first post-fire year (Fernández et al. 2011; Robichaud et al. 2013a, b, c; Prats et al. 2014; Girona-García et al. 2021). Therefore, if mulch application is not timely, the effectiveness of the technique will not be perceived. That

Fig. 5 Results for the selected sub-area: **a** Erosion rates as calculated using RUSLE, **b** Soil, **c** Water, **d** Roads prioritization scenarios, (Blue: Soil1, Water1 and Roads1 scenarios; red: Soil10, Water10 and Roads10 scenarios)
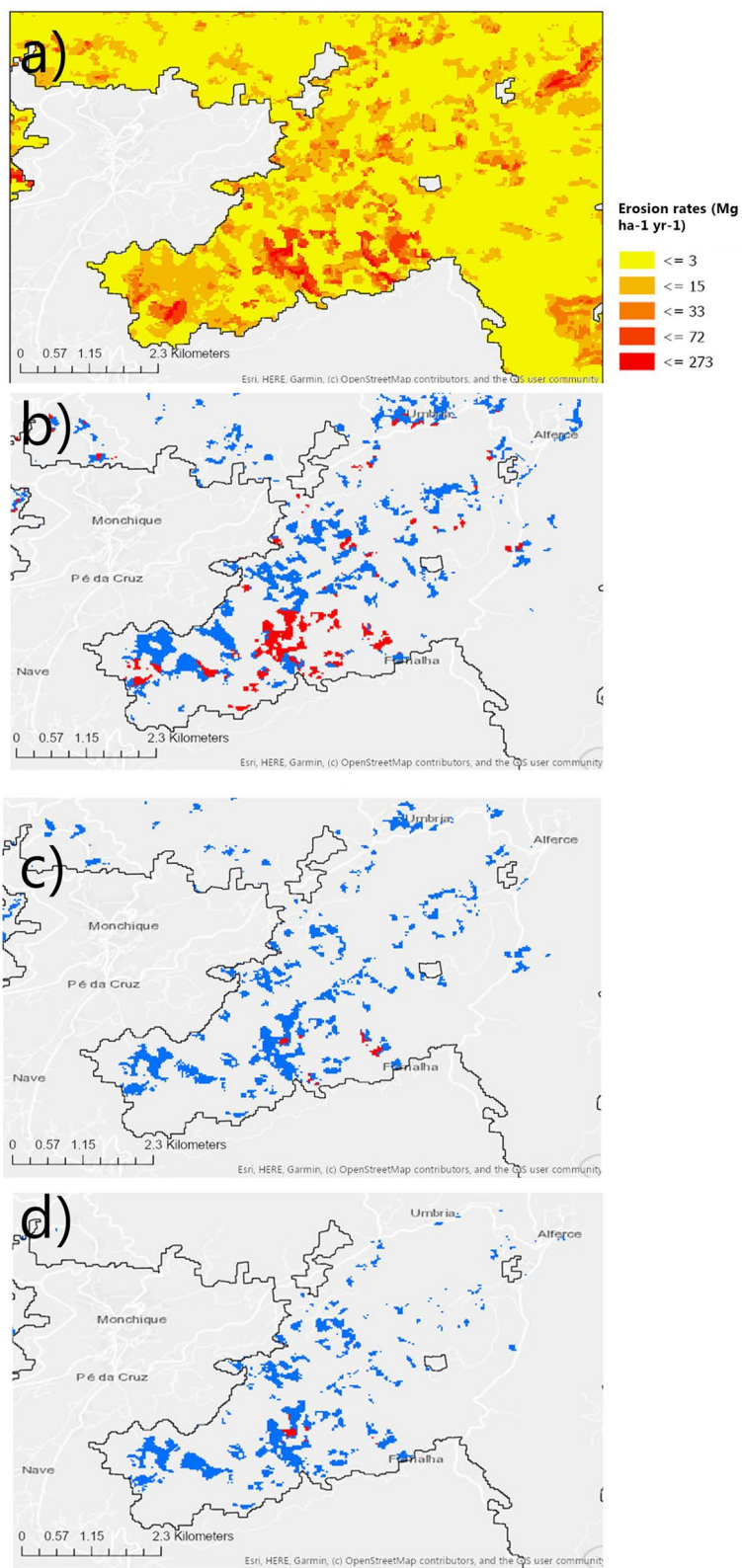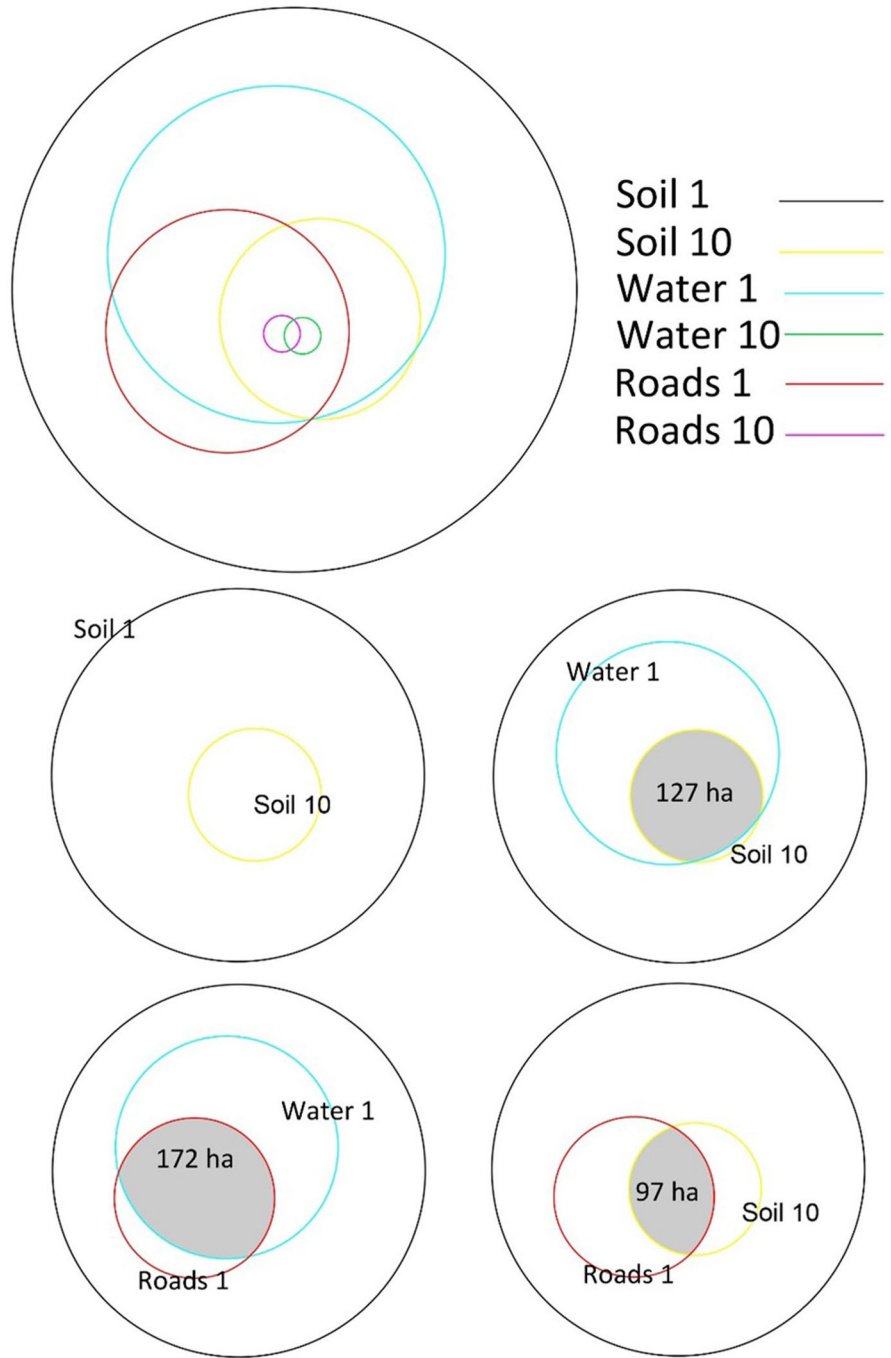
Fig. 6 Venn diagrams showing the size relations, i.e., the overlapping extent between targeted areas

would affect the social criteria and further impede the application of effective measures. Effectiveness and time criteria scored the highest, while cost, on the other hand, scored lower than expected in the comparison matrix (7.7%). This can be partly explained because many experts perceived the technique's costs as secondary in comparison with the benefits of alleviating post-fire erosion. The cost of application can be seen as a trade-off for the benefits that could also be expressed, directly or not, in financial terms (Mavsar et al. 2012). For example, for a forest association or an individual landowner the benefit could be

Table 4 Estimation of costs of each prioritization scenarios, considering the size and median erosion rates for the first post-fire year in Table 3), the hand-applied straw mulch application costs at a rate of 2 Mg ha^{-1} described in Prats et al. (2014) and an erosion reduction of 90% (Fernandez and Vega 2014)

Prioritization scenario	Costs (Total)	Cost (per surface)	Mulch application cost	Distance penalty factor (1 € per m)	Mean erosion reduction (at 90%)		Costs per Mg of erosion reduced
	€	€ ha^{-1}	€ ha^{-1}	€ ha^{-1}	Mg ha^{-1}	Mg	€ Mg^{-1}
Soil1	1,546,665	1455	500	955	3.6	3827	404
Soil10	115,263	855	500	355	12.2	1650	70
Water1	383,679	1010	500	510	7.3	2769	139
Water10	3672	816	500	316	34.8	157	23
Roads1	136,406	690	500	190	8.9	1761	77
Roads10	2837	639	500	139	33.3	148	19

in the form of subsidies. Moreover, actors responsible for water quality could benefit from the reduction of cleaning costs. There are published examples that provide methodologies of economic loss assessments (Morton et al. 2013; Thomas et al. 2016). Finally, it should be noted the BAER database provides tools for carrying out cost–benefit analyses of post-fire rehabilitation practices, either on land, channels or roads (Robichaud et al. 2007a, b).

Regarding the **environmental side-effects**, the perspectives varied on the focus of mulch application. Some stressed that mulch is applied to alleviate the short-term impact of erosion. This is mainly related to threat to life, property or water sedimentation. Other participants highlighted the long-term benefits of reducing erosion as well. Those are, for example, enhancing soil fertility, carbon sequestration, restoring soil biota communities, etc. Some participants noted that the long-term effects are linked to increase of ground cover and characteristics of mulch material. Overall, the environmental effects that scored higher were: Effects on carbon storage (11,9%) and Risk of enhancing invasive vegetation growth (9,5%). The latter's importance is highly case-specific, which is in line with existing literature (Kruse et al. 2004; Hunter et al. 2006; Robichaud et al. 2013a, b, c). Furthermore, more criteria were mentioned during the interviews that were related to the effects on **carbon** storage. For example, one participant elaborated on the role of mulch on soil **biota**, and these opinions were funded in an important body of research (Barreiro et al. 2016; Barreiro & Díaz-Raviña, 2021; Certini et al. 2021). A second example is related to the decrease of **soil fertility** after wildfires. Three

participants elaborated on how mulching could restore soil organic matter, which is in line with recent literature on mulching benefits on soil organic matter (Prats et al. 2019a, b).

It seems clear to all the interviewees that the main reason for applying post-fire mulching is to reduce erosion by increasing ground **cover** (see "Results per criterion" section). Even the long-term advantages of mulching are based on its erosion reduction potential. Although mulching can have unwanted environmental effects, the participants did not strongly emphasize these issues. Overall, the criteria concerning **wildfire risk** enhancement, **risk of compaction** (Prats et al. 2019b) and risk of **inhibiting desired vegetation** growth (Dodson & Peterson 2010) were either rejected or given low importance by the participants, mainly because there are techniques to alleviate these negative impacts.

As for **social criteria**, there was a general agreement that socio-political dimensions of land management, such as land tenure, land abandonment, land exploitation activities, etc., represent barriers to implementation of mulching practices. For example, when burned areas are located on private property, the process of mobilizing and facilitating the landowners to engage in soil restoration activities are an obstacle to timely implementation (Valente et al. 2015; Ribeiro et al. 2020). As noted by one participant, this is exacerbated by the fact that post-fire erosion is often not considered as a major problem by stakeholders since the communities affected face a lot of other issues that they tend to prioritize. As far as the application of mulching in Portugal goes, Keizer et al. (2018) argued that the main barriers against

mulching implementation are its costs and the lack of familiarity with post-fire mulching. These issues are prominent since most land in Portugal is private (Ribeiro et al. 2015). However, some examples exist where local stakeholders organized themselves, with the help of local administration, to plan and implement large scale mulching and planting activities in a burnt area (Prats et al. 2021a, b). The study of Ryan et al. (2009) about the perception of stakeholders on post-fire management suggests that these differences in community engagement can be explained by the impacts of the fire itself, but also by other factors such as the community's dependence on the burnt resources, existing history of cooperation or conflict, and the involvement of individuals in public affairs. Institutional facilitation and social willingness to participate summarize the "social capacity", defined as "people's ability to work together to organize public relationships, rather than give responsibility for those relationships wholly to state actors or the flux of market exchange" (Lichterman 2009). This concept can explain the differences found between active or passive social groups to develop and apply post-fire restoration measures.

One drawback into our expert assessment method can be the small number of interviewees. We stopped to carry out interviews because interviewees were proposing experts who were already interviewed, so we reached satisfactorily the final step, with a sample volume of 16. This value, however, is in the range of other studies using the snowball methodology reported in Tongco (2007), which ranged from 2 to 270. Other drawback is that the participants had similar viewpoints and educational direction. They are almost all researchers in the wider field of environmental management. The results would possibly be more divergent if people from communities, private companies, or local administration were interviewed. A second methodological weakness is that the interviewees were free to remove or add criteria to the table, and some did not have the necessary specific technical experience or knowledge about the case study to fill in the cells of the tables. Finally, some criteria are intertwined to such a degree, that one cannot be imagined independently from others. A way to overcome this is through visualizations of relationships between criteria. Future research should try to extract a fixed set of criteria for subsequent numerical analysis, which would provide a transparent

argumentation for a subsequent Multi-Criteria Analysis (Lindfors 2021).

Selection of prioritization scenarios

The costs of the scenarios with the highest erosion/sediment export threshold (10 Mg ha^{-1} year^{-1}) ranged between 19 and 70 € per Mg of soil saved (Table 4), in line with the range of MacDonald and Larsen (2009), who calculated 47–86 $ (approx. 43–79 €) per Mg of soil saved by hand application using dry straw mulch). However, the ones with the lowest threshold (1 Mg ha^{-1} year^{-1}) were more expensive, between 77 and 404 € per Mg of soil. The total costs of Roads1 and Soil10 (115, 000–136,000 € for the entire Monchique wildfire) are still below the expenditures of land interventions in the USA (270,000-300,000 $, approx. 248,000–276,000 €) per wildfire (Robichaud et al. 2014). The total costs of scenario Water1 (380,000 €) represents a situation similar to these USA expenditures per wildfire, but it is still low if we calculate the expenditures of land intervention per hectare of burnt soil, which is only 5 € per hectare, as compared to the 60–40 $ (approx. 55–36 €) per hectare of burnt soil in the USA. In fact, the Portuguese ICNF suggested an expenditure of 4.1 million € in the recent Monchique 2018 wildfire emergency report, affecting 53,000 ha (https://www.icnf.pt/api/file/doc/b324f8e41c231899), which corresponds to 71 € per hectare of burnt soil, very similar to the USA scenarios, and to the Soil1 scenario.

It is not easy to select a scenario, but the actions taken should be addressed as cost-effective as possible. If the managers would decide to mulch areas of high sediment export to water bodies (Water10), they would significantly minimize the area of mulching application. But if the managers decide to mulch areas of high sediment exportation to roads (Roads10) they would both significantly minimize the area and the distance to reach these areas, which will reduce the mulch application cost and rise the cost-effectiveness relation. Still, both options can also be selected, as the areas of Water and Road scenarios have a small degree of overlap (Fig. 6). Water bodies are natural sinks for the sediment and water running-off from hillslopes, and they are longer and more present in the landscape than regional roads. However, as the roads segments in areas burnt at high and moderate severity use to be connected to the streams (Sosa-Pérez and

Macdonald 2017), these exceptionally high rates of road–stream connectivity should be considered when selecting the target areas. A scenario focused on soil protection with a high erosion threshold (such as Soil10), would not sufficiently address protection of water bodies or roads from sedimentation (Sosa-Pérez and Macdonald 2017).

The use of Sediment Delivery Ratio (SDR) to select target areas for restoration has been successfully assessed only by two studies (Almeida and Cabral 2021; Gashaw et al. 2021). However, the model is sensitive to the calibration parameter K, so calibration of the model is needed (Gashaw et al. 2021). We did not calibrate the results of the SDR model, but the erosion rates magnitudes seemed to fit the ones carried out with RUSLE. Another issue involves the use of Sediment Conectivity (**IC**) for area prioritization. When erosion mitigation measures are planned in an area, IC must be run again, because the C-factor in the IC calculation changes. Mulched areas will deliver very few sediments to points downstream, which will reduce the sediment exportations. Future research should explore how a specific measure impacts sediment exports to points downstream, and if it can be modelled accurately.

Another weakness of the methodology is related to the calculation of ground cover, used as a proxy for **burn severity**, and then used to calculate the C-factor. In practice managers use quantitative and qualitative indicators derived from field surveys to measure burn severity (also called fire severity, or soil burn severity) (Robichaud et al. 2000; Robichaud et al. 2013a, b, c; Fernández and Vega 2016) or also remote sensing methods that need, of course field validation (Robichaud et al. 2007a, b; Parsons et al. 2010). Recent research links remote sensing information to burn severity levels using models (Rozario et al. 2018). Although these models also need to be validated via fieldwork, they will, hopefully, accelerate the process of gathering reliable burn severity information.

How and where: towards an optimization of post-fire emergency response measures

The timely implementation of these measures has often been compromised by the lack of methodologies to carry out a rapid diagnosis for the selection of target areas with high soil erosion after wildfires. Soil erosion modelling arises as a powerful tool, providing crucial information to support decision-making (Parente et al. 2022). The answers to the first research question ("how") yield results which could be used for a spatial multi-criteria decision analysis (MCDA), which is often used in the field of environmental conservation and management (Krois and Schulte 2014; Vogler et al. 2015; Terêncio et al. 2018). Future research should focus on spatial MCDA to create a "suitability map" to measure the application of each criterion. Further research is also needed to develop tools to quantify the effects of wildfire on hydrological services, soil fertility, etc. as well as to compare the cost-benefits of erosion prevention measures (Barbati et al. 2010; Pastor et al. 2019).In general, the use of modelling and weighted criteria helps to incorporate different objectives in area prioritization processes. Especially when models are simple and straightforward, such methods could promote engagement and communication between various stakeholders who might not be experts in land management or soil physics.

Finally, the findings of this study demonstrate the need to enhance preparedness for implementing post-fire emergency stabilization measures. A large part of the procedures could already be completed in fire prone areas. Such procedures include preparing labor, equipment, material availability, and preparing maps and datasets for erosion modelling. Until today, when land managers or other experts address preparedness, they often refer to extinguishing or regulating the fire itself, or emergency practices such as evacuation from burning areas (Monroe et al. 2006; Ryan and Hamin 2008; Mccaffrey 2015). Our study brings forward proposals that can be helpful to manage water quality protection. It is better to identify and map contaminants present in fire-prone landscapes before any fire event, because the subsequent water pollution will depend on the transport pathways and chemical properties of the contaminants (Nunes et al. 2018). Therefore, if managers have this information, they can couple it with modelling results and apply appropriate sediment delivery thresholds to prioritize areas for measure implementation. The results can be used as criteria maps in a MCDA or cost–benefit analysis as described above. That would make the process of protecting water bodies efficient and straightforward with minimal fieldwork or further consultation from scientists.

Conclusion

The conclusions of this research about the optimization of the application of post-fire mulching by using decision-making criteria to select "how" and "where" the technique should be used, and specifically, about which is the optimal prioritization scenario are as follows:

- The participants agreed on the fact that the most important factor is the effectiveness of post-fire mulching in reducing erosion, because **it increases ground cover.**
- To minimize erosion, mulch must be **placed promptly**, before the first major rainfall event and remain on site until vegetation provides sufficient cover.
- The participants agreed on the fact that **knowledge sharing activities** are urgently needed, because the concept of mulching is challenging due to long-established views and practices of land management and because mulching has not yet been widely implemented in time, especially in Europe. The social context should not be underestimated as an influencing factor. Researchers and decision-makers should keep in mind the community connection to the area, conflicts between stakeholders and the level of volunteerism of the fire-affected communities.
- The differences among the participants' answers were dependent on their field of expertise, their academic or "operational" point of view, and their location. Some participants stressed that mulch is applied to alleviate the **short-term** impact of extreme runoff, while others highlighted the **long-term benefits,** but in general, they did not express a strong opinion against post-fire mulching.
- Overall, the Soil scenarios prioritized 1064 ha and 135 ha, respectively for the thresholds of tolerable erosion of 1 and 10 Mg ha^{-1} year^{-1} (Soil1 and Soil10). The Water scenarios prioritized 380 and 4.5 ha and the Roads scenario prioritized 198 and 4.4 ha, respectively. This study found that **the only scenario that protected both water and roads from sedimentation was Soil1, which prioritized an area 3 times larger than the Water1 scenario, although cost 4 times more**. The overall results showed that a target-based model is important to efficiently specify the areas for mulch treatment, and that a mix of scenarios such as Water 10 and Road10 should be assumed as the minimum and more cost-effective post-fire intervention.
- **The scenarios at 10 Mg ha^{-1} year^{-1}** (Soil10, Water10 and Road10), although very cost-effective (19–70 € per Mg of saved soil) were limited by its very small size, (total costs of 2800–115,000 €).
- These costs represent about 0.05 € per each wildfire-burnt hectare, which is still far from the 36–71 € present day expenditures for Portugal and USA. This indicates that a sum of scenarios Water10 and Road10 can be selected, as the areas of these scenarios have a small degree of overlapping.

The results of this study can be further translated into proactive recommendations on how to improve research and practice on post-fire mulching. A systematic literature review is probably not sufficient to close the gap of the negative environmental effects of mulching, and more large-scale mulching monitoring studies are needed. The findings of this study demonstrate the need to enhance preparedness for implementing post-fire emergency stabilization measures and to improve the cost-effectiveness of soil erosion mitigation interventions. Labor, equipment, and material availability could be prepared before a fire event. Maps of land use, contaminant presence, sensitive or valuable environmental features or infrastructure, acceptable sedimentation thresholds etc. can be prepared in advance.

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resources management, were performed by DP, SP and JPN. Validation and supervision were performed by JPN and SP. Software use and data curation were performed by JPN and DP. The first draft of the manuscript based on the MSc thesis of DP for the programme "International Land and Water Management" in Wageningen University. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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