Catena 251 (2025) 108808

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Assessing cost-effectiveness of land management measures to restore forest ecosystem services after fire using hydrological modelling and multi-criteria decision analysis

Beatriz Faria [a,b], João Pedro Nunes [a,b,*], Jantiene E.M. Baartman [a], Luís Dias [b], Jinfeng Wu [c], Sergio A. Prats [d]

[a] Soil Physics and Land Management Group, Wageningen University and Research, P.O. Box 47, 6700 AA Wageningen, the Netherlands
[b] cE3c - Center for Ecology, Evolution and Environmental Changes & CHANGE - Global Change and Sustainability Institute, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[c] China Aero Geophysical Survey and Remote Sensing Center for Natural Resources, China Geological Survey, Beijing 100083, China
[d] MED – Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Instituto de Investigação e Formação Avançada, Universidade de Évora, Pólo da Mitra, Ap. 94, 7006-554 Évora, Portugal

ARTICLE INFO

Keywords:
Forest fires
Soil erosion
Water quality
Soil and water conservation measures
OpenLISEM model

ABSTRACT

Forest fires strongly disturb key hydrological ecosystem services, such as soil protection, streamflow regulation and clear water provisioning, which can affect ecosystems and communities in burnt areas and downstream. Post-fire soil and water conservation (SWC) measures can be expensive, and their effectiveness depends on multiple factors such as the nature of the measures, the targeted areas, and the extent of their application. However, different biophysical and socioeconomic effectiveness criteria are rarely assessed comparatively. This study aims to assess the costs and effectiveness of six SWC measures to mitigate soil erosion and stream water contamination (using sediment yield as proxy): post-fire mulching with straw and forest residue, contour-felled logs, straw wattles, contour bunds and riparian buffers. It was conducted for a wildfire in 2003 in the Odiáxere catchment, southern Portugal. Costs were assessed from the literature and their validity confirmed by consulting an expert panel. Effectiveness was assessed using the hydrological and erosion model OpenLISEM. Measures were compared using a Multi-Criteria Decision Analysis, including criteria such as effectiveness, application costs, and other social costs. Four sets of criteria weights were tested, based on the individual perspectives of soil conservation experts, land managers, and water managers, as well as a combination of the three. Straw mulching was the best performing SWC measure from most perspectives, although closely followed by forest residue mulching and contour-felled logs. However, riparian buffers were the best measure from the water management perspective, with a much better performance than the others. The results illustrate how different intervention objectives affect the cost-effectiveness of each SWC measure. This approach can help forest and water managers, local administrators and environmental stakeholders with different objectives and mandates, to discuss and select the most appropriate SWC measures to mitigate the impacts of forest fires on ecosystem services according to local intervention priorities.

1. Introduction

Forests cover 30 % of the Earth's land surface and they are a source of diverse values to society, providing a wide range of ecosystem services (Jenkins and Schaap, 2018). These services influence the availability of water, regulate surface and groundwater flows, and maintain high water quality. They are also important in disaster risk reduction, including floods, landslides, and droughts (Carvalho-Santos et al., 2014). External disturbances such as climate change, forest fires, and intensive forest management may have an impact on certain hydrological functions of forests, such as the capacity to store water in vegetation and soil, the regulation of water flows, erosion and flood control, water quality, and biodiversity maintenance (Carvalho-Santos et al., 2014; Zema, 2021). Forest fires are amongst the most significant hydrological disturbances

* Corresponding author at: Soil Physics and Land Management Group, Wageningen University and Research, P.O. Box 47, 6700 AA Wageningen, the Netherlands.
E-mail address: joao.carvalhonunes@wur.nl (J.P. Nunes).

https://doi.org/10.1016/j.catena.2025.108808
Received 22 August 2024; Received in revised form 23 December 2024; Accepted 5 February 2025
Available online 12 February 2025

and affect around 4 % of the global vegetated land surface area every year (Nunes et al., 2018b).

In Europe, wildfires have higher incidence and consequences in the Mediterranean region. Between 1980 and 2017, southern European countries (Portugal, Spain, France, Italy, and Greece) were the most affected by wildfires, with Iberian countries (Portugal and Spain) accounting for 68 % of the total number of fires and 60 % of total burnt area (Calheiros et al., 2020). Mediterranean ecosystems have warm dry summers and relatively wet winters, characteristics that make this region prone to wildfires and, consequently, to post-fire soil erosion (Prats et al., 2021; Santos et al., 2015; Shakesby, 2011; Vieira et al., 2018). Wildfires are a natural disturbance in these ecosystems and a fundamental driving force in shaping vegetation dynamics. Wildfires also cause significant changes in the hydrological regime, soil erosion, and water quality degradation (Lucas-Borja et al., 2019; Prats et al., 2016; Santos et al., 2015; Vieira et al., 2014).

Severe wildfires create a highly mobile layer of ash which can contain high concentrations of nutrients, toxic metals, pyrolytic organic matter and other contaminants (Nunes et al., 2018a; Sánchez-García et al., 2023). They also often lead to a reduction in soil structure and aggregate stability, evapotranspiration, storage capacity for water retention and resistance to overland flow (Shakesby, 2011). This leads to more easily eroded soil, increased runoff, and sediment transport by water erosion, which can cause severe soil degradation over time (Föllmi et al., 2022); and can also result in the mobilization of fine sediments, ashes and associated contaminants to surface water bodies, potentially affecting water quality and disrupting the operation of water treatment systems (Nunes et al., 2018a; Paul et al., 2022; Robinne et al., 2021). There are many effective post-fire Soil and Water Conservation (SWC) measures, which promote flood control, reduction in soil loss and sediment yield, restoration of ecological functions, and the management of residual fuels to mitigate future fire risk (Zema, 2021). Some examples include mulching, which has been proven effective in reducing runoff volume and soil erosion by 50 and 90 %, respectively, with a ground coverage of 70 % (Ferreira et al., 2015; Prats et al., 2014) and log erosion barriers, which are widely used because the materials are usually available on site (Robichaud et al., 2008). However, the latter have lower efficacy, which is dependent on the log storage capacity and the intensity of rainfall events (Prats et al., 2014).

It is difficult to decide which are the most adequate SWC measures for the management of burnt areas, since different types of costs and multiple ecosystem services are concerned. However, this comparison can be supported with a Multi-Criteria Decision Analysis (MCDA), a decision-making tool applied when facing several different alternatives and conflicting criteria, characterized by the multiplicity and heterogeneity of objectives and the plurality of decision makers (Więckowski et al., 2023). It is often used to address environmental issues in rural areas, such as managing soil erosion in agricultural fields (Gebre et al., 2021), regulating catchment scale water quality (Akdogan and Guven, 2023) or managing ecosystem services in forests (Blattert et al., 2017). This type of analysis is also useful for SWC planning, as it normalizes the different criteria involved in selecting specific SWC measures, making them explicit and comparable; this holistic approach increases the rationality and transparency of the decision process (Teshome et al., 2014). MCDA has only rarely been applied to support SWC application in burnt areas; however, Petratou et al. (2023) have shown how the normalization of technical (including cost, implementation time, effectiveness), environmental (effects on soils and plants) and social criteria (such as facilitation and social acceptance) can support the selection of priority areas for SWC implementation in burnt areas, maximizing cost-effectiveness.

One of the criteria to assess each SWC measure is its effectiveness in erosion control. Soil erosion models can be valuable tools for this, although they have not been designed for post-fire conditions and, thus, need to be adapted to include fire-induced changes (Lopes et al., 2021). The recognition of wildfires as the main driver of runoff and soil erosion in burnt areas has increased the need for model-based tools to predict the consequences of a wildfire and to predict the effectiveness of post-fire mitigation measures (Vieira et al., 2018). Many models have been adapted and applied to obtain fire-induced erosion predictions (Lopes et al., 2021). These range from empirical models such as RUSLE (Vieira et al., 2023), semi-empirical models such as MMF (Parente et al., 2022), and physically-based models, including SWAT (Nunes et al., 2018b), OpenLISEM (Vieira et al., 2022; Wu et al., 2021c, 2021a) and LAPSUS (Föllmi et al., 2022). Empirical models are simpler and require few input data, whereas physically based models are more complex and data demanding; physically-based models tend to perform better than empirical models for burnt area simulation (Lopes et al., 2021).

The MMF, RUSLE and PESERA models have been successfully used to simulate the effectiveness of different SWC measures at the plot scale in Mediterranean burnt areas (Vieira et al., 2018, 2014). This small-scale application shows that these models can be adapted to predict the mitigation of SWC measures on on-site soil erosion, but the analysis of their effectiveness in mitigating off-site impacts, such as floods and water quality contamination, was not carried out. Similar model applications at the catchment scale have been scarcer (Lopes et al., 2021) but the potential of these approaches is exemplified by recent examples using numerical modelling approaches such as LandSoil (Pastor et al., 2019), SWAT (Basso et al., 2022) and the Index of Connectivity (Martínez-Murillo and López-Vicente, 2018), to assess the impact of SWC on sediment yield in recently burned watersheds. These approaches can provide model-assessed estimates of the effectiveness of different SWC to compare with other criteria using MCDA, an approach which has not commonly been used for SWC assessment in burnt areas.

The main aim of this research was therefore to compare the cost and effectiveness of six common SWC measures (straw mulching, forest residue mulching, contour-felled logs, straw wattles, contour bunds and riparian buffers) in restoring soil and water ecosystem services after a forest fire. The specific objectives were:

i. Assess the effectiveness of the measures at reducing soil erosion and sediment yield (a proxy for water quality) at the catchment outlet by using the OpenLISEM soil erosion model.
ii. Compare these effectiveness criteria with additional criteria for assessing the socioeconomic costs and benefits of these SWC measures, such as application costs, ease of application, and support for vegetation recovery, through an MCDA.

2. Methodology

2.1. Study area

The study area was the Odiáxere catchment, which is located in the Monchique mountain range, in southern Portugal (Fig. 1). This region is characterised by a hot-summer Mediterranean climate, Csa in the Köppen-Geiger classification (Prats et al., 2021). Mean annual rainfall is 624 mm with a strong seasonal pattern, with 70 % of precipitation in the autumn and winter wet season (Wu et al., 2021a). The catchment area is 18.53 km^2, with steepness ranging from 0-36 % and averaging 16 %, and elevations of 83 to 571 m.a.s.l. The two main soil types are Haplic Luvisols (LVh; 55 %) and Chromic Luvisols (LVx; 32 %) developed over ultrabasic sienite, metamorphic schist and also a portion of sedimentary calcareous rocks (Wu et al., 2021c). The study area is mostly covered by forests (69 %), composed of eucalypt plantations and Mediterranean oak forests; and shrubs (21 %) (Wu et al., 2021c). In August 2003, 78 % of the catchment area was burnt at high severity (Fig. 1), leaving the remaining 22 % unburnt or burnt at low severity (Wu et al., 2021b). After the fire, extensive soil erosion was observed in the area; and water quality in the downstream Bravura reservoir (Fig. 1) was severely impacted due to high suspended sediment concentrations (Nitzsche et al., 2024).

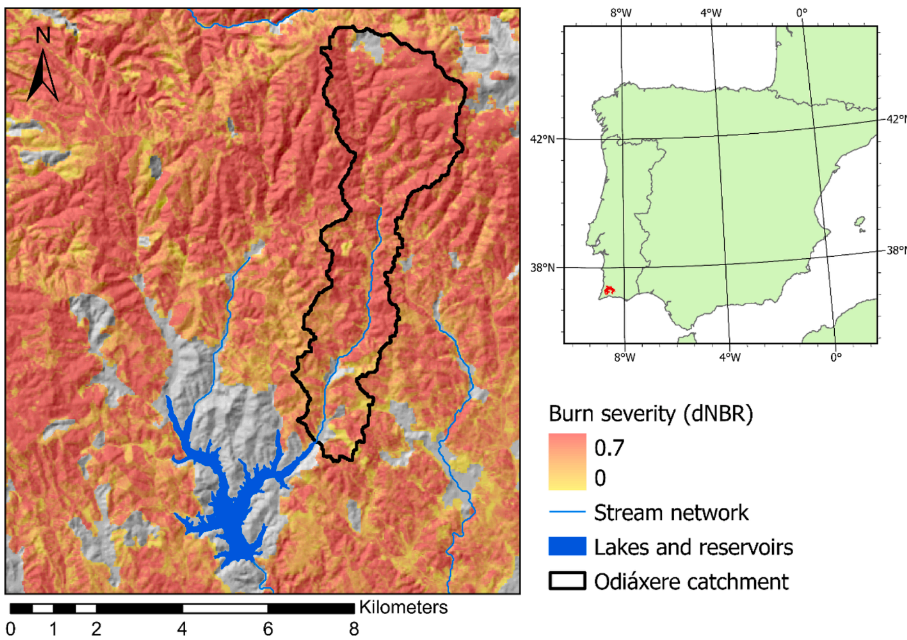

Fig. 1. Hillshade of the study area, including the Odiáxere catchment and the Bravura reservoir, overlaid with a burn severity map showing the difference Normalized Burned Ratio index (dNBR; Keeley, 2009) for the 2003 Monchique fire; values above approx. 0.3 (orange) and 0.7 (red) indicate respectively moderate and high burn severity. The insert to the right shows the location of the 2003 Monchique fire (in red) in the Iberian peninsula.

2.2. Research approach

This study assessed six SWC measures – two types of mulching (straw and forest residue), three types of erosion barriers (contour-felled logs, straw wattles and contour bunds) and riparian buffers – in restoring hydrological ecosystem services affected by fires. The following ecosystem services and indicators were considered, based on the hydrological services typically provided by forests (Carvalho-Santos et al., 2014) which would be therefore affected by wildfires:

- Soil conservation: erosion rates (through splash and overland flow) within the catchment.
- Water quality regulation: sediment yield (sediment load exported by the stream at the outlet of the catchment), used as a proxy for impacts on water quality as this is the most common post-fire contamination issue (Paul et al., 2022), including in Portugal (Nitzsche et al., 2024); it can also represent contamination with ashes and associated contaminants (Nunes et al., 2018a).

The effectiveness of the SWC measures to restore these indicators to the conditions before the fire was assessed using the OpenLISEM model (Wu et al., 2021c, 2021a). The model was applied using standardized design storms to compare the control conditions (burnt catchment without SWC measures) with two other situations: application of SWC measures, and unburnt conditions (section 2.4).

The monetary costs of each SWC measure were taken from a literature review by Girona-García et al. (2023). Additional characteristics such as measure feasibility and impact on forest regeneration were taken from an extensive measure description catalogue by the USDA Forest Service (Napper, 2006), assessed for local conditions with the help of local experts. Each SWC measure was then assessed in terms of effectiveness, costs, and additional characteristics using an MCDA (Teshome et al., 2014). This comparison was made from the perspective of different stakeholders, including soil conservation experts, land managers and water managers using priorities derived from interviews, to assess the suitability of the SWC measures for different management objectives (section 2.5).

2.3. Soil and water conservation measures

After an inventory of commonly applied post-fire SWC measures through literature review (Girona-García et al., 2023, 2021; Robichaud et al., 2000), six SWC measures were selected which prevent and reduce runoff generation and sediment detachment and transport. The measures are depicted in Fig. 2; they were applied to the entire burnt area of the catchment (1445 ha), with the exception of riparian buffers, which were applied only to an area along the river network (93 ha).

Mulching. The application of a thin layer of organic material to the soil surface has been widely studied and constitutes a highly effective post-fire agronomic measure to reduce soil and fertility losses (Prats et al., 2022, 2019; Vieira et al., 2018). Straw, plant leaves, or forest residue (wood chips and wood shreds) can be used as mulch materials to provide an alternative surface soil cover (Zema, 2021). This improves infiltration rates, hydraulic roughness, ground cover and soil quality while lowering runoff velocity, raindrop impact and soil erosion, and further preventing soil sealing (Lucas-Borja et al., 2019; Prats et al., 2016; Vieira et al., 2018). With a mulch cover of 70 % or more, runoff was found to decrease by 50 % and soil erosion by 90 % (Ferreira et al., 2015). The only drawbacks to the use of mulching are that (i) it can inhibit vegetation recovery, if the mulch layer is too thick and does not allow sunlight to reach the soil; and (ii) straw mulch can be displaced by the wind, leaving areas of bare soil unprotected from erosion. In the case of natural protected areas there is also the risk of introducing seeds of non-native or invasive weed species that come with the straw (Lucas-Borja et al., 2019; Zema, 2021). In this work, a 70 % mulch cover was assumed.

Erosion barriers. Structural measures are designed to reduce runoff velocity and increase infiltration and sediment retention by shortening the length of uninterrupted flow paths (Martínez-Murillo and López-Vicente, 2018; Robichaud et al., 2019; Wagenbrenner et al., 2006). The erosion barriers considered here include contour-felled logs, straw wattles and contour bunds. Recent studies have concluded that erosion barriers are not as efficient for soil loss reduction as mulching (Fernández and Vega, 2016a; López-Vicente et al., 2021), but they are still commonly applied in the field (Girona-García et al., 2023, 2021).

Contour-felled logs (cfl) were found to be effective in reducing runoff

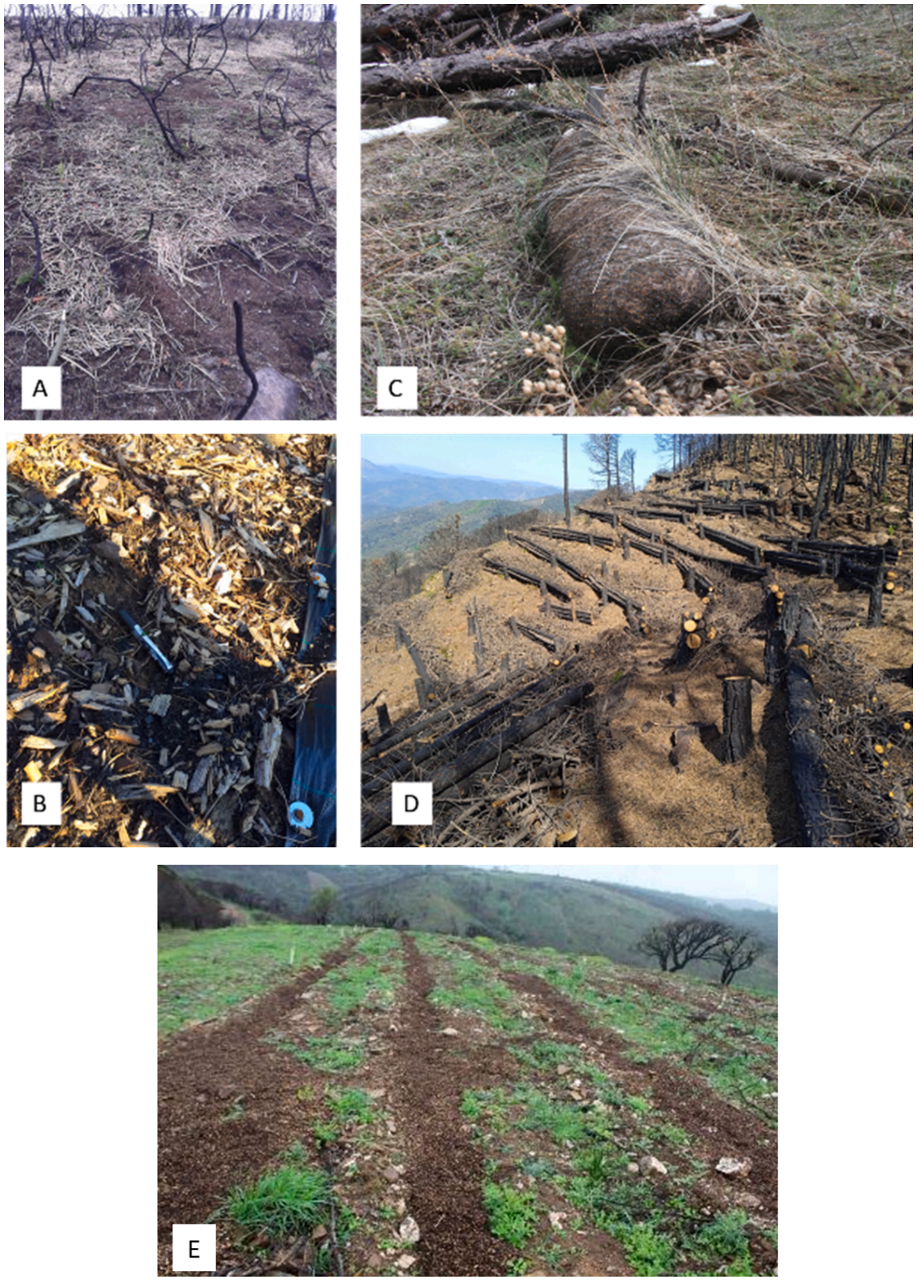

Fig. 2. Exemplification of SWC measures as applied in the field: A) straw mulching, B) forest residue mulching; C) straw wattles, D) contour-felled logs, E) contour bunds. Photos A to D by Sergio Prats and E by Florian Ulm (R3Forest).

and sediment yield in forests subjected to machinery salvage logging, if the barrier distance was less than 20 m. However, this is only true for low-intensity rainfall events, since the barriers can easily be over-topped after high-intensity rains, rendering them ineffective (Fernández et al., 2019; Zema, 2021). Recommendations for each log barrier consist of logs 3 to 6 m long, separated by 3 to 5 m gaps along the contour; the recommended distance between contour barriers is 3 m (Napper, 2006). In the Mediterranean, however, log barriers separated by 10 to 20 m have been applied (Myronidis et al., 2010). In this work, an intermediate value of 6 m separation between barriers was assumed.

Straw wattles (sw), or fibre rolls, consist of prefabricated rolls using rice straw and wrapped in jute netting. They are used where log erosion barriers are not practical, with a spacing between 6 and 15 m according to burn severity (Napper, 2006). Previous studies have considered straw wattles as being less effective than other measures in erosion prevention (Olsen et al., 2012). Despite this, they are still commonly used in the field due to their ease of application, especially in burnt shrublands where logs are not available. In this work, a spacing of 10 m between wattle barriers was assumed.

Contour bunds (cb) have been shown to increase infiltration rates and decrease runoff (de Figueiredo et al., 2012). According to Maetens et al. (2012), the expected reduction in runoff and soil loss is 67 % and 78 %, respectively. The spacing of the bunds ranges between 5 and 20 m and is dependent on the rainfall amounts and intensity, slope soil type, surface roughness and crop water requirements (Oweis, 2017). The height of the bund should be carefully designed to hold the peak storm runoff volume from the catchment (Oweis, 2017). The main disadvantages of contour bunds are the irreversible change of the shape of the hillslope after using heavy machinery, with deep changes in the vegetation and inversion of the soil horizons. In this work, contour bunds were considered to have a ditch 0.2 m deep and 0.2 m wide, spaced every 4 m, following a field experiment in this region (Uyttendaele, 2022).

Riparian buffers are meant to improve water quality, by trapping the sediments and slowing water movement, promoting infiltration, increasing nutrient uptake and storage, increasing transpiration, and promoting denitrification in the shallow subsurface (Momm et al., 2014; Tomer et al., 2009). Studies conducted in field settings have shown that 10 m and 30 m wide buffers can trap approximately 65 and 85 % of sediments, respectively (Sweeney and Newbold, 2014). However, these studies refer to fields, often bounded. When considering unbounded hillslopes or entire catchments, the trapping efficiency can be reduced due to concentrated flow paths (Momm et al., 2014). Aparício et al. (2023) have estimated a watershed-scale efficiency between 24 and 90 %. In this work, a 25 m buffer was considered following the recommendations of Sweeney and Newbold (2014), and therefore occupying around 5 % of the total catchment area.

2.4. OpenLISEM hydrological and erosion model application

The OpenLISEM (v5.97) hydrological and soil erosion model (de Roo et al., 1996b, 1996a; Jetten et al., 2003) simulates catchment-scale hydrological and erosion processes resulting from individual rainfall events using physically-based equations. The simulated hydrological processes include interception, ponding, infiltration, overland flow, and channel flow. The model can simulate both infiltration and saturation excess runoff generation. Simulated erosion processes include detachment by rainfall, throughfall, and overland flow; sediment transport capacity; and deposition. The model is spatially distributed, simulating the landscape in a raster format; and the time-step is usually sub-hourly. It has been successfully applied to simulate hydrological and erosion processes in burnt Portuguese catchments (Van Eck et al., 2016; Vieira et al., 2022; Wu et al., 2021c). Some SWC measures are already implemented in OpenLISEM, including sediment traps/fences and grass strips. OpenLISEM was parameterized, calibrated and validated for the Odiáxere catchment by Wu et al. (2021c), using information on topography, land use, soils and channels with a 25 m resolution, with a good model performance for post-fire conditions: r2 of 0.90 for streamflow, 0.74 for peak flow and 0.92 for sediment yield (with corresponding Nash-Sutcliffe Efficiency values of 0.89, 0.72 and 0.54).

In this work, the existing OpenLISEM application in Odiáxere was also parameterized and evaluated for the six post-fire SWC measures based on literature review (Table 1). Research studies were used to indicate (i) which OpenLISEM parameters should be altered to simulate the effects of the SWC measures, and the acceptable range of changes; and (ii) the effectiveness of the measures. Individual studies were used in combination with a *meta*-analysis to ensure that the measure application parameters and rainfall conditions were consistent with the effectiveness. The evaluation focused on sediment simulations due to lack of information on the impact of SWC measures on runoff.

The model was evaluated using the synthetic Design Storms (DS) built by Wu et al. (2021a) for Odiáxere using statistical information calculated for the region by the Portuguese water authorities, including intensity–duration–frequency curves for different return periods, and dimensionless design storm curves with peak rainfall occurring in different quartiles. This study used only two of the DS, both with a duration of 6 h and peak in the first half of the storm: DS2 (2 years return period) with total rainfall of 68.1 mm and maximum 30 min rainfall intensity ($I30_{max}$) of 35.8 mm/h, and DS5 (5 years return period) with a total rainfall of 87.9 mm and $I30_{max}$ of 53.9 mm/h. Either DS2 or DS5 were chosen according to the greatest similarity with the rainfall conditions used in the studies from which evaluation data were extracted (Table 1).

SWC measures were implemented in OpenLISEM using the parameters shown in Table 1. The two types of mulching (forest residues and straw) and two of the erosion barriers (contour-felled logs and straw wattles) were simulated using the same parameter values, while contour bunds (an erosion barrier) and riparian buffers were simulated with unique values. Model performance with SWC measures was assessed in terms of measure effectiveness, i.e. the decrease in sediment mobilization and transport after implementation when compared with untreated postfire conditions. Since most studies refer to relatively small plots and single hillslopes (Girona-García et al., 2021) but the model generates maps, model performance for most SWC measures was evaluated using median soil loss decrease in the entire watershed, avoiding extremes in areas of concentrated runoff. However, since riparian vegetation buffers act over sediment transport from the entire catchment, for this SWC measure the evaluation referred to sediment yield instead. Most model parameters were kept unchanged from literature values to minimize over-calibration; only the Manning's n for overland flow for barriers was calibrated since the correct literature value to use was unclear, but the calibration was kept within a strict limit (Table 1). This approach was preferred since most available information was for measuring plots smaller that OpenLISEM grid cells, and for areas with different climate,

Table 1
Values for the different parameters changed to implement the different SWC measures in the OpenLISEM model. The values for pre-fire and post-fire (untreated) are based on (Wu et al., 2021c). Values with "NA" are Not Applicable for the simulation; values with a dash were not changed from post-fire (untreated) values.

Model parameters	Pre-fire	Post-fire (untreated)	Mulching (straw, forest residues)	Barriers (contour-felled logs, straw wattles)	Contour bunds	Riparian buffers
Ground cover (%)	35	0	70	–	–	–
Manning's n – overland flow	0.45	0.07	0.17[a]	0.24[b]	0.70[b]	0.80[c]
Manning's n – channel flow	0.05	0.02	–	–	–	0.075[d]
Maximum sediment trapping volume (m^3/m^2)	NA	NA	NA	0.012[e]	0.010[f]	NA
Bulk density of trapped sediments (kg/m^3)	NA	NA	NA	1440[g]	1440[g]	NA
Saturated hydraulic conductivity (mm/h)	3.37	4.63	–	–	–	14.5[h]
Design storm used[i]	DS5	DS5	DS5	DS2	DS2	DS5

[a] Roughness coefficient for sheet flow when residue cover is higher than 20% (USDA, 1986).
[b] Calibrated using roughness coefficients for sheet flow, ranging between 0.24 (dense grasses) to 0.80 (woods – dense underbrush) (USDA, 1986).
[c] Only in buffer zone; roughness coefficient for sheet flow for woods – dense underbrush (USDA, 1986).
[d] Roughness coefficient for main channel with very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush (Chow et al., 1988).
[e] Value calculated with the dimensions of the barriers, for an average slope of 16 %; actual values were spatially modified according to local slope. The model parameter is calculated for a 25x25 m grid cell, i.e. 7.81 m^3.
[f] Calculated from the ditch dimensions of contour bunds. The model parameter is calculated for a 25x25 m grid cell, i.e. 6.25 m^3.
[g] Myronidis et al. (2010).
[h] Only in buffer zone; parameter for unburnt fluvisols estimated by Wu et al. (2021c).
[i] As defined in Wu et al. (2021a).

soil and fire conditions, and the precise measure effectiveness in the conditions of Odiáxere is therefore uncertain.

The model was subsequently applied to simulate the impact of the SWC measures on the environmental ecosystem service indicators described in sections 2.2 and 2.5. One simulation per SWC measures was conducted, using the parameters from Table 1, and storm DS5 for all measures to improve comparability. Storm DS5 has similar characteristics to the most intense rainfall event observed in the three years after the 2003 fire in Odiáxere (as reported by Wu et al., 2021b), and therefore represents an extreme rainfall event that is still likely to occur in the critical post-fire window of disturbance.

2.5. Multi-Criteria Decision Analysis

A Multi-Criteria Decision Analysis (MCDA) is a decision-support approach to conduct comparisons of multiple alternatives according to very different criteria, even when they are conflicting (Monat, 2009; Więckowski et al., 2023). MCDA has been successfully applied to help design SWC implementation approaches in complex situations with multiple stakeholders, considering their effectiveness for different goals, associated costs, and social impacts (Petratou et al., 2023; Teshome et al., 2014). While MDCA has been used to help decide the prioritization of areas to implement SWC after fires (Petratou et al., 2023), its application to help decide between very different post-fire SWC approaches has not yet been well explored.

This work followed the multi-step process described by Gebre et al. (2021):

- Formulate a problem and define objectives; in this work, the MDCA focused on limiting soil erosion and sediment transport in burnt areas (section 2.2).
- Set alternatives; this work used SWC measures commonly used in burnt areas (section 2.3).
- Select criteria and assign weights for each; this work was based on the approach by (Petratou et al., 2023) and additional works on decision-making in Mediterranean burnt areas, as defined below.

The selection and weighting of criteria followed a Multi-Attribute Decision Making approach, commonly used in problems such as this when the number of alternatives is limited and the available information has uncertainties (Gebre et al., 2021). The additive value measurement approach described by Teshome et al. (2014) was used, where the values assigned to each criteria are normalized into a common scale to allow for comparison, an then aggregated in a unified rank, with each criteria given a different weight according to the intervention objectives. This approach is not designed to identify an objective best option, but instead to make explicit the objectives and opinions of different stakeholders, and therefore help decision makers to account for them.

The selection of criteria was based on the work of Petratou et al. (2023), who derived four main criteria to assess SWC interventions in burnt areas after interviewing 16 soil conservation experts with experience in post-fire management:

- Environmental performance: the ability of an SWC measure to restore the affected ecosystem services, i.e. decrease soil erosion and sediment transport, in the short and long term.
- Cost of application: the monetary cost of applying an SWC measure through labour, materials, equipment, transport and other considerations.
- Ease of application: technical knowledge required to implement an SWC measure, speed of implementation (including gathering funding and permissions to implement), and acceptability by stakeholders.
- Support for vegetation recovery: additional benefits from the SWC measure for soil fertility (e.g. increases in soil organic matter) and promotion of vegetation regrowth.

The assessment of SWC measures for each criteria is summarized in Table 2. The following approaches were applied:

- Environmental performance: outputs from the OpenLISEM model (see section 2.4) were used to calculate the reduction in hillslope soil erosion and catchment-scale sediment yield resulting from the application of each SWC measure, when compared with the post-fire untreated conditions. The performance score was the average of both effects.
- Cost of application: unit area costs for most SWC measures were taken from the *meta*-analysis performed by Girona-García et al. (2023); the comparison was made with median costs for Portugal and/or Spain, using a 0.9 conversion rate from the original USD to EUR. Costs for riparian buffers were not available, so they were calculated form labour, material and equipment cost estimates taken from local companies. Most measures were applied to the high severity burnt area, 78 % of the total catchment area; riparian buffers, however, were applied to a 25 m buffer on each side of the stream network, only 5 % of the total catchment area. Additional information on cost calculations is available as Supplementary Information.
- Ease of application: all SWC measures were assessed according to the availability of materials for implementation, the technical expertise required to implement the measure, and the institutional and landowner support required for implementation. A rank between 1 (hard/complicated) and 3 (easy/simple) was assigned for each measure after a consultation of the SWC measures catalogue by Napper (2006), in consultation with Portuguese experts (see below); these experts were also consulted to rank the riparian buffers. The

Table 2
Criteria, units, sources, descriptions and calculations for the Multi-Criteria Decision Analysis (MCDA) used to assess the Soil and Water Conservation (SWC) measures.

Criteria	Units	Sources	Description & Calculations
Environmental performance	ton	Model output	Effectiveness in restoring affected ecosystem services, with two sub-criteria: • Erosion reduction: mitigation of soil eroded from the hillslopes (relevant for soil conservation experts and land managers) • Sediment yield reduction: decrease in sediment load leaving the watershed outlet (relevant for water managers)
Cost of application	K€	Girona-García et al. (2023)[a]	Cost per unit area multiplied by area of application: • Riparian buffers: 25 m to each side of streams • Other measures: area burnt with high severity
Ease of application	Rank: easy (3) to hard (1)	Napper (2006)[b,c]	Three sub-criteria: • Ease in obtaining materials • Required technical expertise • Required institutional and landowner support
Support for vegetation recovery	Rank: good (3) to none (1)	Napper (2006)[b]	Improvements in soil fertility and conditions for vegetation (re)growth

[a] Costs for riparian buffers were calculated separately and are shown as Supplementary Information.
[b] Interpretation of the extensive descriptions by the authors; riparian buffers were ranked separately, in consultation with local experts.
[c] Assessment of required institutional and landowner support for Portugal was based on Petratou et al. (2023).

final rank for each measure was the median of the value for each sub-criteria.

- Support for vegetation recovery: all SWC measures were assessed according to support for soil fertility and vegetation recovery using a rank between 1 (none) and 3 (good) by consulting the Napper (2006) SWC measures catalogue. Riparian buffers were not in the catalogue but were ranked as 1 (none) since they are not applied in the burnt area and therefore have no direct influence on processes there.

The assessments for criteria "Ease of application" and "Support for vegetation recovery" were discussed and confirmed with three local experts active in designing, implementing and assessing SWC measures for burnt area: an SWC expert working on academic research in burnt area erosion processes and mitigation; a forestry engineer working on implementing SWC measures in burnt areas; and a forest ecology expert working on practical projects focusing on burnt area vegetation recovery.

The values for each criterion were then normalized into a common scale. Linear normalization was used in this study, using the maximum and minimum ranges as reference values. Cost of application is a negative criteria, i.e. the higher the value of the criteria, the lower the utility of the SWC measure; it was therefore as decrease from the maximum value (Equation 1a). All other criteria are positive, and were classified as increase over the minimum value (Equation 1b).

$$a)n_{ij} = \frac{s_j^* - s_{ij}}{s_j^* - s_j^-}; b)n_{ij} = \frac{s_{ij} - s_j^-}{s_j^* - s_j^-} \quad (1)$$

where:

n_{ij} is the normalized value *i* for criterion *j;*

s_{ij} is the value *i* for criterion *j*;

s_j* is the maximum value for criterion *j*;

s_j^- is the minimum value for criterion *j*.

The selection of weights for each criteria followed the different perspectives of three stakeholder groups relevant for the region: soil conservation experts, land managers, and water managers. Weights were taken from previous work done in this region, as follows:

- Soil conservation experts: representing managers responsible for implementing emergency soil stabilisation after fires; in Odiáxere, this would be the national Forest and Nature Conservation Institute (ICNF). Weights were calculated by Petratou et al. (2023) from interviews to 16 soil conservation experts with experience in burnt area interventions (not only in Portugal).
- Land managers: representing private land owners, which is the most common owner type in Portugal (Martins et al., 2021), and managers of publicly-owned natural areas. Both these types of land ownership are present in Odiáxere. Weights were assessed by Uyttendaele (2022) from interviews to 8 land managers in Portuguese fire-prone forests, including both private and corporate land-owners, and Non-Governmental Organisations working in natural area management.
- Water managers: representing managers responsible for water supplies for local populations; in Odiáxere these would be the managers of the Bravura reservoir immediately downstream. Weights were assessed from the interviews which supported the work of Nunes et al. (2023). 8 water managers were interviewed, including both managers responsible for national-level risk management, and managers responsible for water supplies in 4 different fire-prone regions of Portugal (including southern Portugal).

Detailed information on the weighting approach and individual criteria used by each author, and how they were combined for this work, is shown as Supplementary Information. Based on these weights, four different MCDA were conducted: three from the different perspectives of soil conservation experts, land managers, and water managers; and one from the perspective of all stakeholders, using an average of the weights from the three groups.

3. Results

3.1. Model performance

The OpenLISEM results of the effectiveness of mulching, contour-felled logs, straw wattles and contour bunds in decreasing soil erosion were close to those reported in the literature (Table 3), using parameters within the range of expected values for each SWC measure (Table 1). The larger effectiveness of mulching as compared to erosion barriers is also consistent with the literature. For riparian vegetation buffers, the simulated effectiveness in decreasing sediment yield was within the range reported in the literature, but close to the lower end of the range. Therefore, and considering that the parameterization was only minimally adjusted, the model was considered to be able to simulate the impact of the selected SWC measures on sediment processes.

3.2. Model results

The model outputs for the pre-fire conditions, post-fire (untreated) conditions and the implementation of SWC measures is shown in Table 4, including the main indicators hillslope soil erosion and sediment yield, and additional explanatory model results. The six post-fire measures are grouped in four post-fire mitigation approaches. The fire caused a moderate increase in hillslope soil erosion (31 %), mostly due to an increase in splash erosion (16-fold). It also caused a large increase in sediment yield (61 %), mostly due to an increase of the sediment delivery ratio (sediment yield divided by the sum of flow, splash and channel erosion) from 0.66 to 0.85, caused by a combination of higher hillslope erosion and less sediment deposition in the channel. These changes resulted from an increase in peak streamflow (24 %) and, consequently, in sediment transport capacity. In contrast, channel erosion was lower (40 % decrease) due to more sediment entering the stream, limiting the capacity to transport additional sediment from the channel; but this change was not reflected in sediment yield.

All SWC measures led to large decrease in hillslope erosion as compared to post-fire untreated conditions, except for riparian buffers (Table 4). Mulching, barriers and contour bunds decreased this parameter by 69 %, 90 % and 71 % respectively, but only mulching was able to effectively reduce splash erosion. Fig. 3 shows where the measures took effect. Before the fire (Fig. 3a), most erosion occurred in cropland areas in the northeastern part of the catchment, and along the channel network. The fire (Fig. 3b) led to an increase in the central and northern part of the catchment, especially in the northeast where soils are more erodible (Wu et al., 2021c). Mulching and contour bunds (Fig. 3c and e) largely counteracted these increases, but erosion barriers (Fig. 3d) had only a small mitigating effect on the northeastern part of the catchment.

Table 3
Evaluation for each SWC measure, in terms of median reduction in soil loss (%) or, for Riparian buffers, reduction in watershed sediment yield (%).

	Mulching (straw, forest residues)	Barriers (contour-felled logs, straw wattles)	Contour bunds	Riparian buffers
Model values	89 %	20 %[a]	72 %[a]	32 %
Reference values	77.7 to 90 %[b]	11.3 to 55.5 %[c]	78 %[d]	25 to 90 %[e]

[a] calibrated.
[b] Ferreira et al. (2015),Girona-García et al. (2021).
[c] Fernández and Vega (2016b), Girona-García et al. (2021),López-Vicente et al. (2021).
[d] Maetens et al. (2012).
[e] Sweeney and Newbold (2014).

Table 4
Model outputs for the indicators for Environmental performance of each measure, i.e. hillslope erosion indicating soil conservation, and sediment yield indicating water quality regulation; and for additional explanatory results. All results were simulated under design storm DS5. Sediment Delivery Ratio = sediment yield / (overland flow erosion + splash erosion + channel erosion). Values between parentheses represent percentage deceases or increases as compared to the control (burnt, untreated) conditions.

Variable	Units	Pre-fire	Post-fire				
			Control (untreated)	Mulching (straw, forest residue)	Barriers (contour-felled logs, straw wattles)	Contour bunds	Riparian buffers
	Main indicators						
Hillslope erosion	ton	6406	8395	2640 (−68.6 %)	870 (−89.6 %)	2443 (−70.9 %)	8155 (−2.9 %)
Sediment yield	ton	4625	7461	2482 (−66.7 %)	772 (−89.7 %)	1562 (−79.1 %)	5076 (-32 %)
	Auxiliary results						
Overland flow erosion	Ton	6345	7376	2413 (−67.3 %)	0.6 (−99.9 %)	1795 (−75.7 %)	7251 (−1.7 %)
Splash erosion	ton	61.2	1019	227 (−77.7 %)	869 (−14.7 %)	648 (−36.3 %)	904 (−11.3 %)
Peak flow	m^3/s	116.8	144.8	136.8 (−5.5 %)	139.6 (−3.6 %)	106.9 (−26.2 %)	116.8 (−19.4 %)
Channel erosion	ton	573	345	361 (+4.6 %)	358 (+3.8 %)	376 (+8.9 %)	190 (−44.8 %)
Sediment Delivery Ratio	–	0.66	0.85	0.83	0.63	0.55	0.61

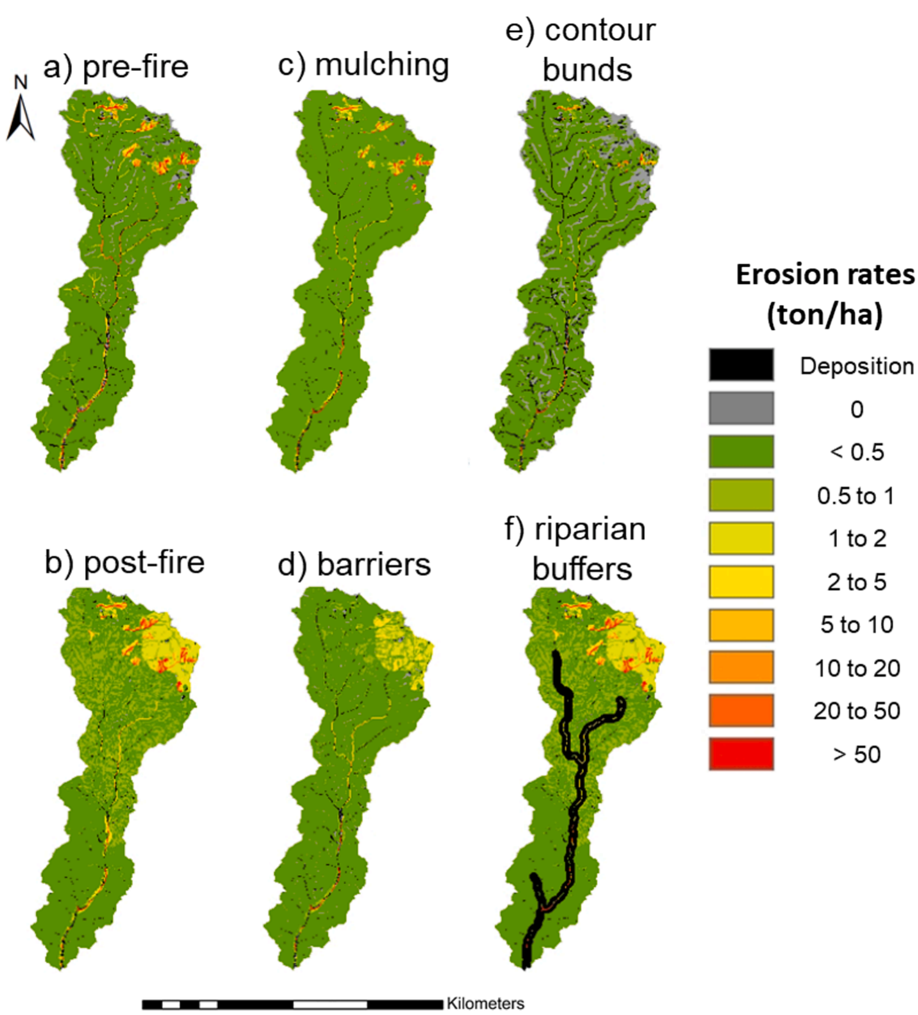

Fig. 3. Soil loss maps for pre-fire (a) and post-fire (untreated) (b) conditions; and for each SWC measure: mulching (c), contour-felled logs/ straw wattles (i.e. barriers; d); contour bunds (e) and riparian buffers (f). In black, negative values represent deposition, the grey areas represent "no change" areas and, ranging from green to red, the positive values represent erosion.

However, only erosion barriers were able to remove areas of severe erosion (red areas in Fig. 3) by limiting concentrated flow erosion. One interesting result is that all these measures also addressed some of the erosion problems that already existed in the croplands on the north-eastern part; since croplands were also burned by the fire, these measures were also applied here for erosion control.

All SWC measures also decreased sediment yield (Table 4), the barriers and contour bunds being slightly more effective (90 and 79 % decrease, respectively) than mulching (67 % decrease). In fact, all the mulching and barrier measures led to lower sediment yields than in the pre-fire situation, which can be attributed to their implementation in burnt croplands. The higher effectiveness of the barriers was due to the larger impact on overland flow erosion. The higher effectiveness of the contour bunds was mostly due to an additional impact on the sediment delivery ratio, following the lower peak flow (26 % decrease) and hence sediment transport capacity. This can be seen by the increased deposition of sediments in the stream beds (Fig. 3e). Riparian buffers led to a smaller reduction of sediment yield (32 % decrease), which resulted mostly from the re-deposition of eroded sediments along the stream banks (Fig. 3f); this was also combined with a lower peak flow (19 % decrease) and lower channel bank erosion (45 % decrease).

3.3. Multi-Criteria Decision Analysis

Table 5 shows the socioeconomic and environmental criteria and the respective normalized values to perform the Multi-Criteria Decision Analysis of the SWC measures. None of the measures had a high score in all criteria, but all measures except straw mulching had the lowest score in at least one criteria. Environmental performance followed the model results presented earlier: contour bunds and straw wattles had the best performance, but both mulching types and contour bunds also had a good performance. The ranking of the measures was similar for hillslope erosion or sediment yield. For Cost of application, contour-felled logs and riparian buffers were the best measures, the first due to the presence of materials on-site and the latter due to the small application area. As for Ease of application, Riparian buffers scored highest since they can be applied before the fire, and do not require permits from landowners which pose a strong limitation for other SWC measures (Petratou et al., 2023); while barriers had the lowest score due to the technical knowledge required for their correct application. Finally, in the support for vegetation recovery, mulching performed the best due to the addition of organic matter to the soil and the promotion of localized vegetation growth.

Fig. 4 summarizes the weights given by the different stakeholder groups to each criteria. The average weight by all stakeholders was quite balanced, with a slightly greater emphasis on environmental performance and ease of application. However, this hides the important differences in the weights assigned by each group. Soil conservation experts put a large emphasis on environmental performance and ease of application. Land managers had a more balanced view of the criteria, with a slightly greater emphasis on environmental performance and support for vegetation recovery. Water managers gave much higher weights to ease and cost of application compared to the other stakeholders, referring that they required interventions in the entire burnt area which were more complex that those required by the other two stakeholder types.

Fig. 5 summarizes the results of the MCDA from the various stakeholder perspectives described in section 2.5. From all perspectives except that of water managers, the highest performing SWC measure was straw mulching, followed by contour-felled logs and forest residue mulching; while the lowest performing measures were straw wattles, contour bunds and riparian buffers. The performance of the different SWC measures did not differ very much from the perspective of all stakeholders, but the differences were more pronounced from the perspective of soil conservation experts and land owners. Interestingly, the ranking of measures from the perspective of these two stakeholder groups was very similar despite marked differences in criteria weights. The perspective of water managers was markedly different from the others, with riparian buffers showing by far the best performance; the other SWC measures were ranked similarly to the other perspectives.

4. Discussion

4.1. Effectiveness of SWC measures

The model outputs of the effectiveness of the treatment at reducing soil erosion impacted different erosion processes for each measure (Table 4). Mulching led to a significant reduction in splash erosion due to the increase in ground cover (70 % cover), but also to a reduction of overland flow erosion. This was caused both by runoff retention and increased flow resistance, which concurs with the literature (Prats et al., 2019; Robichaud et al., 2013, e.g. 2000; Zema, 2021). In contrast, erosion barriers (contour-felled logs / straw wattles) and contour bunds had a much greater impact on overland flow erosion than on splash erosion. This results from their barrier effect, reducing overland flow at the barrier, promoting localized infiltration and sediment deposition, as

Table 5
Socioeconomic and environmental criteria and respective values for all the SWC measures used for the Multi-Criteria Decision Analysis (MCDA). Between parentheses are the values after normalization following Equation (1) (0 to 1, with 1 indicating the highest utility of the SWC measure); note that most criteria are negative, i.e.; high value indicate low utility and vice-versa. The environmental criteria performance was calculated using percentages of the model results in Table 4.

Criteria	Units	Mulching (forest residue)	Mulching (straw)	Barriers (contour-felled logs)	Barriers (straw wattles)	Contour bunds	Riparian buffers
Environmental performance	Change from post-fire						
• Hillslope erosion		−68.6 %		−89.6 %		−70.9 %	−2.8 %
• Sediment yield		−66.7 %		−89.7 %		−79.1 %	-32.0 %
• Average		−67.6 % (0.70)		−89.6 % (1.00)		−75.0 % (0.80)	−17.4 % (0.00)
Cost of application	K€	6 559 (0.00)	3 823 (0.47)	1 367 (0.90)	3 810 (0.48)	3 439 (0.54)	780 (1.00)
Ease of application	Rank: easy (3) to hard (1)						
• Obtaining materials		2	2	3	1	1	3
• Technical expertise		3	3	1	1	1	2
• Institutional and landowner support		1	1	1	1	1	3
• Overall rank		2 (0.50)	2 (0.50)	1 (0.00)	1 (0.00)	1 (0.00)	3 (1.00)
Support for vegetation recovery	Rank: good (3) to none (1)	3 (1.00)	3 (1.00)	2 (0.50)	2 (0.50)	2 (0.50)	1 (0.00)

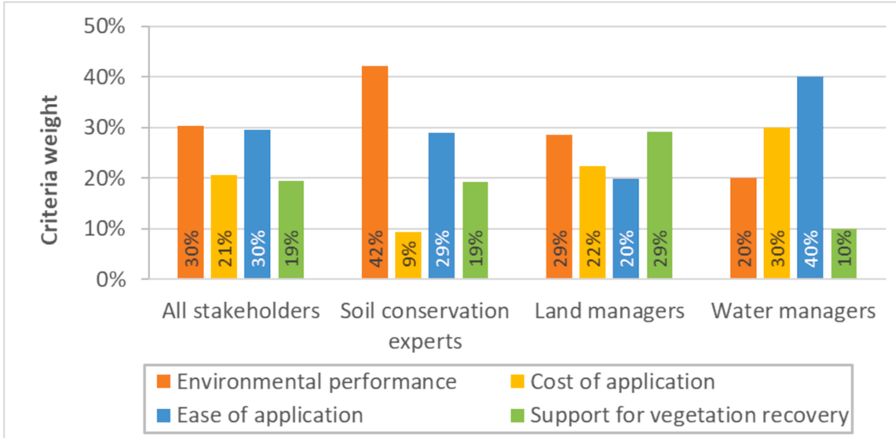

Fig. 4. Criteria assigned by different stakeholder groups to the criteria listed in Table 2.

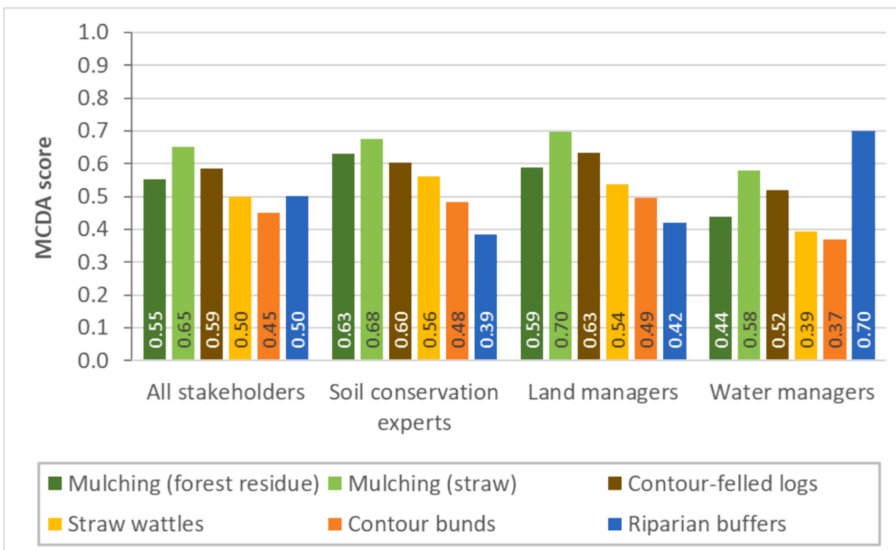

Fig. 5. Results of the various MCDA perspectives for the different SWC measures; higher values represent more effective measures.

reported in the literature (Robichaud et al., 2008, e.g. 2000; Zema, 2021) The limited erosion reduction of riparian buffers can be attributed to the limited area of application (Fig. 3). Overall, this indicates that the simulation of the measures in OpenLISEM is similar to their functioning in reality.

As for sediment yield, all measures showed negligible or, at best, modest reductions in peak flow rates (and hence sediment transport capacity). Mulch and contour logging have been reported to have larger impacts on peak flow than those found in this study, decreasing values by respectively 0 and 45 % (Robichaud et al., 2013) and 35 % (Robichaud et al., 2008). Cawson et al. (2013) also found that riparian vegetation impacted flow velocity to a large extent, but did not quantify this. It should be noted that the former values were derived from smaller catchments than the Odiáxere (0.015 to 0.05 km^2 and 0.01 to 0.13 km^2) without impervious areas. The wildfire did not lead to large impacts on the peak flow rate of the Odiaxere catchment, likely due to the large size of the catchment (18.5 km^2), which strongly limits the hydrological connectivity, as compared to smaller catchments (Wu et al., 2021a). Additionally, most measures except riparian buffers show a small increase in channel erosion; Wu et al. (2021a) noted how fire could decrease channel erosion by bringing sediment-laden flow to the stream (this is also visible in Table 4), and the adoption of SWC measures reverse this change.

The effects on overall sediment yield for mulching were comparable with observations of a decrease of 58 to 62 % observed by Robichaud et al. (2013) in small watersheds. The decrease caused by contour-felled logs in this work was, however, much larger than the decreases of 40 to 66 % observed in small watersheds (Robichaud et al., 2008; Zema, 2021). This could be due to the fact that contour-felled logs were also extended to valleys which concentrate runoff, and therefore can have very high erosion rates; they are in this case acting as check-dams (see the decrease in areas with very high erosion rates in Fig. 3d). This concurs with the observations by Robichaud et al. (2019) of a decrease in sediment yield by 50 % in the first year after the fire.

The modelling exercises of this work are difficult to compare with existing research. There are very few model studies for post-fire SWC measures at the catchment scale; most modelling exercises in burnt areas refer to the plot scale (Lopes et al., 2021). Furthermore, modelling exercises at the catchment scale outside the Mediterranean region do not necessarily lead to comparable results, by not accounting for the local characteristics, for example thin soils with high stone content (Zema, 2021). Two similar watershed-scale models were applied in northern Portugal to assess the impact of mulching on sediment yield reduction. Pastor et al. (2019) used the spatially-distributed Landsoil model to assess the impact of mulching associated with riparian buffers, calculating a 37 % decrease in sediment yield. This low value was attributed to the small size of the wildfire (10 % of the catchment area). In contrast, Basso et al. (2022) used the SWAT model to predict a decrease in post-fire sediment yield of 85 % after mulching, but this was based on a parameterization of mulching impacts on erosion from local measurements which might not be valid for other regions. More catchment-scale studies of post-fire measures using physically-based numerical models are needed to compare with the present results.

4.2. Multi-criteria decision analysis of SWC measures

Straw mulching was the highest scoring measure in all MCDA perspectives except that of water managers, where it was still the second highest scored measure. This can be to a large extent attributed to a combination of a reasonable effectiveness in limiting erosion and sediment yield with added benefits for vegetation recovery, combined with it not being too costly or too difficult to apply compared with other measures. This concurs with the classification of straw mulching as the most cost-effective SWC measure for burnt areas by Girona-García et al. (2023).

Girona-García et al. (2023) also report that the remaining SWC measures (except for riparian buffers) have similar cost-effectiveness, although with a lower performance than straw mulch. This work, however, indicates that forest residue mulching and contour-felled logs performed consistently better than straw wattles and contour bunds. Forest residue mulching had similar scores as straw mulching, except for higher application costs. Contour-felled logs, on the other hand, had contrasting scores to straw mulching; the very good effectiveness and very low application costs were combined with the difficulty of application and limited benefits for vegetation recovery. Straw wattles and contour bunds had similar performances to contour-felled logs, but with higher costs of application.

Riparian buffers was a special case. As a measure targeting streams, it performed very well in cost of application, owing to the small area of application compared with other measures; the costs per unit area were much higher. It also performed very well for ease of application, because it can be applied in the years preceding a fire and to a much smaller area, avoiding the complexity of large-scale emergency interventions required by other SWC measures. However, the environmental performance and support for vegetation recovery were much worse than that of other measures.

The MCDA scores for the different measures highlighted the different management objectives of each stakeholder group, based on the weights they assigned to each criteria. According to Petratou et al. (2023), soil conservation experts prioritized effectiveness; this is reflected not only by the large weight on environmental performance, but also in the emphasis on the ease of application, since effectiveness can greatly decrease if SWC measures are applied long after the fire. Land managers, on the other hand, were reported by Uyttendaele (2022) to be more concerned with restoring land functions affected by fires, explaining the greater emphasis on environmental performance and support for vegetation recovery. For both these stakeholders, the ease of application and added benefits for vegetation recovery can be more important differentiation factors between SWC measures that the cost-effectiveness reported by Girona-García et al. (2023). Interestingly, these stakeholders ranked the measures in a similar way despite prioritising different criteria; mulch is attractive for the experts due to the ease of implementation, and for land managers due to positive impacts on vegetation recovery.

Water managers had different priorities given their need to intervene in the entire burnt area. Environmental performance was not considered as important as the organization and coordination efforts required to make large-scale interventions in a short amount of time after the fire. Some managers reported their preference for interventions in the riparian zone, since they are managed by a single entity (the Portuguese Environment Agency); they believe that SWC measures in hillslopes are too difficult to apply at the catchment scale due to the complexity of dealing with multiple landowners with different interests. These opinions stem partially from the experience with the 2003 fires in Odiáxere, when several intervention and recovery plans were made but could not be implemented in time (Wu et al., 2021b), leading to severe impacts on water quality in the Bravura reservoir (Nitzsche et al., 2024).

In summary, straw mulching might be attractive for managers aiming at an easily-applied SWC measure with good environmental performance, some benefits for vegetation recovery, and not overly expensive. Riparian buffers might be attractive for managers aiming at mitigating off-site impacts of fires without having to deal with complex post-fire management interventions. Contour-felled logs might be interesting for managers prioritizing measure performance over ease of application. Other measures provide similar benefits to either straw mulching or contour-felled logs, but with higher costs. Overall, this highlights that MCDA, rather than a tool to determine the best solution for SWC in burnt areas, is a tool to help clarify the objectives of the post-fire interventions and the objectives of different stakeholders (or, in this case, managers), so they can be considered accordingly (Roy and Roy, 1996).

4.3. Model performance

This work shows that the spatially explicit OpenLISEM model can simulate the implementation of SWC measures at the hillslope scale, and allows the assessment of their impact on watershed-scale processes resulting from changes to water and sediment routing. The simulation of the effectiveness of the treatments was within the range of the reference values shown in Table 3. However, some limitations were present. The simulated effectiveness for the riparian buffers was on the lower end of the reference values. Most reference studies focus on agricultural lands and agroforestry systems where buffers are used to limit the movement of fertilizers and contaminants (Akdemir et al., 2016; Momm et al., 2014; Seobi et al., 2005); the higher effectiveness might result from a lower sediment mobilization when compared with a burnt area. The effectiveness of the remaining SWC measures was only evaluated at the hillslope scale; the limited number of studies at larger scales, such as swales and micro-catchments (Girona-García et al., 2021), prevented a more effective evaluation.

Furthermore, the evaluation focused on soil loss; evaluating the model also for runoff generation might have increased the robustness of the SWC measure simulation. However, published studies on SWC measures in burnt areas usually report impacts on soil loss, with a much lower fraction reporting also impacts on runoff generation (Girona-García et al., 2021); it is therefore harder to obtain a reliable estimate of impacts, limiting evaluation efforts in future studies.

The single-storm structure of the OpenLISEM application also had some limitations in simulating SWC measures. Firstly, SWC measures were parameterized as immediate post-fire interventions for a single storm with a large, but not extreme, intensity (5 year return period). However, most measures naturally degrade with time since fire; e.g. mulch cover decreases in the first year after fire (Robichaud et al., 2013) and contour logs can fill up with sediment, be displaced, collapse, or move off-contour (Robichaud et al., 2008). Furthermore, SWC effectiveness can also vary with storm characteristics; e.g. contour-felled logs are effective for lower intensity storms, but can be easily overtopped by storms with high intensity (Robichaud et al., 2008; Zema, 2021) which can have a disproportionate effect on soil erosion. Since burnt areas are exposed to erosion caused by storms of varying intensity during several years after the fire while vegetation recovers (Shakesby, 2011), it is possible that the actual effectiveness of the measures prone to degradation (i.e. mulch and barriers) or overtopping (i.e. barriers) is less than what the model results indicate. However, this is not necessarily so, since the relationship between the time of storm occurrence and vegetation recovery is also important. In both the Odiáxere fire reported by Wu et al. (2021b) and a fire in a catchment in northern Portugal observed by Nunes et al. (2020), the storms which caused the most erosion were those occurring closely after the fire; larger storms which occurred later in the window of disturbance had notably lower impacts. A more accurate assessment of SWC measure effectiveness might require the application of a model for the entire window of disturbance (e.g. Nunes et al., 2018b), including the effects of both vegetation recovery and measure degradation, which is rarely done in post-fire erosion simulations.

Finally, there was also a limitation on some model assumptions. The pre-fire situation showed an average hillslope soil erosion rate of 3.4 ton/ha (Table 4 values divided by catchment area, 1853 ha) including the agricultural fields, which were the main source of sediments before the fire. After the wildfire, the SWC measures were applied to the entire burnt area, including agricultural fields. In the case of mulch and barriers, soil erosion was reduced to levels below the pre-fire situation, in the range of 0.5–1.4 ton/ha. However, it is possible that after the fire, at least some farmers would remove the SWC measures while cultivating their fields, negating these benefits. Assumptions were also made in the design of the SWC measures themselves, i.e. in the mulching application rate, distance between barriers, contour bund dimensions, and riparian buffer width and composition. However, there are important differences between applications as detailed in section 2.3, with consequences for effectiveness. A more complete model evaluation could have tested the sensitivity of model results to changes in these dimensions. Furthermore, soil compaction caused by the heavy machinery used to build some measures was assumed to be minimal, but it can be present in burnt areas and enhance runoff and erosion responses (Malvar et al., 2017).

4.4. MCDA limitations

The MCDA approach presented some limitations in the way that criteria were chosen, weighted and normalized. The criteria used in this work were based on the shortlist by Petratou et al. (2023). However, the authors mentioned additional criteria which were mentioned by soil conservation experts but not considered important enough to make the final list. The potential introduction of invasive species was not considered a risk in the Portuguese setting (Petratou et al., 2023), but it has been observed in the U.S. after the application of straw mulch (Robichaud et al., 2013); this criteria could therefore reduce the performance of this measure. Soil compaction caused by the heavy machinery used to build some SWC measures can enhance erosion and complicate vegetation recovery (Malvar et al., 2017). Furthermore, riparian buffers are sufficiently different from other measures that they might require specific criteria not considered by Petratou et al., such as the risk of riparian vegetation being burned in very severe fires, or their additional ecosystem services such as acting as fire breaks and as refuge for wildlife (Pettit and Naiman, 2007).

The approach of interviewing experts to determine weights leads to a reliance on subjective judgements (Gebre et al., 2021), although the snowball approach used by Petratou et al. (2023) and Uyttendaele (2022) maximizes the integration of the mainstream opinions within each group. The aggregation of stakeholders in groups indicated that they agree in the weights to a certain extent. Petratou et al. (2023) found a moderate consensus between soil conservation experts, and water managers showed a high consensus in their opinions. However, Uyttendaele (2022) found a marked difference between land managers which gained most of their income from their land, who also found the cost of application important; and the others, who gave it a low weight.

Moreover, the weights assigned to the ease of application criteria are strongly influenced by the property structure of Portuguese forests and natural areas. A considerable part of forest areas in Portugal are privately owned (Martins et al., 2021); this complicates the implementation of post-fire SWC measures due to the need to engage and obtain permissions from multiple landowners before starting the work (Petratou et al., 2023). The preference of riparian buffers by Portuguese water managers derives from this issue; this measure would be less attractive in regions where SWC interventions do not require permissions from a large number of landowners, either due to different property structures or post-fire intervention regulations. Land ownership is also an important factor for fire risk management in Portugal, and therefore several solutions have been proposed to mitigate it, such as delegating management to forestry cooperatives or corporations, or property consolidation (Martins et al., 2022). The implementation of these solutions would probably make riparian buffers less attractive, although the fact that they can be implemented before the fire could still make them interesting.

The impact of each criteria on the final score depends not only on the value and assigned weight, but also on how they are normalized. Multiple normalization approaches exist, each affecting how differences between SWC measures for the same criteria impact the final score (Monat, 2009). Assessing this impact can be difficult since the MCDA score does not have an explicit link with measurable quantities. This work used a local scale for normalization, ranking each criterion from the worst (0) to the best (1). However, this approach risks exaggerating differences that can be rather small in reality. The alternative is to use a global scale, where the comparison is based on the worst possible value for each criterion, which can reduce subjectivity (Monat, 2009). Future work could engage stakeholders also to discuss valid ranges for each criteria; for instance, what are tolerable rates of soil erosion for land degradation, or maximum sediment concentration in streams for water uptake.

SWC measures can also deviate from the design options selected in this study (section 2.3). The costs estimated for this work are median costs for Portugal and Spain (when present) based on the *meta*-analysis by Girona-García et al. (2023). However, mulching costs compiled by the authors vary almost an order of magnitude, despite being all derived from studies in developed countries. Also, an as discussed in section 4.2 for SWC measure effectiveness, costs can vary with measure design which can vary with practitioner and with application (see section 2.3 for an idea of the variation). This indicates that costs are site and application specific.

Furthermore, some of the costs and other benefits could be reduced if the SWC were applied differently. For straw and forest residue mulching, the work of local volunteers to spread it over burnt areas can be highly effective in preventing soil erosion while lowering costs, as found for a fire in NW Spain by Prats et al. (2022). This could have added benefits through the connection of diverse knowledge systems by putting volunteers in contact with technicians, researchers and local government (Prats et al., 2022). Another example is the limited benefits of contour bunds for vegetation recovery, which can be counteracted with the addition of mulch to promote regrowth (Uyttendaele, 2022). Measures can also be applied to different areas according to intervention objectives; e.g. the protection of roads and streams requires a smaller intervention area than soil conservation in all the burnt area (Petratou et al., 2023). Overall, this indicates that variations in SWC intervention design and implementation can lead to important variations on the assessment, adding some uncertainty in applying the conclusions of this study to other areas.

Several of these limitations are inherent to the Multi-Attribute Decision Making method (Gebre et al., 2021); while this approach is appropriate for problems such as these where information is limited, the procedure is based on the judgment and preferences of stakeholders, and hence the final score can be strongly affected by changes in weights, leading to variation between solutions. Gebre et al. (2021) refer Multi-Objective Decision Making approaches that can be applied for specific situations where more accurate and detailed information can be obtained, and which are not constrained to a limited number of alternatives. These approaches might provide better adapted solutions for specific fires, where more information about fire characteristics, local vulnerabilities, and available resources for intervention can be obtained; and where different SWC measure implementations options (e.g. intensity or area of application) can be explored.

4.5. Applying model-based MCDA to support SWC measure application to burnt areas

This work used a combination of numerical modelling to assess the effectiveness of different SWC measures to control post-fire impacts on soil erosion and risk of flood and water contamination, with an MCDA to score them according to both effectiveness and other socioeconomic criteria. While this approach has been used to assess SWC plans elsewhere (e.g. Teshome et al., 2014), it was rarely applied to watersheds affected by fires, where cost-effectiveness or cost-benefit analysis without ranking and aggregation are more common (e.g. Ferreira et al., 2015; Girona-García et al., 2023; Petratou et al., 2023; Robichaud et al., 2000). This MCDA highlighted issues which would not be visible in a cost-effectiveness analysis, such as the expert knowledge required for contour-felled logs, or the negative impact of forest property structure on all measures except riparian buffers.

Despite the limitations of the model and MCDA described above, this approach already highlights some of the costs and benefits of the measures, e.g. how costs, ease of application or co-benefits can compensate for lower effectiveness; or how the best measures depend on the objectives of the intervention, and on the managers who are intervening. The approach presented here can be used to provide detailed insights in the trade-offs between different SWC approaches according to management objectives, and provide a basis for discussion between managers on the best ways to approach soil and water conservation on burnt areas.

A number of improvements can, of course, be done over this methodology. The SWC measures can be tested under different storm regimes, to assess if there is a threshold in their capacity (see Zema, 2021). They can also be assessed in combinations of multiple complementary SWC measures, with different strengths and weaknesses, to explore potential synergies (see Pastor et al., 2019). The effectiveness of locating SWC measures only in sediment transport hotspots can be assessed (e.g. check-dams only; see Robichaud et al., 2019) to see if the decrease in cost would be enough to justify the decrease the effectiveness. And finally, post-fire intervention measures could be compared, in terms of effectiveness and costs, with more structural pre-fire measures, such as fuel management to decrease fire extent and severity (see Salis et al., 2019).

5. Conclusions

This work assessed the effectiveness of soil and water conservation measures – mulching (with forest residue and straw), erosion barriers (contour-felled logs, straw wattles and contour bunds) and riparian buffers – in restoring forest ecosystem services such as soil protection and water quality regulation after disturbance by forest fires in a Mediterranean watershed. The effectiveness in restoring these services was compared with application costs, ease of application and additional impacts on vegetation recovery. This is one of the first Multi-Criteria Decision Analysis for soil and water conservation in burnt areas, which combines costs, effectiveness, and additional biophysical and social criteria in a single score, creating an objective measure for their ranking. The results indicate that:

- All the SWC measures were shown to be effective for soil conservation and controlling sediment yield, except for riparian buffers which only showed a moderate effect on the latter.
- Straw mulching was the most effective SWC measure for soil conservation and land management objectives, but not from a water quality regulation perspective.
- Forest residue mulching, barriers and contour bunds had lower performances from all perspectives. The advantage of straw mulching over these measures was due to having an acceptable performance in all criteria, while forest residue mulching was too costly, while barriers and contour bunds were hard to apply.
- Riparian buffers had a poor environmental performance, but were the best measure for water managers due to the ease of application, related with a smaller implementation area and ability to be implemented before fire occurrence.

The main finding of this work is that a Multi-Criteria Decision Analysis can be a good tool to assess the pros and cons of the application of different soil and water conservation approaches to burnt areas. MCDA can be especially effective when supported by numerical modelling, which can determine the effectiveness of SWC measures both in the burnt area and for downstream impacts. MCDA results should not be used as an indication of which is the best measure; they should be used as a way to highlight how different post-fire restoration objectives and priorities can lead to different optimal approaches.

CRediT authorship contribution statement

Beatriz Faria: Writing – original draft, Methodology, Investigation. **João Pedro Nunes:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Jantiene E.M. Baartman:** Writing – review & editing, Methodology. **Luís Dias:** Writing – review & editing, Supervision, Methodology. **Jinfeng Wu:** Writing – review & editing, Methodology, Data curation. **Sergio A. Prats:** Writing – review & editing, Methodology, Investigation.

Declaration of competing interest

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

Acknowledgments

This work was done within the scope of project FRISCO: managing Fire-induced RISks of water quality Contamination (PCIF/MPG/0044/2018), funded by the Portuguese Foundation for Science and Technology (FCT). Further FCT support was received through an individual research contract for S.A. Prats (CEECIND/01473/2020), the research centre cE3c – Centre for Ecology, Evolution and Environmental Changes (UIDB/00329/2020), and the research centre MED – Mediterranean Institute for Agriculture, Environment and Development (UIDB/05183/2020). B. Faria would like to acknowledge European Commission for supporting their MSc thesis internship at Wageningen University in the Netherlands through the ERASMUS + programme. Finally, the work of L. Dias was supported by the EEA-Financial Mechanism 2014-2021 and the Portuguese Environment Agency, through Pre-defined Project-2 National Roadmap for Adaptation XXI (PDP-2).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.108808.

Data availability

Data will be made available on request.

References

Akdemir, E., Anderson, S.H., Udawatta, R.P., 2016. Influence of Agroforestry Buffers on Soil Hydraulic Properties Relative to Row Crop Management. Soil Sci. 181, 368–376. https://doi.org/10.1097/SS.0000000000000170.

Akdogan, Z., Guven, B., 2023. Multi-criteria decision analysis in assessing watershed scale pollution risk: a review of combined approaches and applications. Environ. Rev. 31, 669–689. https://doi.org/10.1139/er-2023-0017.

Aparício, B.A., Nunes, J.P., Bernard-Jannin, L., Dias, L.F., Fonseca, A., Ferreira, T., 2023. Modelling the role of ground-true riparian vegetation for providing regulating

services in a Mediterranean watershed. Int. Soil Water Conserv. Res. 11, 159–168. https://doi.org/10.1016/j.iswcr.2022.07.005.
Basso, M., Serpa, D., Rocha, J., Martins, M.A.S., Keizer, J., Vieira, D.C.S., 2022. A modelling approach to evaluate land management options for recently burnt catchments. Eur. J. Soil Sci. 73. https://doi.org/10.1111/ejss.13275.
Blattert, C., Lemm, R., Thees, O., Lexer, M.J., Hanewinkel, M., 2017. Management of ecosystem services in mountain forests: Review of indicators and value functions for model based multi-criteria decision analysis. Ecol. Ind. 79, 391–409. https://doi.org/10.1016/j.ecolind.2017.04.025.
Calheiros, T., Nunes, J.P., Pereira, M.G., 2020. Recent evolution of spatial and temporal patterns of burnt areas and fire weather risk in the Iberian Peninsula. Agric. For. Meteorol. 287, 107923. https://doi.org/10.1016/j.agrformet.2020.107923.
Carvalho-Santos, C., Honrado, J.P., Hein, L., 2014. Hydrological services and the role of forests: Conceptualization and indicator-based analysis with an illustration at a regional scale. Ecol. Complex. 20, 69–80. https://doi.org/10.1016/j.ecocom.2014.09.001.
Cawson, J.G., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2013. Effects of fire severity and burn patchiness on hillslope-scale surface runoff, erosion and hydrologic connectivity in a prescribed burn. For. Ecol. Manage. 310, 219–233. https://doi.org/10.1016/j.foreco.2013.08.016.
Chow, V.T., Maidment, D.R., Mays, L.W., 1988. Applied Hydrology. In: McGraw-Hill series in water resources and environmental engineering. McGraw-Hill, New York.
de Figueiredo, T., Fonseca, F., Martins, A., 2012. Soil loss and run-off in young forest stands as affected by site preparation technique: A study in NE Portugal. Eur. J. For. Res. 131, 1747–1760. https://doi.org/10.1007/s10342-011-0581-6.
de Roo, A.P.J., Offermans, R.J.E., Cremers, N.H.D.T., 1996a. Lisem: A single-event, physically based hydrological and soil erosion model for drainage basins. II: Sensitivity analysis, validation and application. Hydrol. Process. 10, 1119–1126. https://doi.org/10.1002/(sici)1099-1085(199608)10:8<1119::aid-hyp416>3.0.co;2-v.
de Roo, A.P.J., Wesseling, C.G., Ritsema, C.J., 1996b. Lisem: A Single-Event Physically Based Hydrological and Soil Erosion Model for Drainage Basins. I: Theory. Input and Output. Hydrol Process 10, 1107–1117. https://doi.org/10.1002/(SICI)1099-1085(199608)10:8<1107::AID-HYP415>3.0.CO;2-4.
Fernández, C., Fontúrbel, T., Vega, J.A., 2019. Effects of pre-fire site preparation and post-fire erosion barriers on soil erosion after a wildfire in NW Spain. Catena (Amst) 172, 691–698. https://doi.org/10.1016/j.catena.2018.09.038.
Fernández, C., Vega, J.A., 2016a. Evaluation of RUSLE and PESERA models for predicting soil erosion losses in the first year after wildfire in NW Spain. Geoderma 273, 64–72. https://doi.org/10.1016/j.geoderma.2016.03.016.
Fernández, C., Vega, J.A., 2016b. Are erosion barriers and straw mulching effective for controlling soil erosion after a high severity wildfire in NW Spain? Ecol. Eng. 87, 132–138. https://doi.org/10.1016/j.ecoleng.2015.11.047.
Ferreira, A.J.D., Prats Alegre, S., Coelho, C.O.A., Shakesby, R.A., Páscoa, F.M., Ferreira, C.S.S., Keizer, J.J., Ritsema, C., 2015. Strategies to prevent forest fires and techniques to reverse degradation processes in burned areas. Catena (Amst) 128, 224–237. https://doi.org/10.1016/j.catena.2014.09.002.
Föllmi, D., Baartman, J., Benali, A., Nunes, J.P., 2022. How do large wildfires impact sediment redistribution over multiple decades? Earth Surf. Proc. Land. 47, 3033–3050. https://doi.org/10.1002/esp.5441.
Gebre, S.L., Cattrysse, D., Alemayehu, E., Van Orshoven, J., 2021. Multi-criteria decision making methods to address rural land allocation problems: A systematic review. International Soil and Water Conservation Research 9, 490–501. https://doi.org/10.1016/j.iswcr.2021.04.005.
Girona-García, A., Vieira, D.C.S., Silva, J., Fernández, C., Robichaud, P.R., Keizer, J.J., 2021. Effectiveness of post-fire soil erosion mitigation treatments: A systematic review and meta-analysis. Earth Sci. Rev. https://doi.org/10.1016/j.earscirev.2021.103611.
Girona-García, A., Cretella, C., Fernández, C., Robichaud, P.R., Vieira, D.C.S., Keizer, J. J., 2023. How much does it cost to mitigate soil erosion after wildfires? J. Environ. Manage. https://doi.org/10.1016/j.jenvman.2023.117478.
Jenkins, M., Schaap, B., 2018. Untapped Potential: Forest Ecosystem Services for Achieving SDG 15. UNFF13 Background Analytical Study.
Jetten, V., Govers, G., Hessel, R., 2003. Erosion models: Quality of spatial predictions. Hydrol. Process. 17, 887–900. https://doi.org/10.1002/hyp.1168.
Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. Int. J. Wildland Fire 18, 116–126. https://doi.org/10.1071/WF07049.
Lopes, A.R., Girona-García, A., Corticeiro, S., Martins, R., Keizer, J.J., Vieira, D.C.S., 2021. What is wrong with post-fire soil erosion modelling? A meta-analysis on current approaches, research gaps, and future directions. Earth Surf. Proc. Land. 46, 205–219. https://doi.org/10.1002/esp.5020.
López-Vicente, M., Kramer, H., Keesstra, S., 2021. Effectiveness of soil erosion barriers to reduce sediment connectivity at small basin scale in a fire-affected forest. J. Environ. Manage. 278. https://doi.org/10.1016/j.jenvman.2020.111510.
Lucas-Borja, M.E., González-Romero, J., Plaza-Álvarez, P.A., Sagra, J., Gómez, M.E., Moya, D., Cerdà, A., de las Heras, J., 2019. The impact of straw mulching and salvage logging on post-fire runoff and soil erosion generation under Mediterranean climate conditions. Sci. Total Environ. 654, 441–451. https://doi.org/10.1016/j.scitotenv.2018.11.161.
Maetens, W., Poesen, J., Vanmaercke, M., 2012. How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? Earth Sci. Rev. 115, 21–36. https://doi.org/10.1016/j.earscirev.2012.08.003.
Malvar, M.C., Silva, F.C., Prats, S.A., Vieira, D.C.S., Coelho, C.O.A., Keizer, J.J., 2017. Short-term effects of post-fire salvage logging on runoff and soil erosion. For. Ecol. Manage. 400, 555–567. https://doi.org/10.1016/j.foreco.2017.06.031.
Martínez-Murillo, J.F., López-Vicente, M., 2018. Effect of Salvage Logging and Check Dams on Simulated Hydrological Connectivity in a Burned Area. Land Degrad. Dev. 29, 701–712. https://doi.org/10.1002/ldr.2735.
Martins, A., Novais, A., Santos, J.L., Canadas, M.J., 2021. Experts' multiple criteria evaluations of fuel management options to reduce wildfire susceptibility. The role of closer knowledge of the local socioeconomic context. Land Use Policy 108, 105580. https://doi.org/10.1016/j.landusepol.2021.105580.
Martins, A., Novais, A., Santos, J.L., Canadas, M.J., 2022. Promoting Landscape-Level Forest Management in Fire-Prone Areas: Delegate Management to a Multi-Owner Collaborative, Rent the Land, or Just Sell It? Forests 13. https://doi.org/10.3390/f13010022.
Momm, H.G., Bingner, R.L., Yuan, Y., Locke, M.A., Wells, R.R., 2014. Spatial Characterization of Riparian Buffer Effects on Sediment Loads from Watershed Systems. J. Environ. Qual. 43, 1736–1753. https://doi.org/10.2134/jeq2013.10.0413.
Monat, J.P., 2009. The benefits of global scaling in multi-criteria decision analysis. Judgm. Decis. Mak. 4, 492–508. https://doi.org/10.1017/s1930297500004034.
Myronidis, D.I., Emmanouloudis, D.A., Mitsopoulos, I.A., Riggos, E.E., 2010. Soil Erosion Potential after Fire and Rehabilitation Treatments in Greece. Environ. Model. Assess. 15, 239–250. https://doi.org/10.1007/s10666-009-9199-1.
Napper, C., 2006. Burned Area Emergency Response Treatments Catalog. United States Department of Agriculture Forest Service, San Dimas.
Nitzsche, N., Nunes, J.P., Parente, J., 2024. Assessing post-fire water quality changes in reservoirs: Insights from a large dataset in Portugal. Sci. Total Environ. 912. https://doi.org/10.1016/j.scitotenv.2023.169463.
Nunes, J.P., Doerr, S.H., Sheridan, G., Neris, J., Santín, C., Emelko, M.B., Silins, U., Robichaud, P.R., Elliot, W.J., Keizer, J., 2018a. Assessing water contamination risk from vegetation fires: challenges, opportunities and a framework for progress. Hydrol. Process. 32, 687. https://doi.org/10.1002/hyp.11434.
Nunes, J.P., Quintanilla, P.N., Santos, J.M., Serpa, D., Carvalho-Santos, C., Rocha, J., Keizer, J.J., Keesstra, S.D., 2018b. Afforestation, Subsequent Forest Fires and Provision of Hydrological Services: A Model-Based Analysis for a Mediterranean Mountainous Catchment. Land Degrad. Dev. 29, 776–788. https://doi.org/10.1002/ldr.2776.
Nunes, J.P., Bernard-Jannin, L., Rodríguez-Blanco, M.L., Boulet, A.-K., Santos, J.M., Keizer, J.J., 2020. Impacts of wildfire and post-fire land management on hydrological and sediment processes in a humid Mediterranean headwater catchment. Hydrol. Process. https://doi.org/10.1002/hyp.13926.
Nunes, J.P., Parente, J., Benali, A., Nitzsche, N., Prats, S., Sa, A.C., Brito, C., Dias, L.F., 2023. Good practices for managing water resources in fire-prone watersheds in Portugal: FRISCO Project: managing risks of fire-induced contamination of water quality. Faculty of Sciences, University of Lisbon, Lisbon. https://doi.org/10.13140/RG.2.2.10569.72808.
Olsen, M.J., Rikli, A.M., Sillars, D.N., 2012. Investigation of Straw Wattle Influence on Surficial Slope Stability. In: Proceedings of the TRB 2012 Annual Meeting.
Oweis, T.Y., 2017. Rainwater harvesting for restoring degraded dry agro-pastoral ecosystems: a conceptual review of opportunities and constraints in a changing climate. Environ. Rev. 25, 135–149. https://doi.org/10.1139/er-2016-0069.
Parente, J., Girona-García, A., Lopes, A.R., Keizer, J.J., Vieira, D.C.S., 2022. Prediction, validation, and uncertainties of a nation-wide post-fire soil erosion risk assessment in Portugal. Sci. Rep. 12. https://doi.org/10.1038/s41598-022-07066-x.
Pastor, A.V., Nunes, J.P., Ciampalini, R., Koopmans, M., Baartman, J., Huard, F., Calheiros, T., Le-Bissonnais, Y., Keizer, J.J., Raclot, D., 2019. Projecting future impacts of global change including fires on soil erosion to anticipate better land management in the forests of NW Portugal. Water (Basel) 11, 1–19. https://doi.org/10.3390/w11122617.
Paul, M.J., LeDuc, S.D., Lassiter, M.G., Moorhead, L.C., Noyes, P.D., Leibowitz, S.G., 2022. Wildfire Induces Changes in Receiving Waters: A Review With Considerations for Water Quality Management. Water Resour. Res. https://doi.org/10.1029/2021WR030699.
Petratou, D., Nunes, J.P., Guimarães, M.H., Prats, S., 2023. Decision-making criteria to shape mulching techniques for fire-prone landscapes. Landsc. Ecol. https://doi.org/10.1007/s10980-023-01659-1.
Pettit, N.E., Naiman, R.J., 2007. Fire in the riparian zone: Characteristics and ecological consequences. Ecosystems. https://doi.org/10.1007/s10021-007-9048-5.
Prats, S.A., Wagenbrenner, J.W., Martins, M.A.S., Malvar Cortizo, M., Keizer, J.J., 2016. Hydrologic Implications of Post-Fire Mulching Across Different Spatial Scales. Land Degrad. Dev. 27, 1440–1452. https://doi.org/10.1002/ldr.2422.
Prats, S.A., González-Pelayo, Ó., Silva, F.C., Bokhorst, K.J., Baartman, J.E.M., Keizer, J. J., 2019. Post-fire soil erosion mitigation at the scale of swales using forest logging residues at a reduced application rate. Earth Surf. Proc. Land. 44, 2837–2848. https://doi.org/10.1002/esp.4711.
Prats, S., Malvar, M., Martins, M.A.S., Keizer, J.J., 2014. Post-fire soil erosion mitigation: a review of the last research and techniques developed in Portugal. Cuadernos De Investigación Geográfica 40, 403–428. https://doi.org/10.18172/cig.2519.
Prats, S.A., Merino, A., Gonzalez-Perez, J.A., Verheijen, F.G.A., De la Rosa, J.M., 2021. Can straw-biochar mulching mitigate erosion of wildfire-degraded soils under extreme rainfall? Sci. Total Environ. 761, 143219. https://doi.org/10.1016/j.scitotenv.2020.143219.
Prats, S.A., Sierra-Abraín, P., Moraña-Fontán, A., Zas, R., 2022. Effectiveness of community-based initiatives for mitigation of land degradation after wildfires. Sci. Total Environ. 810. https://doi.org/10.1016/j.scitotenv.2021.152232.
Robichaud, P.R., Beyers, J.L., Neary, D.G., 2000. Evaluating the Effectiveness Of Postfire Rehabilitation Treatments. General Technical Report RMRS-GTR-63. Fort Collins.
Robichaud, P.R., Wagenbrenner, J.W., Brown, R.E., Wohlgemuth, P.M., Beyers, J.L., 2008. Evaluating the effectiveness of contour-felled log erosion barriers as a post-fire

runoff and erosion mitigation treatment in the western United States. Int. J. Wildland Fire 17, 255–273. https://doi.org/10.1071/WF07032.

Robichaud, P.R., Wagenbrenner, J.W., Lewis, S.A., Ashmun, L.E., Brown, R.E., Wohlgemuth, P.M., 2013. Post-fire mulching for runoff and erosion mitigation Part II: Effectiveness in reducing runoff and sediment yields from small catchments. Catena (Amst) 105, 93–111. https://doi.org/10.1016/j.catena.2012.11.016.

Robichaud, P.R., Storrar, K.A., Wagenbrenner, J.W., 2019. Effectiveness of straw bale check dams at reducing post-fire sediment yields from steep ephemeral channels. Sci. Total Environ. 676, 721–731. https://doi.org/10.1016/j.scitotenv.2019.04.246.

Robinne, F.N., Hallema, D.W., Bladon, K.D., Flannigan, M.D., Boisramé, G., Bréthaut, C. M., Doerr, S.H., Di Baldassarre, G., Gallagher, L.A., Hohner, A.K., Khan, S.J., Kinoshita, A.M., Mordecai, R., Nunes, J.P., Nyman, P., Santín, C., Sheridan, G., Stoof, C.R., Thompson, M.P., Waddington, J.M., Wei, Y., 2021. Scientists' warning on extreme wildfire risks to water supply. Hydrol. Process. 35. https://doi.org/10.1002/hyp.14086.

Roy, B., Roy, B., 1996. Decision aiding: major actors and the role of models. Multicriteria Methodology for Decision Aiding 7–17. https://doi.org/10.1007/978-1-4757-2500-1_2.

Salis, M., Del Giudice, L., Robichaud, P.R., Ager, A.A., Canu, A., Duce, P., Pellizzaro, G., Ventura, A., Alcasena-Urdiroz, F., Spano, D., Arca, B., 2019. Coupling wildfire spread and erosion models to quantify post-fire erosion before and after fuel treatments. Int. J. Wildland Fire 28, 687–703. https://doi.org/10.1071/WF19034.

Sánchez-García, C., Santín, C., Neris, J., Sigmund, G., Otero, X.L., Manley, J., González-Rodríguez, G., Belcher, C.M., Cerdà, A., Marcotte, A.L., Murphy, S.F., Rhoades, C.C., Sheridan, G., Strydom, T., Robichaud, P.R., Doerr, S.H., 2023. Chemical characteristics of wildfire ash across the globe and their environmental and socio-economic implications. Environ. Int. 178, 108065. https://doi.org/10.1016/j.envint.2023.108065.

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. Sci. Total Environ. 526, 1–13. https://doi.org/10.1016/j.scitotenv.2015.04.058.

Seobi, T., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., 2005. Influence of Grass and Agroforestry Buffer Strips on Soil Hydraulic Properties for an Albaqualf. Soil Sci. Soc. Am. J. 69, 893–901. https://doi.org/10.2136/sssaj2004.0280.

Shakesby, R.A., 2011. Post-wildfire soil erosion in the Mediterranean: Review and future research directions. Earth Sci. Rev. 105, 71–100. https://doi.org/10.1016/j.earscirev.2011.01.001.

Sweeney, B.W., Newbold, J.D., 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: A literature review. J. Am. Water Resour. Assoc. 50, 560–584. https://doi.org/10.1111/jawr.12203.

Teshome, A., de Graaff, J., Stroosnijder, L., 2014. Evaluation of soil and water conservation practices in the north-western Ethiopian highlands using multi-criteria analysis. Front. Environ. Sci. 2. https://doi.org/10.3389/fenvs.2014.00060.

Tomer, M.D., Dosskey, M.G., Burkart, M.R., James, D.E., Helmers, M.J., Eisenhauer, D.E., 2009. Methods to prioritize placement of riparian buffers for improved water quality. Agrofor. Syst. 75, 17–25. https://doi.org/10.1007/s10457-008-9134-5.

USDA, 1986. Urban Hydrology for Small Watersheds. USDA Technical Release 55. United States Department of Agriculture (USDA), Washington, D.C.

Uyttendaele, S.A.L., 2022. The effectiveness and feasibility of the adoption of earthen contour bund synergies for post-fire land restoration in Southern Portugal: an integrated approach for the recovery of landscapes affected by wild fires in Southern Portugal (MSc Thesis). Wageningen University, Wageningen.

Van Eck, C.M., Nunes, J.P., Vieira, D.C., Keesstra, S., Keizer, J.J., 2016. Physically-based modelling of the post-fire runoff response of a forest catchment in central Portugal: using field vs. remote sensing based estimates of vegetation recovery. Land Degrad. Dev. 27, 1535–1544. https://doi.org/10.1002/ldr.2507.

Vieira, D.C.S., Prats, S.A., Nunes, J.P., Shakesby, R.A., Coelho, C.O.A., Keizer, J.J., 2014. Modelling runoff and erosion, and their mitigation, in burned Portuguese forest using the revised Morgan – Morgan – Finney model. For. Ecol. Manage. 314, 150–165. https://doi.org/10.1016/j.foreco.2013.12.006.

Vieira, D.C.S., Serpa, D., Nunes, J.P.C., Prats, S.A., Neves, R., Keizer, J.J., 2018. Predicting the effectiveness of different mulching techniques in reducing post-fire runoff and erosion at plot scale with the RUSLE, MMF and PESERA models. Environ. Res. 168, 365–378. https://doi.org/10.1016/j.envres.2018.04.029.

Vieira, D.C.S., Basso, M., Nunes, J.P., Keizer, J.J., Baartman, J.E.M., 2022. Event-based quickflow simulation with OpenLISEM in a burned Mediterranean forest catchment. Int. J. Wildland Fire 31, 670–683. https://doi.org/10.1071/WF21005.

Vieira, D.C.S., Borrelli, P., Jahanianfard, D., Benali, A., Scarpa, S., Panagos, P., 2023. Wildfires in Europe: Burned soils require attention. Environ. Res. 217, 114936. https://doi.org/10.1016/j.envres.2022.114936.

Wagenbrenner, J.W., MacDonald, L.H., Rough, D., 2006. Effectiveness of tree post-fire rehabilitation treatments in the Colorado Front Range. Hydrol. Process 20, 2989–3006. https://doi.org/10.1002/hyp.6146.

Więckowski, J., Sałabun, W., Kizielewicz, B., Bączkiewicz, A., Shekhovtsov, A., Paradowski, B., Wątróbski, J., 2023. Recent advances in multi-criteria decision analysis: A comprehensive review of applications and trends. Int. J. Knowledge-Based Intell. Eng. Syst. 27, 367–393. https://doi.org/10.3233/KES-230487.

Wu, J., Baartman, J.E.M., Nunes, J.P., 2021a. Testing the impacts of wildfire on hydrological and sediment response using the OpenLISEM model. Part 2: Analyzing the effects of storm return period and extreme events. Catena (Amst) 207, 105620. https://doi.org/10.1016/j.catena.2021.105620.

Wu, J., Baartman, J.E.M., Nunes, J.P., 2021b. Comparing the impacts of wildfire and meteorological variability on hydrological and erosion responses in a Mediterranean catchment. Land Degrad. Dev. 32, 640–653. https://doi.org/10.1002/ldr.3732.

Wu, J., Nunes, J.P., Baartman, J.E.M., Faúndez Urbina, C.A., 2021c. Testing the impacts of wildfire on hydrological and sediment response using the OpenLISEM model. Part 1: Calibration and evaluation for a burned Mediterranean forest catchment. Catena (Amst) 207, 105658. https://doi.org/10.1016/j.catena.2021.105658.

Zema, D.A., 2021. Postfire management impacts on soil hydrology. Curr. Opin. Environ. Sci. Health 21, 100252. https://doi.org/10.1016/j.coesh.2021.100252.