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Post-fire management impacts on soil hydrology

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Abstract

Research about soil hydrology after wildfire has widely investigated the impacts of many post-fire management strategies on ecosystems with different characteristics. However, despite this ample literature, clear guidelines about the effectiveness and feasibility of the different restoration techniques in environmental contexts showing variable responses still lack. Furthermore, post-fire hydrological modelling is based on mere adaptations of existing models, which often fail to simulate with accuracy the changes in soil hydrology after fire. After a short review about the effects of wildfire on hydrological processes, this study aims to propose an updated overview of the existing post-fire management techniques at both hillslope (afforestation and seeding, mulching, salvage logging, erosion barriers, soil preparation and other novel techniques) and channel (check dams) scales. Moreover, the results of the most recent studies analysing the feasibility of common hydrological models in predicting runoff and soil erosion are analyzed. Most studies have demonstrated the effectiveness of post-fire management techniques, but some uncertainty remains regarding the opportunity of natural recovering or implementation of soil and vegetation restoration. The optimal solution in fire-affected areas may be a combination of actions (at hillslope and channel scales), whose effectiveness should be evaluated on the watershed scale. The existing hydrological models should be specifically adapted to burned conditions with reliable simulation of soil changes due to fire. Modelling experiences with focus on the effects of post-fire management actions are needed.

Keywords: infiltration; water repellency; runoff; mulching; soil loss; hydrological models.

1. Background

Wildfire is a natural and anthropogenic agent with a long history of influence on terrestrial and aquatic ecosystems [1]. The wildfire effects, which mainly depends on fire severity, extend in several components, such as soil, vegetation, air, and surface and deep water [2], determining strong changes in the ecosystems affected by fire. Wildfire can have positive impacts on soils, increasing fertility and weathering, particularly in fire-affected areas where mild morphological conditions and rapid vegetation cover limit post-fire erosion [3]. The magnitude of these changes varies according to the pre-fire environmental conditions of the burnt areas, wildfire characteristics, and post-fire weather dynamics and human actions [4,5]. The vegetation burning coupled to the alterations in the physico-chemical properties of soils modify the soil hydrology with possible increases in surface runoff as well as soil erosion and degradation rates. Overland flow and eroded sediments generated on hillslopes easily reach the catchment channels, producing severe hydrological effects compared to unburned areas [6]. These negative impacts may lead to loss of biomass productivity and decline on short- to medium-term soil biodiversity [7] beside geomorphologic changes in the rivers and landscape. Moreover, the wildfire effects may extend in the space and in time. As a matter of fact, increases in flood risk and pollution of downstream water bodies can be recorded outside of the burned area, and the pre-fire conditions of the burned ecosystem may be restored after a period varying from few months to several years. Fire-induced changes on soil hydrology also affects forest ecosystem services, including water resource availability, quality of water bodies, erosion and flood control, and biodiversity maintenance [8].

This study carries out an updated overview of the most common post-fire management techniques as well as hydrological models reported in a selection of papers published between 2017 and 2021 and selected using relevant keywords from Scopus and Web of Science databases. This overview aims at: (i) understanding the effectiveness of each technique on post-fire hydrology of burned and restored soils across different environmental contexts; (ii) analysing whether the available hydrological models are effective in simulating post-fire hydrology. Finally, scientific literature gaps and future research directions are discussed.

2. Wildfire effects on soil hydrology

The occurrence of wildfire produces an increased hydrological response in recently burnt areas, especially during the "window-of-disturbance" [9]. In this period, the soil vulnerability to runoff and erosion effects increases compared the unburned forest areas [4,10]. After the window of disturbance ends, the background pre-fire hydrological conditions tend to be restored throughout periods lasting from few months to several years, that is, after the vegetation cover is re-established and the magnitude of soil erosion is reduced [8,11]. The extent of the fire-induced changes in soil hydrology strictly mainly depends on wildfire intensity (i.e., the energy release rate) and severity (i.e., the magnitude of changes in the burned ecosystem) [12]. However, other environmental factors play important role on changes in fire-affected ecosystems, such as type and physico-chemical properties of soils, topography, fire history, fuel quantity, vegetation species, weather patterns, etc. [13][14]. The wildfire characteristics drive the effects of regenerating vegetation cover on hydrological properties of soil as well as the changes in the properties of the affected soils [15,16]. Fire reduces (in the case of low-severity fire) or completely removes (for fires with high severity) the canopy and ground cover of vegetation and litter. Therefore, interception and evapo-transpiration decreases, and net precipitation increases, leading more water available for runoff [8,11]; moreover, a soil left bare due to vegetation burning becomes more susceptible to raindrop impact and particle detachment. Wildfire also modifies the physico-chemical properties of the soil surface in many ways that influence the hydrological response to precipitation events based on the heat released [17,18] (Figure 1). Wildfire impacts on soil properties can be direct or indirect. Direct impacts, which are related to burning duration and fire temperatures, are usually short and restricted to the upper layer of the soil (few centimetres from the surface). The indirect impacts of wildfire depend on several factors, such as the ash release, vegetation cover, morphology as well as post-fire weather patterns and management [13,19–21]. More specifically, ash is a key driver of the hydraulic response of the burned soils (depending on its depth and type). Ash can either increase the soil water retention and reduce the soil water repellency or might seal the soil surface, reducing water infiltration and increasing surface runoff and flooding [15,18,22]. Ash impact on hydrological characteristics of burned soil depends on its colour; in more detail, black ash, generated by lower fire temperatures, acts as a mulch with a wettable cover for soil, retaining rainwater and improving infiltration, while gray to white ashes of higher severity fires, clog soil pores and generates surface sealing, increasing overland flow and erosion processes [23]. As result of wildfire impacts, in burnt areas, sealing, surface crust formation, pore clogging, and bulk density increase [1]; moreover, soil organic matter and macro-nutrients are lost and its structure can be modified by fire. The depletion of soil organic matter has a substantial effect on soil properties such as the structure as well as chemical and biological properties [19]. In turn, these effects on soil physico-chemical characteristics can influence the hydraulic properties, such as water repellency, water retention, hydraulic conductivity and sorptivity. wildfire particularly impacts on aggregate stability and water repellency of soils, and also these effects on soils depend on temperature and duration [24]. Soil aggregate stability is not altered or slightly increases at temperatures up to 220 °C, while it is strongly reduced between 380 and 460 °C [25]. Soil structure is irreversibly disrupted over 460 °C [24], while, in contrast, clayey soils can show increased aggregate stability at high temperatures

[26]. Soil water repellency does not noticeably change at temperatures under 200 °C, increases between 250 and 300 °C, and completely disappears over 300-400 °C [13] [25] (Figure 1).

The changes in soil properties due to wildfire determine noticeable impacts on post-fire hydrology, such as reduction in water infiltration or shifts in runoff generation mechanisms [1,15,18]. However, the changes in soil hydrology are differentiated between low- and high-severity fire. For low severity fires soil heating is negligible and the impact on soil cover is minimal: therefore, overland flow and soil erosion are reduced compared to high severity wildfires; conversely, in areas affected by high-severity fires, large amounts of fuel are burnt and soil can reach very high temperature (up to 600-800 °C): the impacts on soil hydrology can be extremely negative, such as strong water repellency and very low infiltration capacity [13] (Figure 1). Overall, soil burn severity is considered as a key descriptor of the magnitude of the changes in the soil for its implications on both the hydrological response and vegetation recovery [27].

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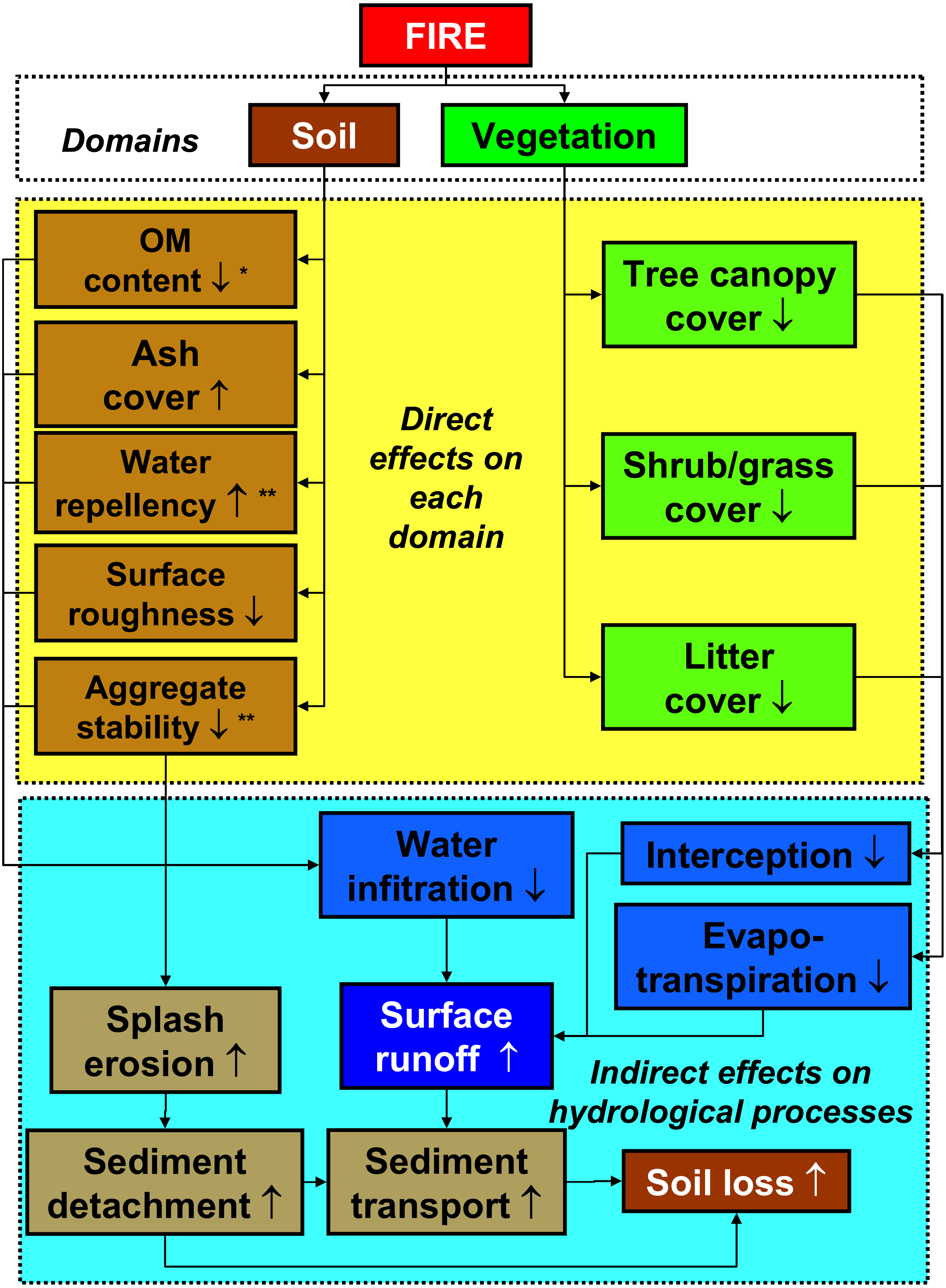

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133 Notes: * Changes in organic matter (OM) content depend on fire severity, since OM can increase in low-severity fires
134 or can decrease after fires with high severity.

** Changes in soil water repellency and aggregate stability depend on fire severity (soil water repellency: no changes under 200 °C, increases between 250 and 300 °C, and disappearance over 300-400 °C; soil aggregate stability: no changes or slightly increases under 220 °C, decreases between 380 and 460 °C, and aggregate destruction over 460 °C, except for clayey soils, which can show increased aggregate stability at high temperatures);

*** green, brown and blue-coloured boxes refer to the three environmental domains affected by wildfire (vegetation, soil and water, respectively).

Figure 1 - Scheme of wildfire effects on soil and vegetation with implications on soil hydrology.

3. Monitoring of post-fire management strategies on soil hydrology

The need to mitigate the fire impacts on soil's hydrological response has increased the use of post-fire treatments, whose effects have been largely experimented mainly in the United States, Australia and Europe [28,29]. The objectives of post-fire management are flood control, reduction in soil loss and sediment yield, restoration of the ecological functions, and management of the residual fuels to mitigate the future wildfire risks [14,30] (Figure 2).

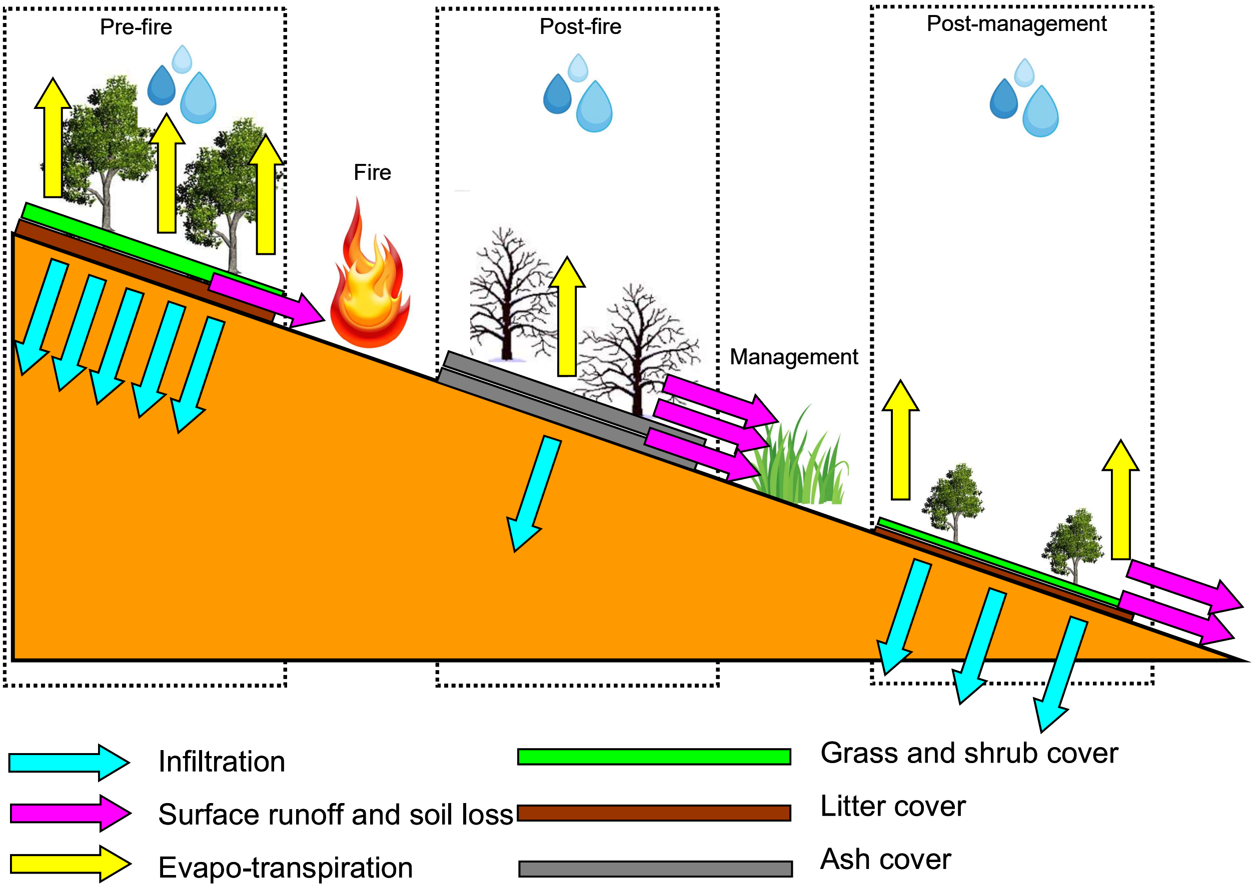

Figure 2 - Scheme of the hydrological processes acting before and after wildfire with the effects of post-fire management (adapted from [31]).

Post-fire treatments can be adopted as emergency or restoration strategies to reduce soil degradation and control floods in fire-affected areas. These treatments can be practised both on hillslopes and river channels. Hillslope treatments (e.g. afforestation, seeding, mulching, salvage logging, erosion barriers - the latter including log erosion barriers or contour felled log debris - or soil preparation) are targeted to quick restore vegetation and soil cover, remove residual fuel to burn, protect soil from raindrop impact, reduce overland flow, trap sediments, and increase water infiltration [13]. Channel treatments (such as the construction of rock or concrete check dams) aim at delaying the flood propagation, reducing the sediment transport in watercourses, and retaining eroded sediments [32].

3.1. Afforestation and seeding

Afforestation is targeted to increase the vegetation cover and improve the soil hydrological properties in areas affected by wildfires. However, the artificial vegetation cover is often less dense and stable compared to natural reforestation. After being seeded, the new plants need time to properly establish in new field conditions, being soil cover by new plants delayed for some years. Although being generally successful, in some cases post-fire afforestation may lead to increased runoff and erosion, because some tree species (such as pines) increase soil water repellency; furthermore, the use of highly flammable trees increases the risk of future frequent wildfires [15].

3.2. Mulching

In agricultural lands, rangelands, fire-affected areas and anthropic sites, mulching is widely used to limit the negative impacts of surface runoff and soil erosion [29,33]. Mulching is targeted to increase infiltration rates, ground cover and soil quality, if used properly and at the correct time [11]. This treatment consists of dispersing on the soil surface organic and inorganic materials as an alternative surface cover, such as agricultural straw, plant leaves, plastic film, logging slash, shredded barks, wood strands, chips and shreds, as well as gravel and loose soil [34,35]. Among the different mulch materials, vegetal residues are considered the most effective to reduce the soil hydrological response also in agricultural soils [33]. In general, organic residues, such as straw and wood residues, are preferred to other mulch materials, due to its wide availability, high soil covering capacity, low cost and easy-of-handling [4]. Agricultural straw can be applied from the air (heli-mulching), thus allowing the treatment of extensive burned areas in a relatively short time

[36]. The selection of the mulch material depends on the local availability and effectiveness, but also on the area to be treated. Large burnt areas with difficult access are more expensive to be treated, forcing the adoption of lower application rates [34,35].

Hydrological response of soil is effectively reduced by mulching, thanks to three effects: (i) increase in interception of raindrops and thus reduction in rain splash detachment; ii) reduction in surface sealing and crusting, thereby increasing infiltration; and (iii) increase in surface roughness and slowdown of velocity of overland flow that results in lower soil detachment by sheet and concentrated flows [35,37]. These effects of mulching help stabilizing soil, reducing sediment movement, preventing the loss of soil productivity and preventing the risk of flooding [38]. Generally speaking, soil mulching after wildfire is more effective against erosion than its impact on runoff discharge [29].

Several factors influence the effectiveness of mulching on soil hydrology (e.g., resistance to physical degradation, strand length, thickness of the application), but the application rate and ground cover are considered as the most important factors [34,35]. Application rates range from 1 to 11 Mg ha^{-1} with straw and forest residue mulches for post-fire unlogged environments until 20-fold values for skidder-compacted soils [35]. More specifically, with regard to the ground cover, a mulch cover rate of 80% using straw and forest residues have been reported to decrease runoff and erosion by 50% and 80-90%, respectively [35,37]. Short-term studies showed that wheat straw mulch treatment reduced the erosion rates by 50-99% in the first two post-fire years at 70% or more ground cover [20]. Concerning to the mulch application rate, straw mulch at rates of 0.6 to 1 Mg ha^{-1} reduces soil losses by 45-70%, while under forest residue mulch at rates of 1 to 2.6 Mg ha^{-1} soil erosion decreases by 65-90% during the first post-fire year [4]. As a general rule, it is widely assumed that mulching at rates of 2-3 Mg ha^{-1} above 60% ground cover can significantly reduce post-fire stream flow and soil loss [20,35].

The presence of a mulch cover on soil is able to increase soil moisture, by slowing runoff and increasing infiltration, and reduce topsoil temperature fluctuations and evaporative loss, by impeding solar radiation reaching the soil surface. Such impacts on soil moisture and temperature support the ability of some plant species to germinate and establish [10,33,39,40]. In addition, mmulching enhances and fastens tree regeneration without influencing plant diversity [41].Therefore, mulch application has the potential to change many aspects of the post-fire environment and therefore mulching has become one of the most direct and effective soil restoring techniques after wildfire [29,39].

However, mulching can also have negative effects as post-fire treatment. In some cases, compared to untreated soils, straw may reduce the soil hydraulic conductivity under unsaturated conditions, particularly in the drier season: this suggests caution in mulch use in the case of heavy storm occurrence in summer [42]. Straw mulch can be displaced by wind, which can leave some slopes bare and too much thick layer of straw in other areas, the latter preventing the emergence of vegetation due to the sunlight absence [20]. Moreover, agricultural straw may contain seeds, chemicals and parasites, which can be the sources of non-native vegetation and plant diseases. A possible solution may be the use of mulches from forest materials (e.g. wood strands, chips or shreds), which are less likely to carry non-native seeds chemical residues,and show greater resistance to wind displacement. The forest materials provide similar protection from erosion at equal ground cover rates and show a longer effectiveness, although requiring higher application rates compared to agricultural straw [38]).

Moreover, the research experiences that are proven the effectiveness of mulching as post-fire management treatment have been carried out mainly at the plot scale; therefore, the extent at which the application rates can be effective and the quantification of hydrological benefits on larger scales are still unknown [34]. This means that further research is needed to quantify these key issues for a consolidated use of mulching, especially in the areas where soil erosion by water represents a severe threat, as the areas affected by wildfires [33].

3.3. Salvage logging

Salvage logging as post-fire management technique is based on the removal of dead and damaged trees, often carried out using machinery that drags the wood over the burned soil. This treatment is generally executed in the first two years after wildfire, in order to recovery the economic value of the wood and to reduce the danger of another wildfire [20]. Salvage logging can sometimes be prolonged, when the recovered wood must be used for other purposes, such as wildfire wood or log home [2].

Generally speaking, salvage logging heavily impacts on soil properties, particularly in the short-term after torrential rainfalls, determining soil degradation [43]. The hydrological effects of salvage logging can be contrasting. This technique may be beneficial, if the water repellent layer is broken up - and thus the infiltration is increased - as well as the addition of logging slash is able to increase the surface cover, with consequent decreased erosion rates. Conversely, salvage logging can have heavy hydrological impacts, since the machinery and logging equipment exert a high pressure on soil, with consequent compaction and rut formation from logging traffic [11,20]. Skid trails formed by machine wheels create preferential flow paths, where surface runoff may concentrate and its sediment transport capacity increases [44]. Post-wildfire salvage logging is able to increase flooding and soil erosion over an area by two orders of magnitude compared to the undisturbed soil [20]. Moreover, the disturbance of salvage logging can affect soil properties and vegetation regeneration for decades [15]. A possible countermeasure may be mitigating the increased erosion rates with post-fire treatments (e.g., distributing available treetops and branches on skid trails and landings), to protect the logged areas from surface erosion [20]. The impacts of salvage logging on vegetation are also uncertain, as shown by the very low vegetative re-growth rates recorded immediately after a wildfire compared to the long-term regeneration [44].

3.4. Erosion barriers

Erosion barriers have been used for decades to stabilize hillslopes and mitigate post-wildfire runoff and erosion. These barriers are made of inert or vegetal materials, the latter having the advantage of being biodegradable. The erosion barriers are classified into contour-felled logs, straw wattles, contour trenches, straw bales, fascines, vegetal strips and buffers [16]. The use of erosion barriers prevents sediment delivery to downstream water bodies by slowing down runoff, causing localized ponding, and trapping sediments [15]. Some erosion barriers have been shown to have a sediment trapping rate of 40% or more, and resulted to be very cheap compared to other hillslope stabilization techniques [16]. Contour-felled logs were found to be even very effective to reduce runoff and sediment yield on burned forest subject to machinery salvage logging, provided that the barrier distance is higher than 20 m [40]. Literature reports also some cases in which erosion barriers have not been successful in reducing post-fire soil erosion, presumably due to the excessive burn severity of the wildfire or defective construction (e.g., [45]). The decrease in post-fire erosion rate over time is also attributed to the soil improvement and vegetation recovery [45]. It has been demonstrated the beneficial effects of log erosion barriers and contour-felled log debris on promote soil multifunctionality and plant diversity to recover community-level properties and forest functions also in the short term after wildfire [46]. In this sense, log erosion barriers are slightly more effective in improving soil quality and vegetation regeneration compared to contour-felled log debris, and these beneficial effects help retaining sediments and limiting nutrient loss, which is essential to recover vegetation after a wildfire [28].

However, this technique is mainly effective for low-intensity rainfalls, since the barriers easily get overtopped after high-intensity rains; furthermore, they lose their effectiveness due to the progressive sediment accumulation and material degradation, if not maintained or regularly cleaned [15,40]. Research still has to quantify the direct impacts of the different types of erosion barriers, since this technique has been generally adopted in combination with other post-fire management strategies (grass and vegetative barriers or contour-felled logs) [16].

3.5. Soil preparation

Soil preparation (e.g., by tillage, conditioning and terracing) is considered as a viable practice to reduce the hydrological response of soil, particularly in croplands (e.g., [47–49]). However, when used for post-fire management, these techniques may be less beneficial for improving soil quality and hydrology (e.g., [37]) and furthermore expensive, when very large forest areas must be treated. As a matter of fact, soil tillage is theoretically able to break up fire-induced soil water repellency or sealing and increase infiltration [20,38]); at the same time, tillage can decrease organic matter content and worsen structure degradation of soil, leading to a decreased infiltration (at least in the short-time) and resulting ineffective to reduce runoff and erosion [50]. Soil tillage may synergistic with other post-fire techniques, since this can increase the capacity of limiting runoff and erosion in same cases by 20% [37]; in this direction, future research must watch at the integration of the most effective post-fire management techniques with soil pre-treatments that are able to increase the hydrological restoration capacity of burned areas.

3.6. Other techniques

The success of natural fibre webs for supporting vegetation growth and soil stabilization in degraded hillslopes, highway and railway embankments and construction sites has recently suggested the use as mats and rolls made of coconut fibres as post-fire restoration techniques. Coconut fibre webs have been found to delay the time to runoff generation, enhance soil infiltration capacity, decrease splash erosion and reduce the velocity of overland flow [15]. The application of moss crust, which is a very fast soil colonizer after wildfires, may also be beneficial in the first periods after wildfire. Although the runoff response of the soil increases, sediment and organic matter losses can be reduced by over 60% and 30%, respectively, especially during the rainiest season [51]. Moreover, mosses are important for restoring soil functionality after high-severity fires (particularly in terms of fertility and microbial activity), thus improving post-fire vegetation recovery [52].

3.7. Check dams

The use of check dams is presumably the most common measure to control soil erosion in channels, particularly under the semi-arid conditions [32,53]. This technique has been proposed and applied since long time to trap sediment and stabilize channels also in burned catchment of different size and conditions. Check dams are built of rock, wood, straw bales, rock gabions or a combination of these materials in ephemeral channels draining low-order catchments [54]. In general, the sediment storage capacity of check dams directly depends on its height and channel slope [55,56]. As post-fire management strategy, the use of straw bale check dams is largely diffused in USA, due to their quick and easy installation in burned catchments. However, the effectiveness of this channel treatment is questionable for three main reasons. First, the treatment is unsuccessful in primary watersheds or small catchments, since fine sediments and ashes wash permeate the structures and are released into higher-order channels. Second, the straw bale check dams are prone to an easy failure, because of piping and stream dragging. Third, once the check dams are filled with sediments, their storage capacity is depleted, and this occurs just after two years post-fire. Overall, the installation of light check dams such as straw bales is viable only in areas with low rainfall intensities and soil with low erodibility [54]. However, research about the effectiveness of check dams in burned catchments has not been sufficient to explore the large variability of climatic, geomorphological and vegetation conditions, in order to deeply assess the contribution of channel structures as catchment level. It is likely that check dams are able to reduce the catchment connectivity, but their effectiveness in reducing the runoff and erosion rates is less pronounced compared to hillslope treatments, once the water and sediment flows are already mobilised across the torrent system.

4. Modelling post-fire management impacts

In areas affected by high-severity fires, accurate hydrological predictions using computer-based models help land managers in the adoption of the most suitable actions to mitigate post-fire land degradation and rehabilitation planning [57,58].

An ample and eminent literature exists about modelling experiences in burned forests [59]. To summarise, simple empirical and semi-empirical models (such as the Universal Soil Loss Equation, USLE, the Morgan–Morgan–Finney model, MMF and the revised versions [31,57,60], and physically-based models (such as the Water Erosion Prediction Project, WEPP, the Pan-European Soil Erosion Risk Assessment, PESERA, the Soil and Water Assessment Tool model, SWAT) have been widely tested with results generally showing sufficient reliability and accuracy [58,61]. These modelling experiences have relied on adaptations of existing hydrological models to fire-induced changes [31,62]. A recent review of Lopes et al. [63] reports that 73% of the related case studies involved model adaptation to burned conditions. The existing models do not usually account for the impacts of wildfires on vegetation cover and soil properties [64]. In general, fire-adapted algorithms, methods to parameterize post-fire vegetation and soil properties, empirical “fire factor” or adjustments of input parameters - such as ground cover, surface roughness or soil hydraulic properties - have been proposed for the existing models (e.g., [31,58,60,63]). According to the latter authors, only 21% of the reported studies attempted to accommodate new processes and 27% of the papers have tested the accuracy of the models in simulating the effects of mitigation measures. Referring only to the most recent experiences, only Nunes et al. [64], using SWAT to simulate post-fire afforestation, Pastor et al. [65], working with the long-term soil erosion “LandSoil” model under post-fire mulching, combined with riparian vegetation maintenance/restoration and reduced tillage, as well as Vieira et al. [31], comparing MMF, RUSLE and PESERA models for mulched areas, and Zema et al. [57], using an adapted version of MMF in post-fire pine stands treated with mulching, have evaluated the accuracy of these hydrological models to simulate soil hydrology under post-fire management measures. Vieira et al. [31] concluded that the RUSLE model seems to be ideal for prioritization of areas prone to wildfire risks, mainly due to its simplicity and reduced data requirements, while the more complex MMF and PESERA models are more suitable for testing different land management scenarios. Zema et al. [58] have adopted a novel approach to post-fire hydrological modelling, proposing an Artificial Neural Network to predict with very satisfactory results surface runoff and soil erosion after wildfire under Mediterranean climate conditions.

Overall, it can be concluded that the available literature about post-fire hydrological modelling is not homogeneously distributed worldwide, in accordance with Lopes et al. [63]. Erosion modelling is well developed in the U.S.A., where post-fire prediction models are commonly applied, but in other regions, where the hydrological processes may be site-specific, research is still far from being exhaustive [60]. For instance, Mediterranean burnt areas have intrinsic conditions (e.g., very shallow soils, strong soil water repellency, peculiar hydrologic regime). In these environments, the available hydrological models, developed in other climatic contexts and not in fire-affected areas, may find limited applicability and therefore require targeted modifications [31]. As previously outlined, the hydrology of burned areas is extremely complex, due to the large number of influencing factors, and the post-fire management techniques are numerous and different in nature. Therefore, the simulation of the hydrological response of burnt and treated soils is a challenging task, which requires further research [61]. The statement by Lopes et al. [63] can be shared, given the evidences that such studies should alternatively adapt the existing models to the hydrology of burned and treated soils or develop new prediction tools under variable post-fire conditions and management [63]. The exploitation of powerful analytical techniques, such as the remote sensing, to derive ground cover and soil properties (e.g., water content and burn severity maps) from soil survey maps may enhance the prediction accuracy and the easiness of use of these tools.

5. Future perspectives and conclusions

The intense research and discussions about the hydrological effects of post-fire management is still open, and even some uncertainty remains whether some areas should recover naturally or it is more convenient to implement soil and vegetation restoring measures [14,30]. On this context, the discussion above has demonstrated the general effectiveness of hillslope and channel measures after wildfire on both soil and vegetation components.

However, despite the large availability of effective post-fire management techniques, it is clear that the optimal solution in fire-affected areas remains a combination of these actions. In other words, the post-fire management techniques should be synergistically integrated in a holistic approach that has to consider the integrated hydrological response of the watershed system [66]. Moreover, because of the wide-ranging temporal and spatial effects of each management technique, upscaling the research from the hillslope or channel scale to the watershed scale is warmly recommended, in order to better understand the effects of each technique at large spatial scales [11]; their effects after years or decades must not be neglected rather than limiting the analysis to the short-time impacts.

Despite the large body of studies that have evaluated the effectiveness of the post-fire management techniques in a wide range of climatic, geomorphological and ecological conditions, more experiences are needed to identify the most effective strategy, which should to be tailored to site and wildfire characteristics [15]. In this sense, comparative studies of more than one technique against the negative hydrological impacts of post-fire management are welcome. These studies would give as support the scientific evidence about the effectiveness of each action in a territory of specific characteristics. However, there is also a need to develop methods of feasibility assessment using suitable indicators about the sensitivity of each environmental context to wildfire and the benefits of the different techniques. This assessment can help prioritising the management actions in restoration projects, due to the fact that the cost of mitigation measures may be prohibitive over very large fire-affected areas [67].

Regarding the prediction of the hydrological effects of post-fire management using computer models, future research paths should go towards a large applicability of post-fire models, which currently is not homogeneously distributed worldwide. The existing models should be adapted as much as possible to burned conditions with attention to the impacts of soil changes in runoff and erosion generation mechanisms. Many studies have limited their evaluations to existing models under burned and unburned conditions; research should go ahead, focusing the effects of post-fire management actions, since these types of modelling experiences are generally scarce and confined to very few environments and techniques. Finally, future modelling studies should include uncertainty analysis, in order to give modellers the level of reliability and accuracy of their hydrological predictions [63].

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