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Quantification of water erosion in a burnt *Pinus halepensis* Mill. pine forest in Gouraya National Park (Bejaia, Algeria) and restoration proposals

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Summary: The present study assesses the efficacy of a technique for mitigating soil erosion following a forest fire at the Fort Lemercier site, situated within the Gouraya National Park in Bejaia. The treatment employed was the utilization of burnt tree branches harvested on site from the bases of burnt trees and shrubs. Sediment yields were quantified through the use of sediment fences in eight plots, each measuring 15 m², with four plots remaining undisturbed and four plots covered with burnt tree branches. The study examines soil losses subsequent to a fire, revealing notable discrepancies between menaged plots (MP) and unmanaged plots (UNP). The soil loss for MP ranged from 5.50 g to 319.00 g, while for UNP it ranged from 13.00 g to 3238.50 g. The maximum average loss was observed in UNPs, reaching 856.00 ± 32.62 g, compared with 139.36 ± 26.57 g for MPs. A significant negative correlation was established between soil losses and the degree of vegetation regeneration, as measured by cover. This correlation was stronger in MPs (coefficient = -0.85) than in UNPs (-0.61), indicating that vegetation regeneration has a greater impact on managed plots. From February 2018 onwards, significant revegetation of the plots led to a significant reduction in soil losses, which reached very low levels.

Key words: Forest fire, quantification, water erosion, erosion control, burnt branches, pine forest.

Introduction

Forest fires are a common and natural occurrence in Mediterranean ecosystems, resulting in increased soil erosion, transport, and sediment production in the short and medium term (Fernández-García, 2019 and Rodrigo-Comino et al., 2020). To mitigate the immediate impact of these fires and heavy rainfall, the implementation of post-fire management strategies is crucial for promoting long-term ecosystem recovery. This can be achieved by reducing runoff velocity and sediment transport processes (Robichaud et al., 2013 and Vieira et al., 2016).

Among the emergency stabilization measures, two main techniques are typically employed. The first approach entails the protection of the soil through the implementation of mulching or reforestation techniques. The second strategy is designed to retain runoff and sediment by the installation of physical barriers along slopes and watercourses (Aristeidis and Vasiliki, 2015; Badía et al., 2015 and Girona-García et al., 2021).

Nevertheless, it is frequently advised that the natural regeneration of burnt forests be encouraged in order to accelerate the vegetation recovery process and protect the soil. The findings of studies have demonstrated that plantations, when considered in isolation, can have constrained effects. This underscores the significance of enabling the forest to regenerate naturally with minimal intervention (Vacca et al., 2000). It is essential to monitor natural regeneration meticulously and implement targeted intervention only when necessary. It is crucial to avoid heavy intervention that could exacerbate soil erosion (Valette, 1999).

A variety of techniques are employed to stabilize areas affected by forest fires. Among these techniques, log retention barriers are considered to have the least impact on the environment and are relatively affordable. This approach is designed to control erosion processes and promote natural forest regeneration (Dimitrakopoulos et al., 2011; Fernández-García et al., 2019; Figueiredo et al., 2017; Hosseini et al., 2016; Robichaud et al., 2008b; Robichaud et al., 2010; Robichaud et al., 2013 and Robichaud et al., 2020).

In Algeria, despite the significance of fires, particularly in the coastal zone, which is the country's most densely forested region, techniques for restoring burnt areas have yet to be tested.

In this study, we propose to test the efficacy of a restoration technique analogous to that of log retention barriers in areas of the *Pinus halepensis* pine forest in Gouraya National Park (GNP) (Bejaia, Algeria) that have been subjected to fire. The primary objective of this study is to assess the efficacy of the employed treatment in terms of soil stabilization and erosion reduction, as indicated by the quantity of sediment retained in comparison to untreated control plots. Furthermore, the impact of this restoration technique on post-fire vegetation dynamics is assessed.

Approach and description of the study area

The study area is situated in eastern Algeria, covering an area of 2080 hectares. It is located at the following coordinates: 36° 46' North and 05° 06' East. The topography of the area is defined by precipitous slopes, which typically exceed 25% in gradient. From a phytogeographical perspective, the park is situated within the Petite Kabylie sub-sector, the Kabyle and Numidian sector, and the Mediterranean Maghreb domain, as defined by Quezel and Santa (1962). The park area is characterised by a diverse range of rock types, including liasic limestone, Numidian sandstones and clays, dolomitized limestone, conglomerates, sandstone marls, quartzite sandstones, shaly marls, red and green shales, interbedded lenticular limestone, marnocalcareous and flysch, as well as alternating large quartzite beds and phyllite shales (Duplan and Grevelle, 1960).

The present study was initiated three months after the fire that occurred on July 21, 2016, which resulted in the destruction of 165 hectares of vegetation, including the Fort Lemercier pine forest, which is situated within the boundaries of the GNP. The study area is distinguished by a sub-humid Mediterranean climate, characterised by arid, hot summers. The rainy season in this region extends from late September to mid-May, with an average annual rainfall of 921.04 mm (climate data recorded at the Bejaia-aeroport station for the period 1970-2015).

Before the fire, the burnt area consisted mainly of matorral planted with Aleppo pine (*Pinus halepensis*), with undergrowth dominated by *Quercus coccifera*, *Olea europaea*, *Ceratoniasiliqua*, *Pistacia lentiscus* and *Myrthus communis*. The private land surrounding the burnt area is made up of small olive orchards and other fruit trees, where the owners also used to keep bees.

Figure 1: The limits of the July 2016 fire (source: Google Earth, image from May 2017)

Choice of experimental site

The experimental site was selected for its topographical homogeneity (15 to 20% slope), homogeneity of the pre-fire vegetation cover, and its location within a protected area (Gouraya National Park), which provides optimal security for the experimental site.

Installation of the experimental set-up

Following an examination of the area affected by fire, homogeneous plots with equivalent slopes were selected for the experimental set-up. The spatial resolution of the erosion measurements was defined at the scale of individual 15 m² plots (3 × 5 m, in the direction of the slope), permitting quantification of local erosive processes. This scale was chosen in order to accurately assess the effectiveness of burnt branches as a localized treatment.

Plot limits were materialized by tarpaulins buried at a depth of 10 cm to avoid lateral transfers of sediment, thus ensuring the independence of measurements between adjacent plots.

Eight (08) experimental plots were delimited. Four of them serve as controls (without intervention, PNA), while the other four are covered with burnt tree branches (PA). These branches are placed on the ground in such a way as to establish direct contact with the surface, in order to block sediment transfer.

The sediment clotures, which are U-shaped and placed transversely over a 30 cm rise to effectively capture runoff water and sediment transported by rain. The fences are constructed from perforated plastic material connected to 60 cm-long steel bars and reinforced with large stones for enhanced structural integrity. To prevent underflow, the edges have been securely affixed to the ground surface.

In the aftermath of heavy precipitation, the sediment clotures are subjected to routine inspection. In some locations, new sediment clotures were installed in the period following the summer of 2017. Subsequent to each episode of heavy precipitation, the accumulated sediment was subjected to drying in order to ascertain its dry weight. Subsequently, the material was weighed using a balance. Moreover, branches were positioned on the ground in a manner that facilitated contact between the branches and the soil, thereby impeding the transfer of sediment. The extent of soil erosion over the initial two-year period following the fire (October 2016 to June 2018) was quantified in order to evaluate the efficacy of this restoration method.

Sediment clotures are routinely inspected after heavy rainfall. In some locations, new sediment clotures were installed in the period following the summer of 2017. After each episode of heavy precipitation, the accumulated sediment was dried to determine its dry weight. The sediment was then weighed using a balance. In addition, branches were placed on the ground in such a way as to facilitate contact between the branches and the soil, thereby impeding the transfer of sediment. The extent of soil erosion during the first two years after the fire (October 2016 to June 2018) was quantified to evaluate the effectiveness of this restoration method.

Additionally, direct observations of vegetation cover regeneration were conducted on the various parcels, employing a scale of 0 to 5 to assess the degree of regeneration on each parcel.

Results

1. Post-fire erosion evolution

The fire resulted in the complete destruction of the vegetation, thereby rendering the soil vulnerable to the effects of precipitation. The initial post-fire procedures entailed the felling of burned trees and the establishment of experimental plots just prior to the onset of autumn rains.

The results demonstrate statistically significant variations (P < 0.001) in soil loss over time following fire for both MP and UNP (Table1). Indeed, the data demonstrated a range of soil loss values for MPs, with an average of 5.50 g. to 319.00 g., representing a notable difference of 313.50 g. In contrast, UNPs exhibited a broader range of soil loss values, with an average of 13.00 g. to 3238.50 g., indicating a considerable difference of 3225.50 g.

Table 1: Soil loss (in grams) from MP and UNP in the first two years after fire. Values are means ± standard error (SE). Values with different letters for each plot type are significantly different (Anova and LSD test, p<0.05).

Post-fire date	Aerage ± SE soil loss (SL) in g. (MP) en g.	Aerage ± SE soil loss (SL) in g. (UNP) en g.
07 months (02. 2017)	250,75 ± 41,99 ab	1278,00 ± 39,62 c
10 months (05. 2017)	319,00 ± 46,99 a	1002,00 ± 55,44 d
16 months (11. 2017)	179,75 ± 28,88 bc	3238,50 ± 69,02 a
17 months (12. 2017)	269,00 ± 64,81 ab	1695,00 ± 77,91 b
18 months (01. 2018)	124,25 ± 36,51 bc	252,50 ± 17,01 e
19 months (02. 2018)	32,75 ± 4,17 cd	71,75 ± 4,96 f
20 months (03. 2018)	38,25 ± 7,82 de	82,75 ± 11,61 f
21 months (04. 2018)	35,00 ± 7,33 de	70,50 ± 14,91 f
23 months (06. 2018)	5,50 ± 0,65 e	13,00 ± 3,11 f

The results demonstrate that during the initial seven-month period following the Fort Lemercier pine forest fire, specifically after the first precipitation event, the mean soil loss was 250.75 ± 41.99 g for the MP and 1278.00 ± 39.62 g for the UNP (Table1). It is important to note that the soil measurements were taken after the debris had been sieved. During the initial period following the fire, this debris, along with the ash, constituted the majority of the material retained by the system. Consequently, following the initial effective precipitation in January 2017, the quantity of retained soil exhibited diminished values in comparison to the period between May and December 2017 (Table1).

A statistical analysis of the data indicates that the greatest soil loss occurs during the initial 18-month period following a fire, regardless of whether the area in question has been managed or left unmanaged.

The extent of vegetation recovery beyond 18 months after the fire, i.e., from January 2018 onwards, has a positive effect on erosion, considerably reducing soil loss. Indeed, despite the fact that the plots are undeveloped, they do not exhibit as much soil loss as was observed during the initial monitoring period, when compared to the developed plots. As evidenced in Table1, the recorded soil erosion levels demonstrate a notable decline from 124.25 ± 36.51 g to 32.75 ± 4.17 g for MP and from 252.50 ± 17.01 g to 71.75 ± 4.96 g for UNP, representing a reduction of approximately 75% between January and February 2018. It can be concluded that burned areas are particularly vulnerable before the spring of the second year after disturbance. Following this date, the vegetation is sufficiently recovered to protect the soil from erosion.

2. Effect of management on soil loss

The use of burnt-cut branches as a management strategy demonstrated a significant effect on the amount of soil eroded, particularly during the initial observations conducted within the first 18 months following the fire. The results demonstrate a statistically significant reduction in soil loss in the MPs (Table 2). Indeed, the maximum average soil loss over the entire sampling period was observed in the UNPs, with a value of 856.00 ± 32.62 g, in comparison to 139.36 ± 26.57 g in the MPs. The data indicate a notable reduction in soil loss during the second year following the fire (February to June 2018), even during the most intense rainfall events (as observed during the period from March 17 to 27, 2018; see rainfall data in the appendix). This reduction was observed in both MPs and UNPs, with respective averages of 27.88 ± 4.99 g and 59.50 ± 8.65 g.

Table 2: Comparison of soil losses between MP) and UNP for each sampling date (t test, N1 = N2 = 4, theoretical t = 2.45, non-significance is indicated by NS).

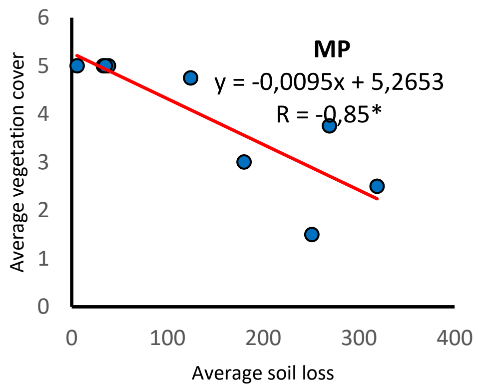
	07	10	16	17	18	19	20	21	23

	months	months	months	months	months	months	months	months	months
$t_{observed}$	17,79	9,40	40,88	14,07	3,18	6,02	3,18	2,14	2,36
p-value	<0,001	<0,001	<0,001	<0,001	0,019	0,001	0,019	0,077	0,056
Signification	***	***	***	***	*	**	*	NS	NS

The results demonstrate that erosion is most pronounced in the MPs (t-test, Table 2). The erosion rate is 18 times higher at 16 months post-fire, and 3 and 5 times higher, respectively, at 10 and 7 months post-fire. Following the 18-month period following the disturbance, erosion levels in unmanaged plots are approximately twofold those observed in managed plots. It is noteworthy that, with the exception of the final two sampling dates, erosion is statistically higher in UNPs across all sampling dates. This is likely due to the effective recovery of vegetation. These results demonstrate the effectiveness of the management techniques used to limit water runoff and the transport of soil particles.

3. Effect of management on vegetation regeneration

Figure 2 illustrates a notable negative correlation between soil loss and the degree of vegetation regeneration, as indicated by cover on a scale from 0 to 5. This correlation is particularly pronounced for MP, with a coefficient of -0.85, and less so for UNP, with a coefficient of -0.61. However, this correlation was found to be significant for MPs and not significant for UNPs (Pearson correlation coefficient test, $p < 0.05$). From February 2018 onwards, the very important regrowth of vegetation in the parcels considerably reduced soil loss, bringing it down to very low levels. This correlation corroborates the results of the effect of revegetation on erosion, as well as that of management, since despite the relative importance of the correlation for UNPs (R = -0.61), it is considerably weaker than that observed for MPs (R = -0.85).



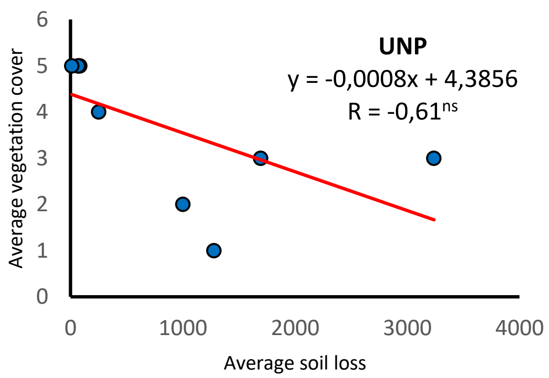


Figure 2: Correlation between soil loss and vegetation cover rate for MP and UNP. The significance of the correlation coefficient (R) is indicated by a star (*) and non-significance by (ns) for P<0.05.

Discussion

1/ Evolution of soil losses after the fire

The 2016 fire caused important damage to the vegetation at Fort Lemercier, leaving the soil exposed and susceptible to intense precipitation. In order to reduce the impact of this situation and to protect the land, experimental parcels were established on the site. These parcels, constructed before the end of October 2016, just before the onset of autumn rains. The objective of these plots was to assess the efficacy of a post-fire treatment utilizing branches from burnt trees and shrubs that had been recovered on the site in question.

Forest fires have been demonstrated to exert a considerable influence on soil loss and post-fire erosion (Dlapa et al., 2013; Dlapa *et al.*, 2015; Pereira et al., 2014; Tsibart et al., 2014 and Tessler et al., 2015). The temporal evolution of soil losses observed during the course of this study revealed some interesting trends. In the initial seven-month period following the fire, relatively minimal soil loss was observed following the first precipitation events in late autumn and winter, as well as subsequent to the destruction of the vegetative cover by the fire. The low soil losses observed can be attributed to the presence of ash and partially burnt plant debris, particularly pine needles, which acted as a mulch. These debris helped to control and mitigate soil losses while protecting the soil from erosion induced by the first winter rains, as the autumn rains were insufficient to cause important losses.

It is evident that the reduction in above-ground vegetation following the fire resulted in alterations to the physico-chemical properties of the soil, leading to a decline in its infiltration rate. This resulted in increased water runoff, transporting the partially burnt plant debris and ash left by the fire (Badía et al., 2011 and Debano et al., 1979). The work of Robichaud et al. (2008, 2010) has also demonstrated that the initial precipitation following a forest fire has the potential to mobilize fine ash particles and transport them in suspension downstream. Prior research has also indicated an inverse correlation between soil erosion and litter cover (Cerdà et Doerr, 2008 and López-Bermúdez et al., 1998).

The study revealed that peaks in soil losses, which contribute to erosion, occurred at the end of winter, 10 months after the fire, and during the spring of 2017, 16 months after the fire. These losses persisted throughout the autumn of 2017 and the beginning of winter 2018, a period of 17 months after the fire, despite lower rainfall during these months. This situation can be attributed to the absence or low presence of protective vegetation cover or residues, in combinations with the impact of precipitation. These observations are consistent with the findings reported by Cerdà et al. (2016), which emphasize the crucial role of vegetation in protecting the soil by intercepting raindrops.

The results of our study are in concordance with the findings of various other studies that have also observed an increase in erosion rates following a fire. Indeed, numerous studies have observed this trend, including those by Campo et al. (2006), Johansen et al. (2001), Giovannini and Lucchesi (1983), Martin and Lavabre (2000), Martin and Moody (2001), Meyer et al. (2001), and Robichaud and Brown (2000). This phenomenon can be attributed to a number of factors, such as the reduction or elimination of above-ground vegetation, the impact of heat on the soil, reduced organic matter, ash cover, and changes due to precipitation on the soil surface (Mataix-Solera et al., 2011; Novara et al., 2011 and Novara et al., 2013). Consequently, the soil is exposed to the impact of raindrops, which reduces its infiltration capacity (Cerdà and Robichaud, 2009; Larsen et al., 2009 and Neary et al., 2005).

In the Mediterranean region, the risk of erosion is particularly high in the first months after a fire, especially after the first autumn rains (Martin and Lavabre, 2000). In Spain, Diaz-Fierros et al. (1987) found that 80% of the total erosion of the year occurred in the first six months after a fire. The main difference with our study is the time frame for erosion, which was extended by more than 7 months due to the very low rainfall in autumn 2016. However, a gradual decrease in soil losses was observed over time, with equivalent and very low values, which can be explained by the regeneration of the vegetation cover. This natural regeneration provides effective protection against erosion. Indeed, the presence of well-established vegetation limits the impact of precipitation on the soil, thus reducing water runoff and the transport of soil particles.

The findings of our study align with those of previous research, indicating that soil erosion rates progressively decline following a wildfire, returning to levels observed prior to the disturbance (Shakesby and Doerr, 2006). Indeed, during the subsequent spring, 19 months after the fire, the notable revegetation of the plots resulted in a pronounced reduction in soil losses, which reached minimal values in June 2018. Indeed, this recovery can extend over a period of three to ten years, depending on the severity of the fires and the post-fire climatic conditions (Giovanninie et al., 1987 and Robichaud, 2009).

This evolution in soil losses highlights the significance of vegetation cover in mitigating soil losses and, subsequently, controlling erosion. In general, an increase in vegetation cover is associated with a decrease in losses, as demonstrated by Gomer and Touaibia (1991) and Mathys et al. (2003). As evidenced by the findings of Meddi and Morsli (2001), soil losses are influenced by a number of factors, including rainfall, vegetation cover, and soil surface condition, with notable seasonal variations. Indeed, vegetation provides a protective barrier against erosion caused by rainfall. Areas exhibiting high vegetation cover have been observed to exhibit notably lower soil loss than areas devoid of such cover.

2/ Efficacy of treatment on post-fire erosion

The management of plots with burnt branches had a significant impact on reducing the amount of eroded soil, particularly during the first months following the fire. This intervention made it possible to establish targeted recommendations for post-fire management.

The detailed temporal analysis (Table III) reveals that the maximum treatment effectiveness is between 0 and 16 months, with a reduction in erosion ranging from 3 to 18 times. During this period, unmanaged plots (UNP) recorded maximum losses of 856 32.6 g, compared to only 139 26.6 g for managed plots (MP). This period corresponds to the one where the branch cover compensates for the absence of vegetation, playing a key role in soil protection. However, after the rain events of the second year (>18 months), the quantities of eroded soil tend to equalize, with losses reduced to 59.5 8.7 g for UNP and 27.9 5.0 g for MP. The difference becomes insignificant during the last samples ($p > 0.05$), which is explained by the good recovery of vegetation on all plots. Fernandez et al. (2011) also observed a similar trend, with very low sediment production during the second year after treatment.

The results of our study confirm the effectiveness of cover treatments, including the use of burnt branches, in reducing soil erosion. These branches were compactly arranged and the parcels were covered with multiple branches, which played a critical role in limiting soil erosion. The compact arrangement of the branches was essential to increase their resistance to natural elements such as wind and rain.

This arrangement of branches allowed to slow down the runoff of water on the plots, acting as obstacles that slowed down the water movement, thus favoring its infiltration into the soil and reducing the risk of water erosion. In addition, the branches promoted plant growth over the entire surface of the PAs, unlike the PNA. Wood residues were also effective due to their resistance to decomposition, while straw mulches, for example, tend to decompose quickly and be carried away by the wind (Badía and Martí, 2000; Faucette et al., 2007 and Fernández et al., 2011), and their ability to absorb the impact of precipitation, thus limiting the movement of sediments. This notable effectiveness is also attributed to the soil cover they provide in the short term, with an optimal coverage of 80 to 90% to reduce erosion. Previous studies such as Robichaud et al. (2000), Ferreira *et al*. (2015) and Vega *et al*. (2013) have validated the effectiveness of cover treatments, particularly wood mulches, in reducing soil erosion. The results of this study support this conclusion and highlight the effectiveness of burned branches.

These results highlight the need to devise combined technical strategies specifically adapted to extreme conditions, such as steep slopes or episodes of intense precipitation, especially during the first post-fire months. With this in mind, the use of fascines made from burnt tree trunks (10 to 15 cm in diameter), fixed by wooden stakes placed perpendicular to the slope, appears to be a promising way of considerably mitigating the high risks of erosion and runoff in these environments.

3/ Effect of treatment on vegetation regeneration

The results of our study revealed a rapid recovery of vegetation. Initially, vegetation regeneration was concentrated on the managed parcels and then gradually extended to all the unmanaged parcels. This evolution of regeneration suggests that the management has favored the stabilization of seeds on the surface of the plots and the capture of seeds mixed with sediment from the outside. The accumulation of sediment behind the branches testifies to their effectiveness in preserving the soil.

The later regeneration observed on unmanaged parcels may be attributed to germination of the seed bank at depth, as surface seeds were likely washed away by runoff, supported by the germination observed first along sediment fences.

The reduction in sediment yield observed during the second year after fire is consistent with results reported in previous studies (Robichaud and Brown, 2000; Robichaud et al., 2008a, 2008b and Wagenbrenner et al., 2006), although longer recovery times have also been reported (Robichaud et al., 2008b). This decrease is due to the natural revegetation of the site, and the treatment had no significant effect on the rate of vegetation cover recovery, which was 80% at the end of the study. Indeed, a study conducted by Ouali and Sekhri (2018) on the vegetation state of a *Pinus halepensis* pine forest in Fort Lemercier (study site) two years after a fire concluded that the vegetation recovered quickly and returned to its pre-fire composition in just two years, and that the most represented botanical families in both vegetation states (pre- and post-fire) were Asteraceae, Fabaceae, Lamiaceae, and Poaceae. These families probably play a crucial role in protecting the soil from erosion since their biological characteristics, such as deep root systems, evergreen leaves forming a dense canopy, fibrous roots acting as a retention network, and robust roots contributing to soil stability, are major assets in preventing soil loss due to erosion. These results highlight the importance of ground cover in reducing soil loss after fire, thereby promoting conditions conducive to forest self-regeneration (Bombino et al., 2023).

Conclusion

In conclusion, this study highlights once again the importance of vegetation cover in protecting against water erosion, as bare soils are more exposed to this phenomenon. Indeed, the presence of vegetation cover or plant residues such as branches and leaves plays a key role in soil conservation by reducing the risk of erosion. Therefore, the integration of burnt tree branches into post-fire management can be a crucial solution to limit soil loss. Through the strategic use of burned branches, it is possible to create physical and biological barriers that promote soil stability and encourage natural vegetation regeneration. This innovative approach demonstrates the importance of taking a holistic view of post-fire management by evaluating the resources available on site to sustainably restore forest ecosystems. Continued research and implementation of such practices is imperative to ensure effective soil management in wildfire-impacted areas.

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