Assessing the Impact of Wildfire Intensity on Soil Hydrology and Stability: The Role of Soil Organic Matter and Mulching Strategies

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ABSTRACT

Wildfires significantly impact hydrology and geomorphology by altering soil properties, which depend on the fire intensity, duration, and frequency. Soil organic matter (SOM) is vital for forest ecosystems, acting as fuel. In this study, unburnt and burnt soils were collected from nearby locations for a prescribed fire site. Additional samples were tested where unburnt soil was mixed with 25% volume of mulch and exposed to a temperature of 150°C and 650°C in a furnace to simulate the exposure to soil with organic matter to high temperatures experienced during wildfires. The variation of soil-water characteristic curves (SWCCs) for these different soil samples was evaluated to assess the impact of exposure to high temperature during wildfires. Results showed that low-intensity fires did not alter soil properties, while high-intensity fires resulted in a change in the soil property in terms of SWCC and physical and hydraulic characteristics, and posed greater erosion risks and disrupt soil stability, highlighting the need for better soil management strategies.

Keywords: Wildfire, soil water characteristic curve (SWCC), natural hazards, mulches

INTRODUCTION

Wildfires are increasingly recognized as significant agents of environmental disturbance, altering soil hydrology, structure, and stability across diverse landscapes. Numerous studies have highlighted the role of fire severity in reshaping hydrological and geomorphological processes. The severity, duration, and frequency of fires determine the extent of soil alteration, with high-intensity fires often leading to substantial degradation of soil organic matter (SOM), increased hydrophobicity, reduced infiltration, and enhanced erosion (Agbeshie et al., 2022; Shakesby and Doerr, 2006). SOM is vital to soil structure and water retention, and its thermal decomposition during wildfires challenges both ecological recovery and slope stability (Santín and Doerr, 2016).

Extensive studies have documented the physical and chemical changes in soil following fires. When soil is heated beyond 300°C, their water holding capacity significantly decreases, and the soil-water characteristic curves (SWCCs) are altered (Akin et al., 2021). Pyroclastic soils subjected to high temperatures show decreased shear strength and increased risk of landslides

(Peduto et al., 2022). Likewise, wildfires lead to increased rockfall activity, attributed to the loss of vegetation and alterations in rock mechanics (Sarro et al., 2021). These results underline the necessity for a deeper understanding of how the soil behaves at various fire intensity levels.

Mulching has become a prevalent strategy used after wildfires to mitigate erosion and support the recovery of soil organic matter (SOM), as well as to demonstrate its beneficial effects on slope stability and plant regrowth (Santos et al., 2020; Kellogg and Vahedifard, 2021). However, there is still a lack of quantitative data concerning its interaction with thermally affected soil and its impact on soil water characteristic curves (SWCCs). SWCC is an essential parameter that governs the strength, stiffness, and hydrological properties of soils (Banerjee et al., 2020c, Ghosh and Banerjee, 2025). Factors such as fire severity, ash accumulation, and the combustion of litter considerably impact the SOM recovery path and water retention properties (Hrelja et al., 2020). Additionally, conceptual frameworks have been developed to clarify geomorphic processes following fires. One biogeographic model suggests that landscapes with intermediate net primary productivity (NPP) are the most susceptible to erosion following a fire, due to optimal fuel levels and soil structure (Noske et al., 2024). Furthermore, hydrological responses and sediment transport differ non-linearly across various environmental gradients, and while models for classifying fuel loads help predict fire behavior, they often fail to integrate with soil hydrological processes (Moody and Martin, 2009; Sikkink et al., 2009). Despite these developments, significant knowledge gaps remain. As fire seasons become more severe, it is crucial to develop a deeper understanding of how SOM and mitigation tactics like mulching affect soil behavior after fires.

This study explores the effects of SWCC in soils subjected to burns at 150°C and 650°C, both with and without 25% mulch coverage. It examines the impact of fire intensity on hydrological behavior and assesses the potential of mulching to mitigate soil degradation. The results aim to inform effective and sustainable soil management strategies in areas prone to wildfires.

Project Description and Site Details

The study was conducted in South Dakota's Black Hills National Forest, a region affected by a mixed-severity wildfire (Figure 1). This site was selected to investigate the impact of various fire intensities on soil hydrology, organic matter degradation, and the effectiveness of mulching strategies in post-fire restoration. Two sites were selected based on burn severity classifications derived from the USGS and the USDA Forest Service Geospatial Technology and Applications Center (GTAC). The dominant vegetation consisted of ponderosa pine (*Pinus ponderosa*), accompanied by a diverse understory of grasses, forbs, and shrubs that added to the fuel load and post-fire ash content.

Two experimental plots, approximately 300 meters apart, were established to investigate soil behavior under varying post-fire conditions. The first plot, known as the "dead tree site," was in a high-severity burn zone marked by total canopy consumption, exposed mineral soil, ash deposition, and visible macropores created by burnt roots (Figure 1-d). The second plot, referred to as the "live tree site," was placed in an area of low to moderate severity where some canopy and litter remained intact (Figure 1-e). This plot served as a baseline to evaluate differences in soil response and recovery (Bonnot et al., 2009).

Soil samples were collected from a depth of 0–10 cm at both sites for laboratory analysis of SWCCs. The wet range was determined using the evaporation method, while the chilled mirror method was used for the dry range. SWCCs enabled the assessment of the soil ability to retain water across different matric suctions, indicating that fire-induced changes in soil texture, structure, and soil organic matter (SOM) content impact hydraulic properties. To evaluate mulching effect, collected soil was applied to mulch at a 25% volumetric weight. This experimental design highlighted that mulch could mitigate the hydrological effects of burn severity by enhancing infiltration, stabilizing the surface soil, and promoting the retention of soil organic matter (SOM). These efforts contribute to a quantitative understanding of the soil hydraulic function in response to wildfire disturbances and management practices in the ponderosa pine ecosystems characteristic of the Black Hills National Forest region in South Dakota, USA.

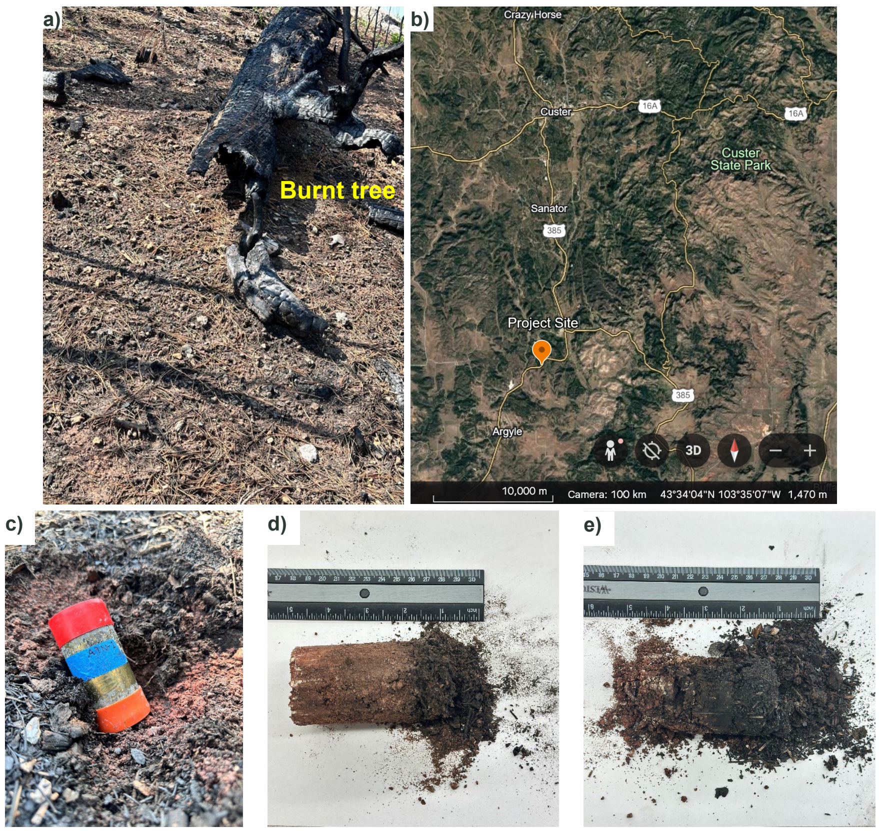

Figure 1. (a) Sample collection area covered with a layer of unburnt soil), (b) site location in western part of South Dakota, USA, (c) undisturbed soil collection area, (d) less severe burnt sample, and (e) highly severe burnt soil

EXPERIMENTAL PROCEDURE

Sample Preparation

Soil samples, both bulk and intact, were collected to a depth of 1.5 meters for soil profile analysis, standard classification, and hydrological tests. Bulk samples were obtained using a hand auger, while intact samples were collected with thin-walled samplers that are 0.127 meters long to preserve their in-situ structure. Additional samples were taken from the surface and a depth of 0.5 meters, aiming to avoid the organic-rich upper horizon and ensure representative data for key parameters related to slope stability and hydrological modeling, including the soil friction angle, saturated hydraulic conductivity, and soil water characteristics.

Samples from both the surface and 0.5-meter depth were analyzed to evaluate organic content, fine fractions, and water repellency, which aid in understanding how wildfire intensity affects hydraulic behavior. Additionally, bulk soil samples underwent loss-on-ignition tests to estimate soil organic matter, while SWCC were measured using a dew-point potentiometer alongside standard classification analyses. The Atterberg limits were determined following ASTM D4318-17e1 standards and shown in Table 1, providing a method for classifying the plasticity of fine-grained soils. Both the intact burnt samples from sites and remolded samples burned at 150°C and 350°C with 25% mulches by volume were used for Atterberg Limit tests. SWCC were obtained with a WP4C dew point potentiometer, using protocols similar to those described by other studies (Akin and Akinleye 2021; Banerjee et al., 2020b, 2022; Schindler et al. 2010). Bulk samples were oven-dried at 105°C, rehydrated to reach saturation levels before dew point potentiometer measurement. Loss-on-ignition (LOI) tests, conducted in accordance with ASTM D2974-14, were used to determine organic matter content (Robichaud et al., 2013). Afterwards, unburnt soil samples from the site were combined with mulch and burned in a furnace for 30 minutes at temperatures of 150°C and 650°C. This approach helped to demonstrate the effects of low- and high-intensity fires on the soil (Caon et al., 2014; Akburak et al., 2018; Agbeshie et al., 2022). Wooden shreds, consisting of a mix of coarse wood chips and finer particles, are commercially available and used as mulch on the unburnt soil (Jonas et al., 2019). This sampling strategy produced an extensive dataset for evaluating the impacts of wildfire severity and mulch treatment on soil hydraulic function and structural integrity.

Table 1 Soil and Mulch Properties

Properties	Standards	Unburnt Sample	Burnt Sample	BS (150°C and 25% by vol. mulch)	BS (650°C and 25% by vol. mulch)
Specific Gravity, G_s	ASTM D854	2.6	-	-	-
Liquid limit, *LL* (%)	ASTM D4318	22.5	53	28	19
Plasticity Index, *PI* (%)	ASTM D4318	7.19	NP	NP	NP
Gravel and Sand content (%)	ASTM D7928	94	96	-	-
Silt and Clay content (%)	ASTM D7928	6	4	-	-
USCS Classification	ASTM D2487	ML	-	-	-
Moisture content, *w* (%)	ASTM 2216	28	-		
Bulk density (kN/m^3)	ASTM D7263-21	16	-	13	12
Mulch moisture content (%)		1.67	-	-	-
Mulch density (kN/m^3)		3.5	-	-	-

Note: ASTM: American Society for Testing and Materials, BS: Burnt sample
- Represents parameters that were not measured in this study

Unsaturated Hydraulic Property

This method involves measuring pressure heads at two different depths within a 5 cm long saturated cylindrical soil sample. As water evaporates from the surface of the sample, an automated weighing system tracks mass changes to ascertain water content and fluid flux over time. The obtained pressure heads, water contents, and evaporation fluxes are subsequently used to estimate the SWCC curve and the unsaturated hydraulic conductivity function (Pertassek et al., 2015; Schindler et al., 2010). The measurement range for hydraulic conductivity on the wetter side is limited by how sensitive tensiometers are to minimal pressure head differences. On the drier side, however, measurement accuracy is hindered by phenomena such as water outgassing, bubble formation, and subsequent expansion within the tensiometers, which typically occur around a pressure head of approximately −850 cm of water. Pressure heads are continuously monitored at two fixed depths: 1.25 cm and 3.75 cm below the evaporating surface. Simultaneously, evaporation rates are evaluated via automated mass assessments. Water retention and hydraulic conductivity values are determined based on the average water content of the sample, the pressure readings from both tensiometers, and the calculated total head gradient between them. This method assumes a linear vertical distribution of both pressure head and water content, a premise supported by earlier research (Bezerra-Coelho et al., 2018).

RESULTS AND DISCUSSION

Figure 2 shows the relationship between matric suction (soil water potential) and volumetric water content. The mulched unburnt soil (Figure 2(a)) retains more water at most suction levels compared to bare unburnt soil. This indicated that adding mulch significantly improved the soil's ability to hold moisture, probably due to better structure and the organic matter from the mulch. Soils exposed to high temperatures (650°C) show reduced water retention across the suction range (Figure 2(b)), pointing to a substantial loss of soil organic matter (SOM) and damage to pore structure. Soils burned at 150°C hold more moisture than those heated to 650°C, but still less than what is typically observed in prescribed-burnt soil. Based on the slope of SWCC, it was observed that more energy is needed to remove water from unburnt soil and soil exposed to low-temperature fires as compared to soil exposed to high-temperature fires, like soil burned at 650°C.

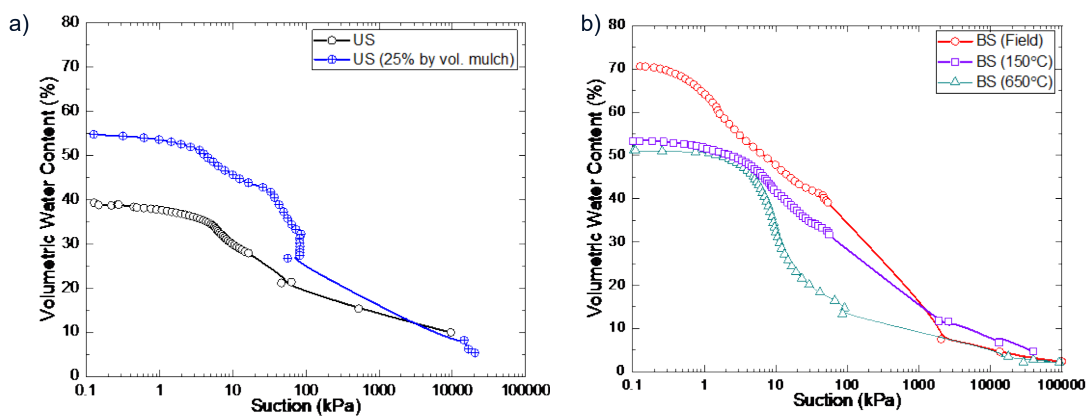

Figure 2. SWCC for (a) unburnt soil and (b) burnt soil highlighting the changes in saturated water content, changes in slopes of the curves with exposure to higher temperature fires, and presence of mulch.

The field sample shows the highest water retention, likely due to partial combustion combined with possible ash or unburnt organic matter, which can temporarily increase moisture retention. The burnt soil collected from the site was sieved through a 0.075 mm mesh and thoroughly washed to remove fine particles like fly ash, which may accumulate in soil pores after wildfire. This cleaning step was necessary to ensure that the observed hydrological behavior accurately reflected the soil matrix, unaffected by temporary residues from the fire. Fly ash can temporarily alter pore structure and water retention properties by blocking pore spaces or forming artificial hydrophobic films on soil particles, impacting hydraulic behavior during early post-fire stages (Kim et al., 2022). Despite this cleaning, the volumetric water content of the treated soil samples was similar to that of burnt samples with residuals, indicating that the soil's inherent properties—such as texture, structure, and residual organic matter—played the main role in water retention. This supports the idea that fire intensity and SOM loss, rather than just superficial ash, are the key factors driving post-fire changes in soil-water retention behavior.

The soil sample containing 25% mulch by volume demonstrates improved water retention at higher suctions (more negative values) when compared to soil without additional mulch (Figure 3(b)). Mulch significantly contributes to enhancing pore structure and increasing soil organic matter (SOM) content, leading to sustained water retention during dry spells. The samples from field burning and at 150 °C exhibit moderate water retention, while the 650°C sample shows the lowest retention, indicating a notable loss of SOM and pore structure (Figure 3(b)). Hydraulic conductivity notably rises in the 650 °C sample, suggesting a more permeable, yet unstable soil matrix resulting from heat-related aggregation breakdown. The 150 °C sample outperforms field-burnt soil (Figure 3(d)). The mulch was not consistently mixed into the soil matrix, which may have introduced local variations in pore structure (Figure 3). Although heterogeneity was not quantitatively measured, this is a plausible factor influencing the observed inconsistencies in water retention behavior, as suggested in similar post-fire mulching studies (Robichaud et al., 2013; Fernández and Vega, 2016).

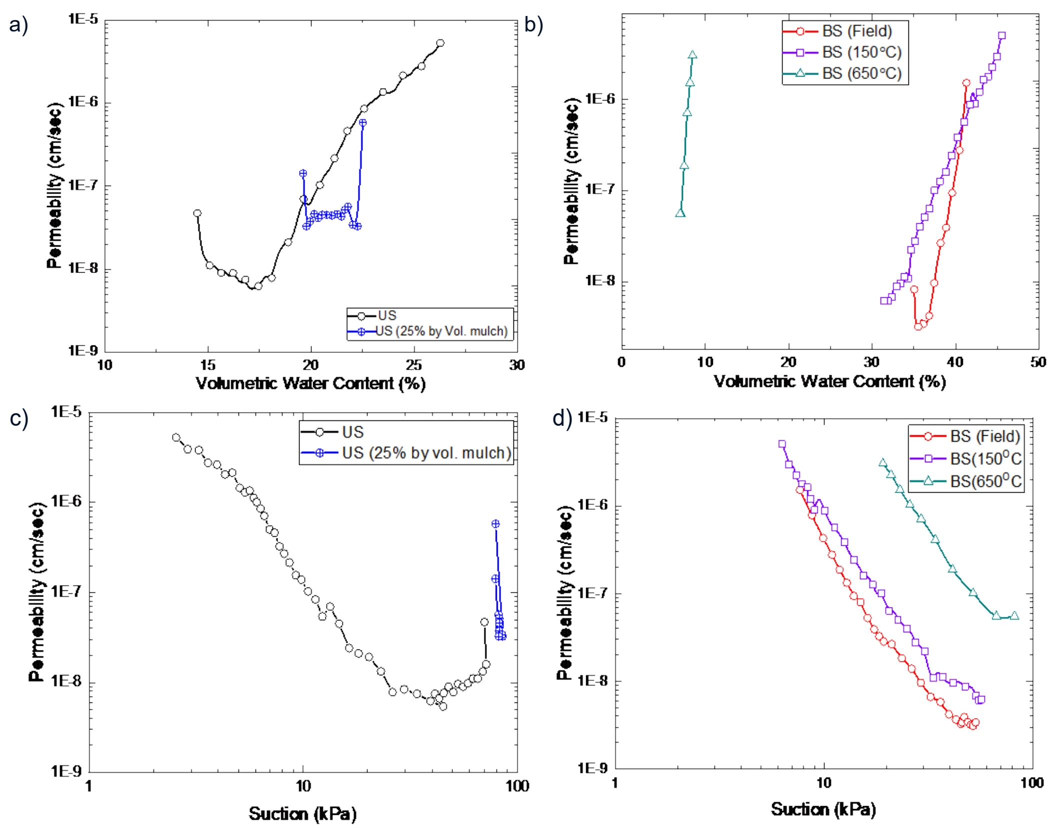

Figure 3. Variation of unsaturated permeability for burnt and unburnt samples with volumetric water content and matric suction

Furthermore, this may be due to the formation of larger, less stable pores within the mulched matrix, which facilitate rapid initial drainage while allowing smaller pores to retain residual moisture (Zhang et al., 2009). This results in step-like changes in the retention curve, rather than a gradual gradient, as shown in Fig. 3(c). The fine organic particles in the mulch may have facilitated micropore development, allowing water to be held more tightly and thereby reducing unsaturated flow rates. Advanced studies for pore-distribution such as mercury intrusion porosimetry could confirm the findings.

The water retention behavior of the unburnt soil samples mixed with organic mulch (Figures 3a and 3c) displayed irregular, non-monotonic patterns, particularly in the mulch-amended samples. These anomalies likely arise from local heterogeneities in the soil-mulch mixture, as the mulch was not homogenized within the matrix, where the mulch diameter varies from 2 mm to 0.075mm. Organic mulch can introduce disconnected macropores or capillary interruptions, leading to preferential water flow, temporary water accumulation, and sudden drainage events. Such behavior may mimic the formation of a capillary barrier effect—a phenomenon where layers with contrasting pore sizes disrupt capillary continuity, causing uneven water distribution. While, direct evidence such as pore-size distribution or imaging was not collected in this study, the observed trends are consistent with previous findings on layered soil systems and mulch-amended textures (Dikinya and Hinz, 2003; Assouline et al., 1998; Nimmo, 2012). The changes to the SWCC affect the water retention, strength, and stability of slopes (Banerjee et al. 2020a; Ghosh and Banerjee, 2024). These results highlight the importance of mixture uniformity and structural characterization in interpreting water retention data from amended soils.

This research analyzed liquid limit (LL) and plastic limit (PL) tests on both unburnt and burnt soil samples (Table 1). The plasticity index (PI), which indicates the moisture content range where soil behaves plastically, was derived from these tests. Alongside particle size distribution analysis, the soil was categorized as low plastic clay in accordance with the Unified Soil Classification System (USCS), highlighting its granular characteristics and placement on the plasticity chart. However, assessing the Atterberg limits on the burnt samples, whether from field burning or furnace heating, was found to be impractical. The combustion process dramatically altered the texture of the soil, making it similar to crushed stone dust, which exhibited minimal cohesion and no significant plasticity. This reduction in plasticity is likely due to changes in clay minerals resulting from high-temperature exposure. Specifically, heating may cause the release of hydroxyl groups from the clay mineral structure, leading to alterations that reduce the soil's ability to retain moisture and establish cohesive bonds (Table 1). As a result, the burnt soil could not produce the necessary workable paste for LL and PL tests. This could be confirmed from X-ray diffraction (XRD) or other microscopic studies. The inability to carry out standard rolling technique indicated a notable alteration in the mineralogical and physical properties of the soil. These findings show that thermal changes from fire significantly reduce soil plasticity, primarily due to the breakdown of clay structures, rendering traditional Atterberg testing methods unsuitable for burnt soils (Sapkota et al., 2025).

CONCLUSION

This research shows that wildfire intensity greatly affects soil hydrological behavior and geotechnical stability, mainly by impacting soil organic matter (SOM) and soil structure. The laboratory data indicated that fires with temperatures exceeding 300°C led to thermal degradation of SOM and changes to soil structure along with permeability, which severely reduce the soil moisture retention. The novelty of the work includes the consideration of saturated water content, changes to the slopes of SWCC, and unsaturated permeability of soils with presence of mulch and exposure to higher temperature fire. The diminished plasticity and cohesion in burnt soils, highlighted through Atterberg limit tests, emphasize the irreversible changes in soil behavior after an intense fire.

- SWCC and hydraulic conductivity analyses indicate that severely burnt soils at 650°C retain less water at a given suction, and less energy is needed to dry the soil. Although saturated permeability may remain unchanged, the observed increase in suction and reduced water retention capacity suggest that these soils may experience earlier runoff during precipitation events and diminished soil moisture storage during dry periods. These shifts could significantly affect post-fire hydrological response and vegetation recovery.
- Mulch, which is shredded wooden residue, proved to be an effective post-fire treatment from previous studies, enhancing water retention, controlling hydraulic properties, reducing evaporation, and supporting infiltration. In this study, the saturated water content increases due to the hydrophilic nature of mulch and increased void ratio in a mixture of soil and mulch. This allows higher storage of moisture for vegetation.
- Mulch, being combustible, may act as fuel in dry conditions. Exposure to high temperatures, such as 650°C, alters soil structure and reduces water retention, indicating conditions favorable to combustion. While beneficial for post-fire hydrology, mulch application before fires must be managed to prevent increasing fire intensity. Future research should focus on timing, composition, and treatments like fire-retardant coatings to maximize benefits and reduce risks.

The findings highlight the role of soil organic matter in maintaining soil hydraulic function during wildfires. Further studies are needed to confirm the changes in SWCC and hydrological properties of wildfire-burnt soils. Management should also consider degradation thresholds, soil type, and mulching techniques to aid recovery and reduce geomorphological risks. As climate extremes intensify, management of wildfires is essential for protecting soil health and landscape stability.

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