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THERMAL EFFECTS ON SOIL WATER REPELLENCY: EXPERIMENTAL EVIDENCE AND RELEVANCE FOR POST-FIRE SLOPE STABILITY

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EXTENDED ABSTRACT

Gli incendi boschivi sono tra i fenomeni naturali più impattanti sugli ecosistemi e sulla stabilità dei versanti. Il loro aumento in frequenza e intensità, in gran parte determinato dal cambiamento climatico e dalle attività umane, ha suscitato un crescente interesse nello studio delle dinamiche legate alla propagazione degli incendi e degli effetti post-incendio, finalizzato alla prevenzione e alla mitigazione del rischio.

Oltre alla distruzione immediata della vegetazione, gli incendi innescano infatti una serie di effetti a cascata all'interno del sistema ambientale, modificando in modo significativo i processi superficiali. Nelle regioni montuose, dove la pericolosità idro-geomorfologica è già elevata, tali effetti possono compromettere ulteriormente la stabilità dei versanti e la sicurezza delle comunità locali. In particolare, gli incendi alterano in modo significativo l'idrologia e la risposta geomeccanica dei terreni, aumentando spesso la suscettibilità dei versanti a frane superficiali e colate detritiche. Diversi autori hanno evidenziato che, tra le alterazioni indotte dal fuoco associate alla predisposizione al dissesto dei versanti, lo sviluppo dell'idrorepellenza del terreno svolge un ruolo cruciale nel controllo delle dinamiche di infiltrazione post-incendio e della generazione del deflusso superficiale. Tuttavia, a seconda della copertura vegetale e delle caratteristiche del terreno, l'idrorepellenza può già caratterizzare i versanti prima degli incendi. Studi di laboratorio hanno dimostrato che l'insorgenza dell'idrorepellenza è fortemente influenzata dalla composizione granulometrica del terreno, dal contenuto di sostanza organica e dall'aumento di temperatura indotto dagli incendi, mentre la sua degradazione può avvenire sempre per un ulteriore aumento di temperatura. Data la complessità dell'interazione tra questi fattori e gli altri effetti indotti dagli incendi, il contributo diretto delle variazioni dell'idrorepellenza del terreno nei processi di instabilità dei versanti rimane poco chiaro.

Il presente studio analizza l'influenza della temperatura sullo sviluppo e sulla degradazione dell'idrorepellenza del terreno, nonché l'effetto di questa proprietà sulla capacità di infiltrazione. Sono stati condotti esperimenti di laboratorio su campioni di terreno omogenei ed eterogenei sottoposti a trattamenti termici controllati, entro intervalli di temperatura riportati in letteratura come rappresentativi delle condizioni di innesco e degradazione dell'idrorepellenza durante gli incendi boschivi. I materiali testati includono una sabbia quarzosa commerciale (non idrorepellente), un terreno naturale prelevato da un bosco di conifere dell'Italia settentrionale (idrorepellente) e loro miscele, con contenuti definiti di frazione inorganica (sabbia) e materia organica (aghi di conifere). Le prove sono state svolte mediante l'impiego di un bruciatore e di un forno a muffola, monitorando la propagazione del calore tramite termocoppie. Dopo il riscaldamento, il comportamento idrofobico è stato valutato mediante il test del tempo di penetrazione della goccia d'acqua (*Water Drop Penetration Time*, WDPT), mentre la conducibilità idraulica è stata determinata utilizzando un permeametro ed eseguendo simulazioni di pioggia. I campioni non riscaldati sono stati utilizzati come riferimento per quantificare le variazioni indotte dalla temperatura.

I risultati mostrano una risposta dipendente dalla temperatura esclusivamente nei campioni contenenti sostanza organica, nei quali un riscaldamento moderato favorisce lo sviluppo dell'idrorepellenza del terreno, mentre temperature più elevate ne determinano la progressiva degradazione attraverso la decomposizione termica dei composti organici responsabili dell'idrofobicità. I test hanno inoltre mostrato come le differenze nella conducibilità termica tra i materiali abbiano prodotto risposte eterogenee al riscaldamento, suggerendo una distribuzione non uniforme delle modificazioni indotte dal fuoco, anche dopo un'esposizione prolungata a temperature elevate. La temperatura esercita quindi un controllo complesso e non lineare sulla bagnabilità del terreno, sulla sua alterazione strutturale e, di conseguenza, sui processi di infiltrazione post-incendio, evidenziando l'importanza del contenuto di sostanza organica. Le trasformazioni termo-strutturali indotte dal fuoco possono modificare in modo sostanziale la risposta idrologica dei versanti, incidendo sull'infiltrazione, sulla generazione del deflusso superficiale e, in ultima analisi, sulle condizioni di stabilità dei versanti.

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ABSTRACT

Wildfires are among the most impactful natural phenomena affecting ecosystems, with a concerning increased frequency driven by climate change and human activity. Beyond the immediate destruction of vegetation, wildfires trigger a series of cascading effects within the slopes, significantly modifying shallow processes and compromising their stability. Wildfires significantly alter the hydrological and geo-mechanical properties of soils, often increasing the susceptibility to shallow landslides and debris flows. Several authors have reported that the development of soil water repellency plays a crucial role in controlling post-fire infiltration dynamics and runoff generation. However, depending on vegetation coverage and organic matter content, soil water repellency may already characterize slopes prior to wildfires. Laboratory studies have shown that the onset of soil water repellency is strongly influenced by granulometry, organic matter content and temperature rise, whereas its breakdown occurs at higher temperatures. Yet, the direct contribution of temperature-induced changes in soil water repellency to slope failure processes remains unclear. The present study investigates how temperature influences the development and breakdown of soil water repellency, and how this property influences soil infiltration capacity. Controlled thermal treatments were conducted on soil samples in laboratory, coupled with the assessment of the hydrophobic behaviour through Water Drop Penetration Time (WDPT) tests and the evaluation of the hydraulic conductivity with a permeameter after heating. Results reveal a temperature-dependent response only in samples containing organic matter. Differences in thermal conductivity among the tested materials produced heterogeneous responses to heating, suggesting a non-uniform alteration even after prolonged exposure to elevated temperatures. These findings indicate that temperature exerts a complex control on soil wettability and, consequently, on post-fire infiltration behaviour.

Keywords: *wildfire, soil water repellency, slope stability, hydrology, geohazards*

INTRODUCTION

As reported by many authors in the literature (*e.g.* Shakesby *et alii*, 2006; Parise & Cannon, 2012; Abbate *et alii*, 2019), wildfires induce profound and long-lasting alterations in soil properties, hydrological processes, and slope stability. These changes can persist for years, influencing runoff generation, erosion rates, and the overall equilibrium of drainage basins, which makes understanding these dynamics essential for developing effective risk mitigation strategies and improving predictive models for post-fire landscape evolution. Several authors have reported that, among the fire-induced alterations coupled with slope failure predisposition, the development of soil water repellency (WR) plays a crucial role in controlling post-fire infiltration dynamics and runoff generation (*e.g.* DeBano, 1981). During wildfire conditions, the intense heating at the surface causes the volatilization of the organic compounds, derived from living or decomposing plants and microorganisms, that induce hydrophobicity. These vapours migrate downward following the soil's thermal gradient and subsequently condense onto cooler mineral particles at depth, coating them and making them hydrophobic (Debano & Krammes, 1966; Robichaud & Hungerford, 2000; Negri *et alii*, 2021). Consequently, the organic matter content is a crucial soil property that influences repellency. Laboratory studies report that even relatively small amounts of organic matter (2-5%) can induce strong water repellency when subjected to heating (DeBano, 1981; Doerr *et alii*, 2000). Anyway, repellency may already characterize slopes, independently of wildfires. Vegetation type is recognised to primarily influence this property of soils. Plant species particularly associated with strong water repellency include evergreen trees such as pines and eucalyptus, due to their production of resins and waxes (Doerr *et alii*, 2000; Butzen, 2015; Negri *et alii*, 2021). Regarding thermal response, water repellency can be first induced at temperatures around 175-200°C, or increased if already naturally present, and finally destroyed if certain high temperatures are exceeded (T > 250-350°C). Authors reported maximum water repellency occurring around 200-250°C. Beyond this threshold, WR drastically decreases, coinciding with a marked increase in soil pH and a sharp decline in organic carbon content. This suggests that high-temperature heating leads to the destruction of water repellency due to the thermal degradation of organic matter (C). Additionally, around 350-460°C, processes of clay dehydroxylation begin, with the loss of hydroxyl groups (OH) from clay minerals that leads to a structural alteration of the soil, making it more susceptible to erosion (Parise & Cannon, 2012; Shakesby & Doerr, 2006). Other factors reported to support the development of repellency are soil granulometry and water content (DeBano, 1981; Robichaud & Hungerford, 2000; Negri *et alii*, 2021). Finally, soil thermal conductivity influences WR propagation, as temperature increase is confined to the uppermost centimetres of the soil profile (*e.g.* Chicco *et alii*, 2023). Consequently, the 0–5 cm surface layer is generally the most affected by thermal alteration during fire events (Costa *et alii*, 2021; Negri *et alii*, 2021).

Even if these processes are described in detail in the literature, a clear relationship between the temperature-induced changes and local hydrology is yet to be defined. Moreover, the thermal thresholds and the exposure duration for the formation and destruction of repellency do not precisely coincide among studies. This paper focuses on the hydrological behaviour of soils under increasing temperature in terms of soil water repellency and infiltration capacity. Laboratory experiments were conducted on both homogeneous and heterogeneous soil samples subjected to controlled thermal treatments within temperature ranges recognised as representative of soil water repellency initiation and degradation under wildfire conditions. The tested materials included a commercial quartzose sand (non-repellent), loamy sand soil collected in a conifer forest (naturally water repellent), and their mixtures. After heating, soil hydrophobic behaviour was assessed through the Water Drop Penetration Time (WDPT) test, while hydraulic conductivity was measured using a permeameter. In addition, rainfall simulations were conducted to evaluate potential changes in infiltration and runoff behaviour. Unheated samples were used as reference to quantify temperature-induced variations.

This study highlights the role of organic matter content in the development of soil water repellency and in controlling thermal conductivity, emphasizing the importance of heating duration in reaching high levels of fire severity, with potential implications for slope stability.

MATERIAL AND METHODS

Soil samples were exposed to temperature rise using two different apparatuses in the laboratory: a burner and an electric muffle furnace, characterized by different sample sizes and heating velocities. The first experimental setup, shown in Fig. 1 and referred to as the "shock-tube test", used the burner unit of a shock-tube apparatus described by Colombo *et alii* (2011), to expose a soil sample to a controlled flame. The shock wave generation system was not employed. To replicate, as closely as possible, the thermal conditions of a real wildfire, reference was made to the temperature–time curves obtained under a medium fuel load scenario during prescribed fire experiments conducted by Chicco *et alii* (2023) in a pine forest in Susa Valley (northern Italy). The heating curve applied with the burner reached approximately 900°C in 20 minutes (total test duration) and corresponds to an intermediate condition between the HydroCarbon EC1 and ISO-834 fire curves (see Colombo *et alii*, 2011). A single test was performed on a cylindrical sample with a height of 39 cm and a diameter of 50 cm, leaving an 11 cm gap between the top of the sample and the flame. The material used was a natural loamy sand collected in a conifer forest (Sorico municipality, northern Italy), close to an area affected by a wildfire in 2019, as described by Corti *et alii* (2022). The soil was not sieved in order to preserve its original organic content. After allocating the soil into a custom-made cylindrical sample holder made of S235 steel, the specimen was rotated to ensure proper alignment and then positioned in contact with the burner. To ensure sufficient cohesion during sample preparation and rotation, water was added to achieve a volumetric water content of approximately 30%, as measured by Time Domain Reflectometry (TDR).

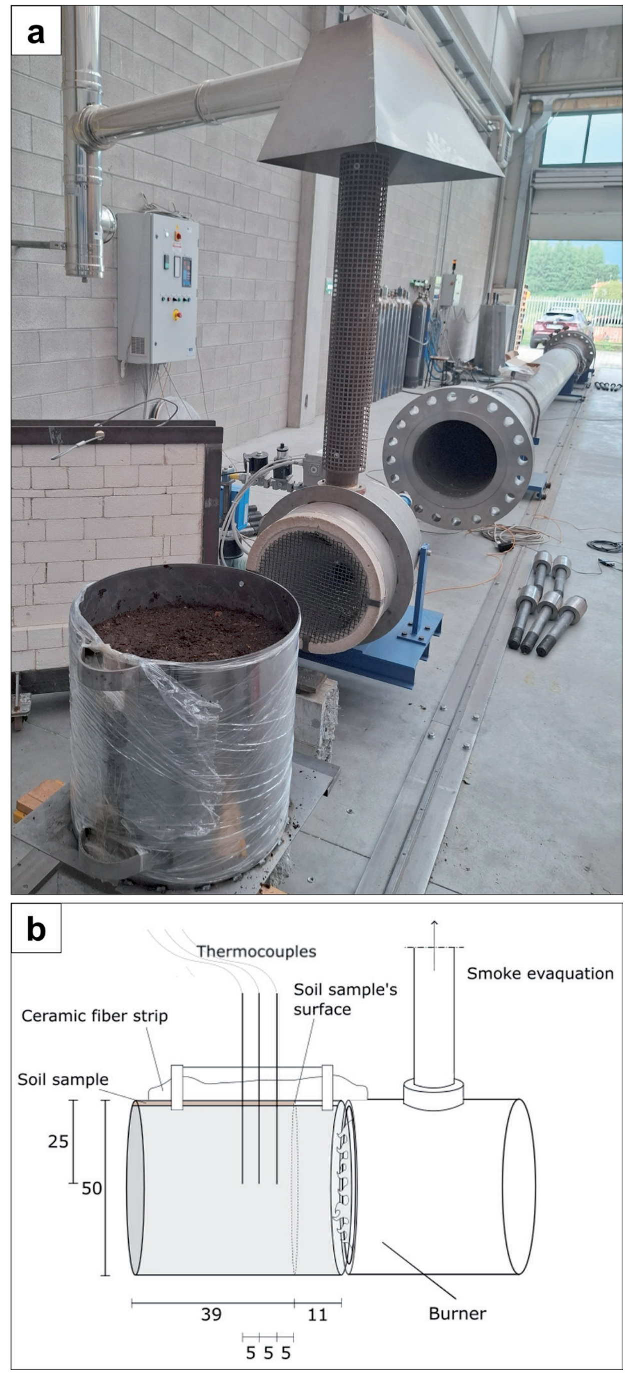

Fig. 1 - Shock-tube experiment: (a) the shock-tube facility and the cylindrical sample of natural soil; (b) schematic representation of the experimental setup

A ceramic fibre strip was placed along the lateral inspection opening of the cylinder to limit the escape of flames and vapours. Temperature propagation during the test was monitored using three Type K thermocouples (RS PRO), placed at depths of 5,

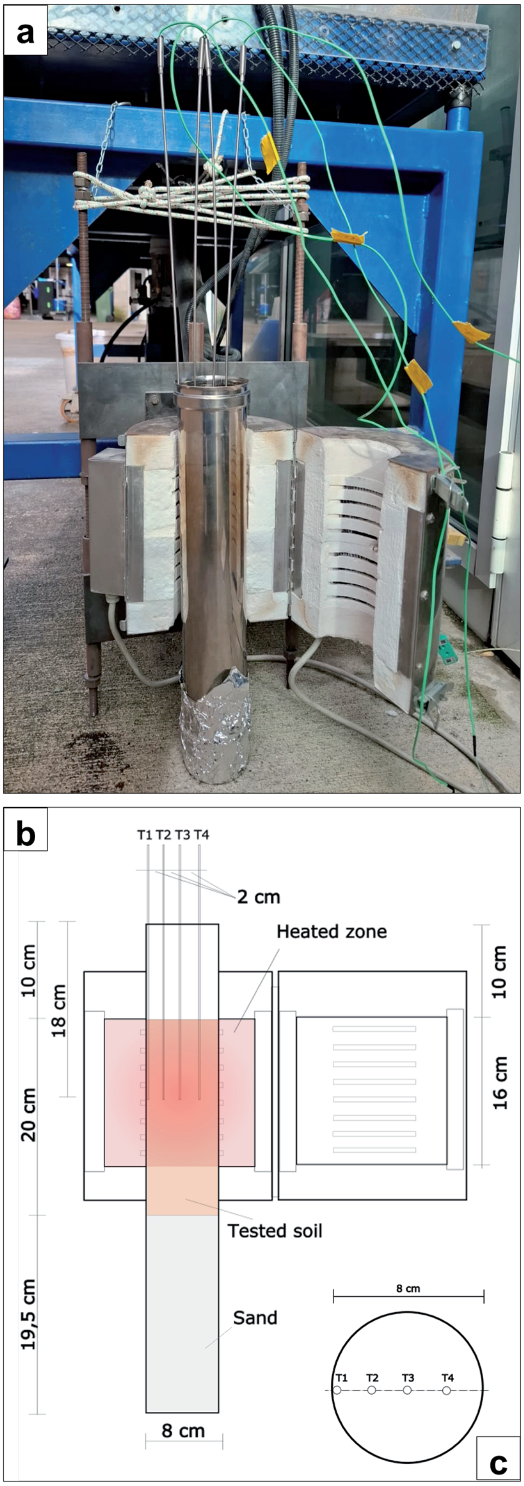

Fig. 2 - Muffle furnace experiment: (a) photograph of the open furnace with the soil sample; (b) schematic representation of the experimental setup; (c) detail of the thermocouple positioning. The sample location is highlighted. The upper 10 cm of the sample holder was left, while the lower part was filled with sand

10, and 15 cm from the top of the sample. After cooling, soil water repellency was evaluated through WDPT tests.

To investigate the thermal response of soil samples within predefined temperature intervals, tests were performed using an electric muffle furnace (Fig. 2). This apparatus consists of a cylindrical heating chamber that transfers heat primarily through radiation. In these tests, the soil samples were also cylindrical but smaller (8 cm in diameter and 20 cm in height). Unlike the burner setup, heating occurred mainly along the height of the chamber rather than at the sample surface; therefore, the symmetry of the second test was rotated with respect to the first. Four thermocouples were inserted to a depth of 8 cm within the sample cross-section, at radial distances of 0, 2, 4, and 6 cm from the sample holder wall. The first thermocouple was put in direct contact with the holder to measure the actual temperature inside the furnace. A total of five different materials were tested to assess the influence of organic matter content on thermal effects. They include a commercial quartzose uniform medium sand (CU = 2.1), the Sorico loamy sand (see Table 1), and mixtures of sand and organic matter. In this case, the natural soil was sieved at 2 mm, for scaling purposes and to prevent heterogeneous ignition within the sample. The organic matter consisted of biological material (mainly pine needles) collected from the litter of the same conifer forest. In particular, mixtures containing 1%, 3%, and 20% organic matter were tested.

Soil	D_{10} [mm]	D_{50} [mm]	D_{60} [mm]
Sand	0.30	0.54	0.60
Natural soil	0.013	0.40	0.50

Tab. 1 - Main granulometric characteristics of the soil materials considered in the experiments. Their complete description can be found in Longoni *et alii (2025)*

The investigated temperature intervals included values reported in the literature as characteristic of water repellency development and degradation (100, 200, 300°C), as well as an extreme scenario at 600°C. Samples were exposed to the target temperature for 30 minutes then allowed to cool under ambient conditions before evaluating the level of water repellency. The volumetric water content (VWC) was approximately around 5% at the beginning of all tests.

Water Drop Penetration Time (WDPT) test was used to assess soil water repellency. This simple and inexpensive test consists of pouring drops of water onto the soil surface using a pipette and measuring the time required for complete infiltration (DeBano, 1981; Bisdom *et alii*, 1993). Based on the absorption time, Bisdom *et alii* (1993) defined five classes of water repellency as follow:

- ≤ 5 s: wettable;
- 5-60 s: slightly repellent;
- 60-600 s: strongly repellent;
- 600-3600 s: severely repellent;
- ≥ 3600 s: extremely repellent.

Falling-head permeameter tests were performed to assess potential variations in hydraulic conductivity (k_s) by comparing heated and unheated samples. Owing to the larger sample dimensions, the shock-tube experiment also allowed rainfall simulations to be conducted. These tests consisted of two consecutive rainfall events lasting 10 minutes each, applied at an intensity of 260 mm/h and separated by an 18-minute interval. Volumetric water content (VWC) was monitored throughout the experiments using a TDR probe inserted 8 cm below the soil surface. The lateral opening of the sample holder was sealed using transparent plastic film, leaving only the lower portion open to allow water outflow. To further facilitate drainage, the sample was slightly inclined. To quantify the temperature-induced variation, a second test was performed after removing the thermally altered surface layer, thereby testing the same sample under conditions representative of unburned soil. This procedure was justified by the shock-tube results, which showed that heat penetration was limited to shallow depths and did not affect the underlying material. The rainfall test setup is shown in Fig. 3.

RESULTS

Shock-tube test

The shock-tube test showed that, although the flame temperature exceeded 800°C for a prolonged period, the soil sample itself never reached such high temperatures due to its low thermal conductivity (Fig. 4). Only the surface layer closest to the flame reached approximately 500°C. After about 20 minutes, partial collapse of the material brought the first thermocouple (T1) closer to the heat source. Prior to collapse, the maximum temperature recorded by T1, located 5 cm below the soil surface, was 125°C, while T2 and T3 (at depths of 10 and 15 cm, respectively) never exceeded 100°C. These results confirm the extremely low thermal conductivity of natural soil and are consistent with the findings of Chicco *et alii* (2023), who observed heat confinement within the upper 4 cm of soil, with temperature peaks in the first 2 cm, during prescribed fire experiments. Additional qualitative evidence of heat propagation within the sample is provided by the colour variations observed on the steel sample holder (Fig. 5a). The transition in steel colour from golden/dark-straw yellow (at 4.5 cm below the soil surface) to grey-blue (at 2 cm below the surface) corresponds to temperatures of approximately 230-240°C and 330°C, respectively, according to the standard steel colour–temperature reference scale (SIDEX S.R.L., n.d.). Conversely, the brownish colours observed along the upper 11 cm of the holder, which contained only air, indicate temperatures exceeding 600°C. These colour gradients reveal a pronounced thermal gradient along the cylinder surface over only a few centimetres, further highlighting the limited thermal conductivity typical of soils.

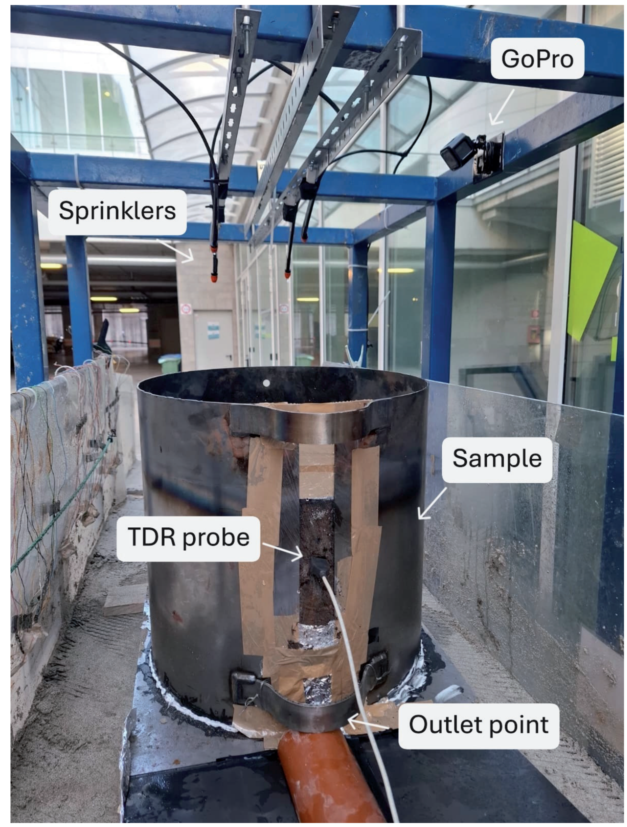

Fig. 3 - Rainfall test setup

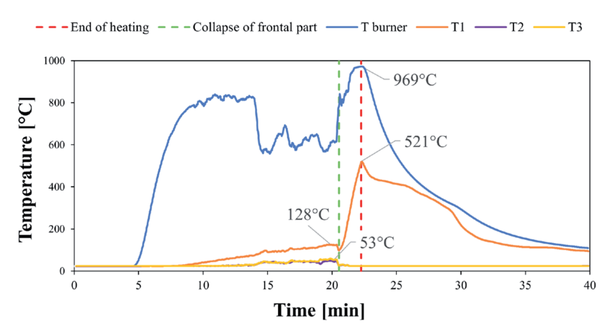

Fig. 4 - Temperatures recorded by thermocouples during the shock-tube test. T1 is the closest to the fire source (5 cm). The decrease in burner temperature at approximately 15 minutes is likely due to a temporary flame suffocation

Post-test soil alteration reflects the described heating pattern, with the upper centimetres being the most affected. In particular, four distinct domains are clearly distinguishable: a dark, burnt surface crust, locally covered by grey ash, a lighter thin interface layer between the crust and the underlying soil, a light-brown transitional layer and the underlying unaltered brown soil (Fig. 5b). The burnt crust appears fragile and is intersected by diffused cracking.

In terms of water repellency, the intact burnt crust presented severe to extreme water repellency (areas 1, 2 and 5 in Fig. 5b), with droplets persisting for more than 600 s and, in several cases, exceeding 3600 s. The thin interface layer between the crust and the underlying soil was characterized by extremely water-repellent behaviour, representing the most hydrophobic portion of the profile (visible in area 1). Immediately below, the light-brown transitional layer showed variable behaviour, ranging from slight to strong water repellency (areas 3, 6 and 7), whereas the deeper unaltered soil was generally wettable (area 3). Ash-covered zones (*e.g.*, area 4), characterized by loose and highly permeable material, displayed non-repellent behaviour due to immediate infiltration. The vertical section in Fig. 5c shows that the carbonized crust had an average thickness of approximately 2 cm and that the underlying soil was extremely water repellent.

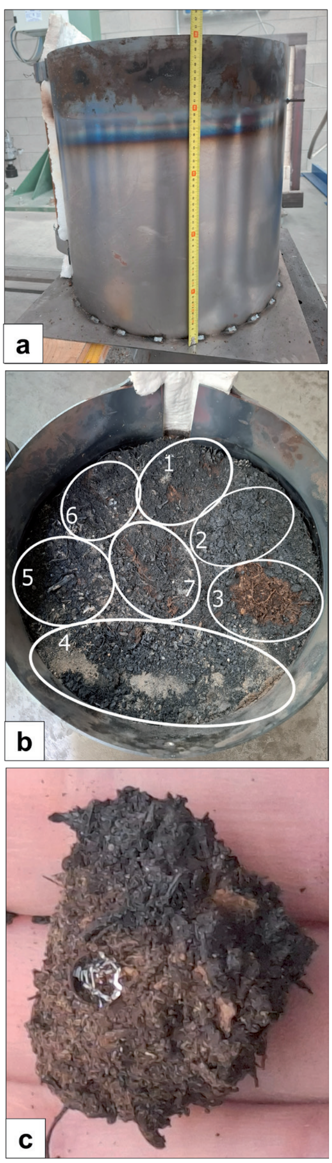

Fig. 5 - Shock-tube test results: (a) evidence of heat penetration (up to 3.5 cm); (b) areas with different degrees of water repellency; (c) vertical section of the soil sample with evidence of the burnt crust and underneath persistent water repellency

Therefore, the test indicates a widespread extremely water-repellent behaviour affecting much of the specimen surface, particularly where a compact carbonized crust was present and at the interface between the crust and the underlying soil. The burned surface can be described as a heterogeneous carbonized layer exhibiting contrasting hydraulic responses: highly water repellent where the crust is compact, but locally wettable where poorly cohesive ash accumulates or where cracks facilitate rapid infiltration.

Muffle furnace tests

The muffle furnace tests yielded results consistent with those obtained from the "shock-tube" experiment, confirming both the persistence of soil water repellency under heating and the low thermal conductivity of organic soils. The outcomes, summarized in Table 2, highlight the key role of organic matter content in the development of soil water repellency. The pure sand sample, taken as a control, indeed never develops water repellency. On the contrary, mixtures of sand and 1-3% organic material developed water

Material	WR	ΔV [%]	ΔVWC [%]
100% Sand	Never water repellent	0	-4.5
1% Organic	Slightly at 300°C, > 600°C wettable	-7.5	-4.5
3% Organic	Slightly at 250°C, extreme at 300°C, > 600°C partially wettable	-20	-4.0
20% Organic	Repellent, > 600°C partially wettable	-35	-2.0
100% Natural	Extremely water repellent	-70	-5.0

Tab. 2 - Overview of the results obtained for the four tested materials at the end of the experiments: WR is Water Repellency; ΔV and ΔVWC are the differences in sample volume and volumetric water content between the beginning and end of the tests

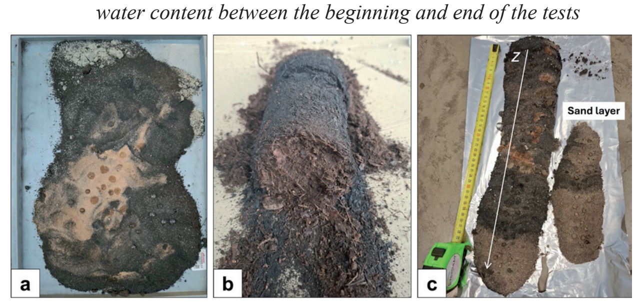

Fig. 6 - Soil samples after heating in the muffle furnace: (a) layers with different water repellency in natural soil after T ≈ 500°C; (b) thin external burnt crust in natural soil; (c) vertical distribution of water repellency in the 20% organic matter mixture and in the underlying sand layer (depth axis, z)

repellency at approximately 250-300°C, which was subsequently disrupted at higher temperatures. This trend was more marked in the 3% mixture, which showed stronger repellency that was not completely eliminated even at temperatures exceeding 600°C. The natural soil, initially extremely water repellent, exhibited only partial wettability after heating to approximately 500°C. This wettability was mainly observed in lighter-coloured layers (Fig. 6a) and along the external portion of the sample, where a thin burnt crust developed (Fig. 6b) while the inner core remained extremely water repellent. An intermediate behaviour was observed in the 20% mixture, where the initial WR was largely disrupted after heating to 600°C, but hydrophobic behaviour appeared to migrate downward, affecting the underlying sand layer (Fig. 6c). A significant volume reduction was also observed, particularly in the natural soil. The initial sample height of 20 cm decreased to 13 cm after heating to 150°C and to 9 cm after heating to 250°C.

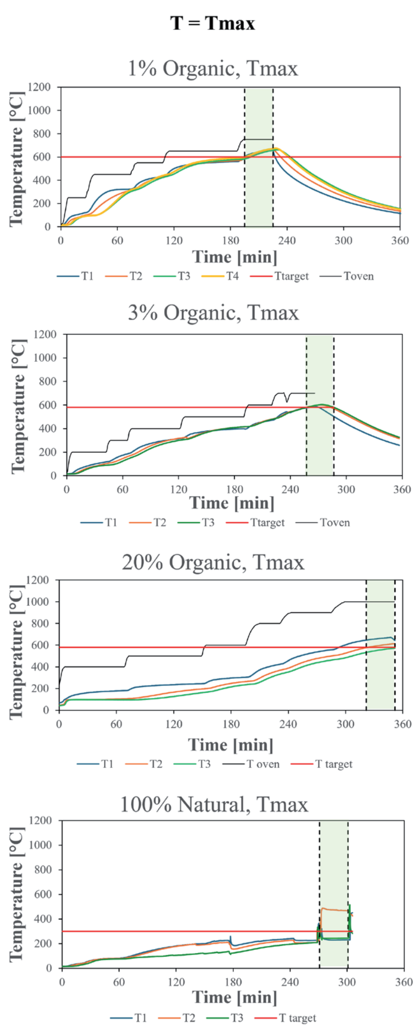

Fig. 7 - Comparison of the analysed mixtures at maximum temperature (> 300°C)

After reaching 500°C, the height further decreased to 6 cm, corresponding to an overall volume reduction of 70%. Although volume reduction occurred in all mixtures, it was proportionally greater in samples with higher organic matter content. Temperature propagation within the sample during tests is shown in Fig. 7 and Fig. 8. These plots show the marked difference in temperature propagation, which is slower at higher organic matter content, while sand is thermally conductive due to the presence of quartz. Also, when organic matter is present, the temperature remains close to the boiling temperature of 100°C for an extended period.

Falling-head permeameter tests (Fig. 9) did not reveal significant variations before and after heating. Consistent with the granulometric characteristics of the investigated materials, the median k_s value for pure sand is generally higher than that of the other materials, whereas the natural soil exhibits lower k_s values. The sand–organic mixtures (1%, 3%, and 20% organic matter) show k_s values broadly comparable to one another, remaining within the same order of magnitude and falling between the two extreme cases represented by pure sand and natural soil.

When comparing pre- and post-heating conditions, no clear distinction between heated and unheated samples emerges. As noted in the previous paragraph, the sand sample did not present any variation in terms of soil water repellency. In contrast, saturated hydraulic conductivity (k_s) could not be measured for the natural soil after heating due to the substantial volume reduction, which prevented reliable testing. For the remaining mixtures, although minor differences were observed among individual measurements, these variations are small and likely fall within the experimental uncertainty of the permeameter. This indicates that the instrument may not be sufficiently sensitive to detect subtle changes in saturated hydraulic conductivity induced by thermal treatment. Consequently, no systematic trend related to heating can be confidently identified. Overall, these results suggests that variations in saturated hydraulic conductivity alone may exert only a limited local influence, particularly under non-extreme fire severity conditions. It should also be noted that the permeameter tests were performed on remoulded samples, in which the thermal layering was disrupted, potentially masking localized permeability contrasts induced by heating.

In contrast, rainfall simulation tests performed on the shock-tube sample provided more informative results (Fig. 10). Although infiltration rates remained generally low in both tests, a slight advancement of the wetting front was observed in the test with the burnt soil surface, as suggested by the gradual increase in VWC values recorded by the TDR probe (Fig. 10c).

This behaviour indicates a modest alteration in infiltration dynamics. The relatively greater infiltration response observed in the burned sample is likely related not to a complete loss

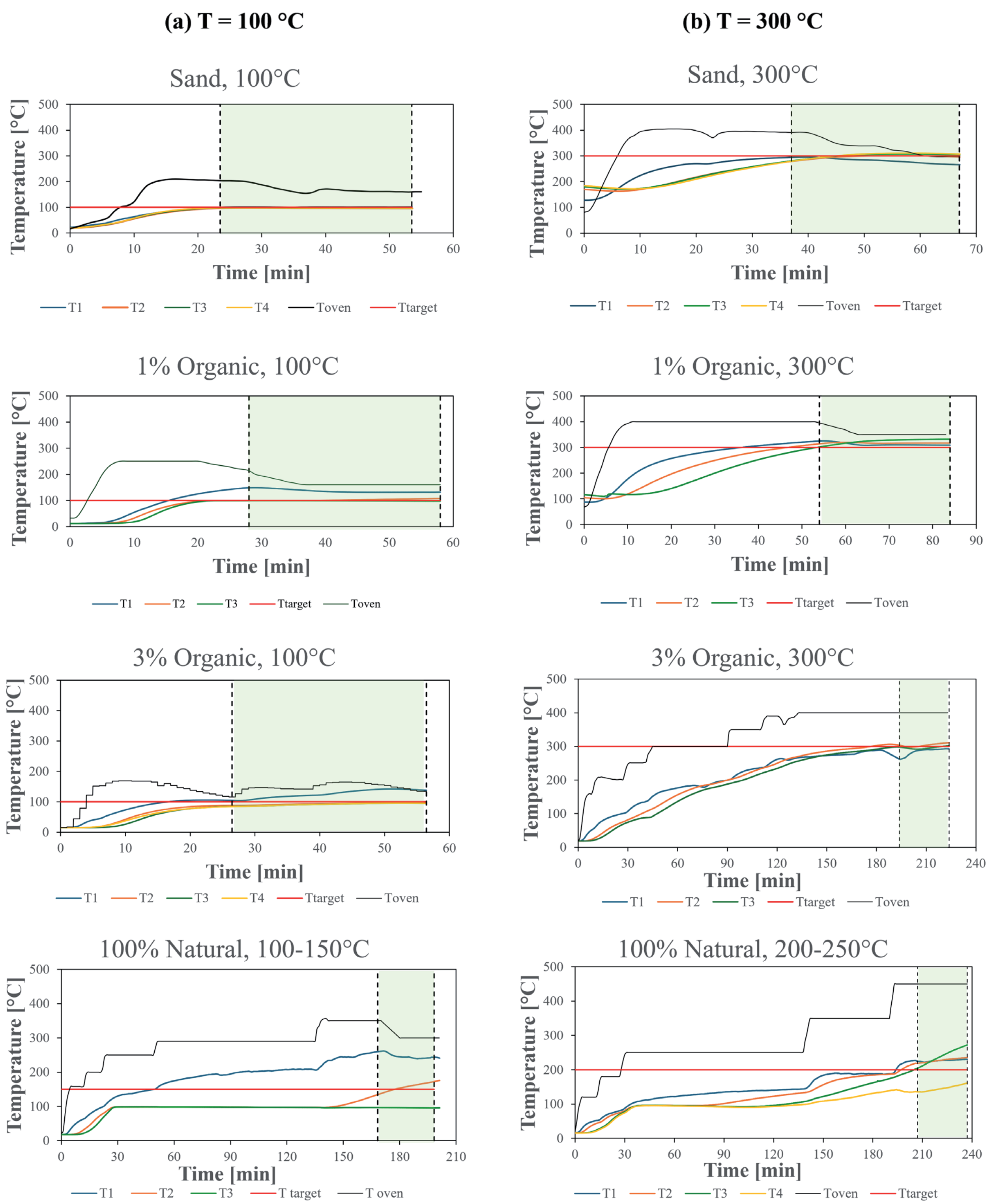

Fig. 8 - Temperature evolution for the different sample types (sand, sand–1% mixture, sand–3% mixture, natural soil): (a) target temperature 100°C; (b) target temperature 300°C. The green shaded area highlights the 30-minute interval during which the temperature measured by the thermocouple was maintained constant

of water repellency, but to the fractured and structurally discontinuous nature of the thermally altered surface layer, which locally promoted preferential flow paths (Fig. 10a). In contrast, the non-burned sample behaved as a more compact and hydraulically resistant surface, favouring rapid ponding and lateral runoff rather than vertical infiltration (Fig. 10b).

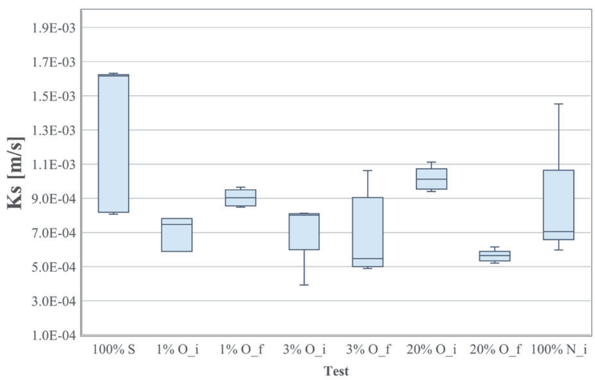

Fig. 9 - Falling-head permeameter tests performed before and after heating, presented in order of increasing organic matter content, from pure sand to natural soil. S = sand; O = organic mixture; N = natural soil; i = initial condition; f = final condition. Saturated hydraulic conductivity (k_s) could not be measured for the natural soil after heating

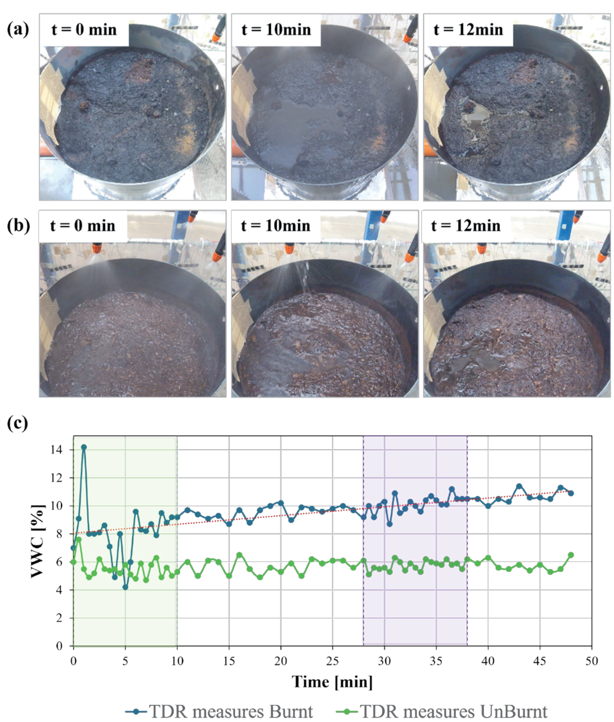

Fig. 10 - Rainfall simulations performed on the shock-tube sample: (a) rainfall applied to the burnt soil surface; (b) rainfall applied to the unburnt soil surface; (c) TDR-recorded volumetric water content (VWC, %) over time

DISCUSSION

Heating effects and heat-induced water repellency

The experimental results highlight a strongly heterogeneous soil response to heating, depending on soil characteristics and fire exposure conditions. Organic matter, in particular, emerged as the key controlling factor. In samples containing organic matter, a clear temperature-dependent behaviour was observed: moderate heating promoted the development of soil water repellency where it was initially absent, whereas higher temperatures led to its partial or complete degradation through the thermal breakdown of hydrophobic organic compounds. With increasing organic content, water repellency became progressively stronger and, at higher organic contents, was already present prior to thermal treatment. In contrast, no significant changes were observed in purely mineral samples. These results confirm that organic matter is a necessary condition for the development of heat-induced soil water repellency, and that repellency intensity increases with organic content.

Regarding thermal thresholds, induced water repellency developed at temperatures around 250°C and peaked near 300°C under the experimental conditions adopted in this study. At higher temperatures and sufficient exposure times, repellency progressively decreased due to combustion of organic matter. These threshold values, however, should be interpreted as system-specific rather than universal, depending on initial VWC and soil properties.

As evidenced also by Negri *et alii* (2021), higher organic matter content was also associated with lower thermal conductivity. In particular, the markedly reduced thermal conductivity of natural soil limited heat penetration even under prolonged exposure. Sandy samples showed rapid and relatively homogeneous heat diffusion, whereas organic mixtures exhibited delayed heat penetration and pronounced internal temperature contrasts. This behaviour was especially evident in the shock-tube test, where thermal disturbance was confined to the upper few centimetres.

Structural transformation and hydrological implications

In the shock-tube test, near-surface instabilities developed due to cohesion loss following water evaporation and direct flame interaction, associated with the experimental configuration. Ash-rich portions, which did not form in the furnace experiment, became more erodible and lost their water-repellent properties, confirming that intense heating and complete organic combustion can locally override hydrophobicity. Therefore, heating does not uniformly alter soil but rather produces a stratified system in which intensely altered zones coexist with minimally affected portions.

The partial transformation of the material observed in the furnace at higher temperatures further supports this interpretation. The uneven heat transfer produced a visible heterogeneous material transformation within the soil profile, likely related to the combined effects of local water evaporation, organic combustion, and clay dehydroxylation. Heating indeed produced substantial volumetric reduction, particularly in organic-rich samples. The natural soil exhibited up to 70% volume loss at 500°C, far exceeding the initial volumetric water content (2–5%), indicating that contraction cannot be explained solely by water evaporation. Additionally, macroscopic observations revealed the presence of newly formed sand lenses within the specimen.

This resulted in the coexistence of wettable lenses within still water-repellent soil. When these materials were remoulded for hydraulic conductivity testing, the mixing of wettable and hydrophobic portions likely reduced vertical contrasts, thereby masking localized permeability variations. In contrast, the rainfall tests performed on the undisturbed shock-tube sample preserved the layering of cracked burnt crust overlying wettable and water repellent zones. Under these conditions, the tests revealed a modest increase in infiltration capacity after heating with respect to the unaltered soil. This behaviour can be explained by the presence of fractures within the crust that locally promoted preferential flow paths and facilitated water entry into underlying wettable zones. Conversely, removal of the thermally altered surface layer restored infiltration behaviour closer to pre-fire conditions.

Finally, preferential flow paths, combined with reduced aggregate stability, may increase susceptibility to shallow landslides and debris flows under intense rainfall. As also shown by the shock-tube experiment, heating-induced structural degradation, cohesion loss, and spatial heterogeneity result in a mechanically weaker soil system. Thus, high fire severity may simultaneously reduce surface water repellency while increasing mechanical vulnerability, thereby promoting slope instability.

CONCLUSIONS

This study highlights the complex role of temperature in controlling soil wettability and, consequently, post-fire infiltration behaviour. Experimental results demonstrate that soil heating produces a highly heterogeneous transformation of soil properties, rather than a uniform modification of soil water repellency. The development or degradation of hydrophobic behaviour depends primarily on organic matter content, thermal conductivity, exposure duration, and heat intensity. Moderate heating promoted the onset or persistence of soil water repellency, particularly in organic-rich samples, whereas sufficiently high temperatures combined with prolonged exposure led to its partial or complete destruction.

The results confirm that organic matter is a necessary condition for heat-induced soil water repellency and that increasing organic content enhances both hydrophobic intensity and thermal insulation effects. Reduced thermal conductivity in organic-rich soils limits heat penetration, leading to localized persistence or destruction of hydrophobic properties.

Beyond changes in wettability, high-temperature exposure induced transformations of soil material, including marked volumetric contraction and the formation of sand lenses, associated with organic matter combustion and mineralogical alterations. These changes, together with heat-induced fracturing, further influence infiltration behaviour.

In the context of climate change and the increasing frequency of extreme events, understanding how infiltration processes evolve following wildfires and shifts in precipitation regimes is of critical importance, particularly in mountain environments where slope stability is highly sensitive to hydrological changes. Overall, these findings highlight the non-linear nature of post-fire soil response and the need for integrated, multi-scale approaches combining laboratory experiments, field measurements, and long-term monitoring to improve prediction of post-disturbance hydrological dynamics and support effective risk mitigation and land management strategies.

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REFERENCES

Abbate A., Longoni L., Ivanov V. I. & Papini M. (2019) - *Wildfire impacts on slope stability triggering in mountain areas*. Geosciences, Switzerland, **9**(10): 417.

Bisdom E. B. A., Dekker L. W. & Schoute J. T. (1993) - *Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure*. In Soil structure/soil biota interrelationships. Elsevier: 105-118.

Butzen V., Seeger M., Marruedo A., De Jonge L., Wengel R., Ries J. B. & Casper M. C. (2015) - *Water repellency under coniferous and deciduous forest—Experimental assessment and impact on overland flow.* Catena, **133**: 255-265.

Chicco J. M., Mandrone G. & Vacha D. (2023) - *Effects of wildfire on soils: field studies and modelling on induced underground temperature variations.* Frontiers in Earth Science, **11**: 1307569.

Corti M., Corti L., Abbate A., Papini M. & Longoni L. (2022) - *Post-wildfire terrain evolution in an alpine area.* International Multidisciplinary Scientific GeoConference: SGEM, **22**(3.1): 159-166.

Colombo M., Di Prisco M. & Martinelli P. (2011) - *A new shock tube facility for tunnel safety*. Experimental Mechanics, **51**(7): 1143-1154.

Costa K. O. B., Xavier G. C., Marvila M. T., Alexandre J., Azevedo A. R. G. & Monteiro S. N. (2021) - *Influence of high temperatures on physical properties and microstructure of gneiss.* Bulletin of Engineering Geology and the Environment, **80**(9): 7069-7081.

DeBano L. F. (1981) - *Water repellent soils: a state-of-the-art.* US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, **46**.

Debano L. F. & Krammes J. S. (1966) - *Water repellent soils and their relation to wildfire temperatures*. Hydrological Sciences Journal, **11**(2): 14-19.

Doerr S. H., Shakesby R. A. & Walsh R. (2000) - *Soil water repellency: its causes, characteristics and hydro-geomorphological significance*. Earth-Science Reviews, **51**: 33-65.

Longoni L., Scaioli A., Panzeri L., Arosio D., Corti M., Hojat A. & Papini M. (2025) - *A new Landslide Investigation and Simulation Archive through down-scaled landslide experiments*. Scientific Data, **12**(1): 1668.

Negri S., Stanchi S., Celi L. & Bonifacio E. (2021) - *Simulating wildfires with lab-heating experiments: Drivers and mechanisms of water repellency in alpine soils.* Geoderma, **402**: 115357.

Parise M. & Cannon S. H. (2012) - *Wildfire impacts on the processes that generate debris flows in burned watersheds*. Natural Hazards, **61**(1): 217-227.

Robichaud P. R. & Hungerford R. D. (2000) - *Water repellency by laboratory burning of four northern Rocky Mountain forest soils.* Journal of Hydrology, **231**: 207-219.

Shakesby R. A. & Doerr S. H. (2006) - *Wildfire as a hydrological and geomorphological agent.* Earth-Science Reviews, **74**(3-4): 269-307.

Sidex S.R.L. (N.D.) - *Steel colour–temperature reference scale*. Available online: https://www.sidex.it (accessed November 2025).

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