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Analyzing fire-induced water repellency and runoff in forest soil from beech forest: A controlled laboratory experiment

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Forest fires are a common ecological disturbance affecting soil properties and hydrological processes. In this study, we investigated the impact of fire on surface runoff and soil water repellency (SWR) in beech forest through a laboratory experiment. Our main goals were to quantify the severity of SWR caused by low-intensity fires (simulated at 300°C in a muffle furnace) using contact angle measurements with an optical goniometer and to analyze the relationship between heat-induced alterations in SWR and subsequent surface runoff generated by a rainfall simulator in laboratory conditions. The secondary goal of this study was to propose an innovative laboratory approach as an alternative for fire experiments in real forest environments.

We collected six monoliths, each with a forest soil surface layer measuring 20 cm x 15 cm x 10 cm, from the Zvolen-Budča site. These monoliths were heated at 300°C for 20 minutes in a muffle furnace to simulate the impact of low-intensity wildfires. Subsequently, the burnt monoliths and the Control were exposed to artificial rain from a rainfall simulator, and surface runoff was measured.

The results showed a significant increase in surface runoff from the burnt monoliths compared to the Control, indicating the impact of fire-induced changes in soil structure and SWR. Additionally, contact angle measurements using an optical goniometer showed increased SWR in the burnt disturbed samples.

The findings of our study underscore the significance of the interplay between fire-induced alterations in SWR and surface runoff. They offer valuable insights into the post-fire hydrological responses and erosion risks in forest ecosystems. These insights could help develop effective strategies to mitigate the environmental impacts of forest fires.

KEY WORDS: forest fires, soil hydrophobicity, surface runoff, contact angle

Introduction

Forest wildfires have the potential to cause significant disruptions and changes to the ecosystem. Soil properties can experience short-term, long-term, or permanent fire-induced changes, depending chiefly on the type of property, severity and frequency of fires, and post-fire climatic conditions (Certini, 2005; Derafshi, 2022).

Many studies have suggested that surface runoff and overland flow increase with an increase in soil water repellency (SWR) (Keizer et al., 2005; Gomi et al., 2008; Miyata et al., 2010; Valeron and Meixner, 2010; Ferreira et al., 2016). A majority of these studies focused on the impact of forest fires. Fires induce SWR due to the combustion of organic matter, producing waxy substances that coat soil particles (DeBano, 2000). The type and density of forest vegetation, organic carbon content, and soil properties play crucial roles in altering SWR (Arcenegui et al., 2007; Mataix-Solera et al., 2008; Negri et al., 2021). Notably, high temperatures, between 175 and 270°C, increase the formation of organic carbon coatings responsible for SWR, while temperatures between 270°C and 400°C destroy hydrophobic substances, suppressing SWR (Dekker et al., 1998; Doerr et al., 2004; Varela et al., 2005; Wu et al., 2020). The intensity of the fire and soil characteristics, such as moisture and particle-size distribution, primarily influences the depth of the water-repellent (WR) front in the soil. However, regardless of the severity of the fire and soil features, the depth of the WR front rarely exceeds 6-8 cm (Huffman et al. 2001).

Fires can decrease soil infiltration capacity relative to unburned areas (DeBano, 2000; Doerr and Moody, 2004; Shakesby and Doerr, 2006; Larsen et al., 2009; Ebel and Moody, 2017; Zvala, 2022; Hološ, 2023). The study by Robichaud (2000) found that the hydraulic conductivity of soil under *Pseudotsuga menziesii* and *Pinus contorta* was reduced by 40% after a fire. Similarly, Everett et al. (1995) found that water drop penetration time to soil increased significantly from instantaneous to over 270 seconds following slash burning in a mixed forest dominated by *P. contorta*.

The combination of wildfire-induced changes to soil and vegetation often results in increased runoff and erosion, driven in many cases by infiltration-excess overland flow (Benavides-Solorio and MacDonald, 2001; Moody and Ebel, 2014). Runoff behaves in a threshold manner, meaning that a certain amount of rainfall is needed to initiate it. When the rainfall rate becomes greater than the infiltration rate, excess water accumulates on the soil surface in depressions, forming puddles. Runoff begins once the surface storage is fully occupied and the puddles overflow (Horton, 1933). The rate of runoff depends on various factors, including soil surface conditions such as micro-topography, depressions, stone cover, water repellency, and surface hydraulic conditions.

When trying to simulate natural fires, soil samples are often heated in laboratory muffle furnaces. However, using a muffle furnace can result in significant differences from natural fires since the samples are heated from all sides instead of just the soil surface (Brucker et al., 2022). A muffle furnace experiment conducted by Martínez et al. (2022) confirmed that the hydraulic conductivity (both saturated and unsaturated) of sandy loam soil increased with temperature while the organic matter content of the soil decreased. Negri et al., 2021 found that SWR was maximized at 200°C during the muffle furnace heating experiment and dramatically lost above this temperature in loamy sand from beech forest, regardless of the SWR displayed by samples at lower temperatures.

Rainfall events that cause runoff are challenging to study due to their unpredictable nature. In order to recreate scenarios under semi-controlled conditions, rainfall simulators are often used, as they are considered to be reliable (Zhang et al., 1997). However, these studies have limitations such as their small scale, the differences between simulated and natural rainfall (Lascelles et al., 2000), and high experimental costs. In a review of rainfall simulation techniques, many authors highlighted these issues associated with different approaches and concluded that there is no ideal rainfall simulator.

Understanding the dynamics of SWR induced by fires in forest ecosystems is crucial for assessing the environmental impact of forest fires. As vital components of terrestrial ecosystems, forests are vulnerable to wildfires that can significantly alter their hydrological processes. Fire-induced SWR can lead to increased surface runoff, erosion, and altered nutrient cycling. These changes have far-reaching implications, including potential threats to water quality, ecosystem health, and human settlements downstream. Conducting experiments to study fire-induced SWR in natural forest settings is challenging due to the unpredictable nature of wildfires and safety concerns. Therefore, developing innovative laboratory approaches is essential. Controlled laboratory experiments offer a safe environment to simulate fire-induced SWR accurately. These laboratory approaches allow for precise control of variables, enabling systematic investigations into the effects of different fire intensities, soil types, and vegetation cover. Moreover, they facilitate the development of predictive models to assess the potential impact of forest fires on hydrological processes under various scenarios. Through these experiments, scientists can identify effective mitigation strategies, enhance ecosystem resilience, and inform land management practices to minimize the adverse consequences of fire-induced SWR and increased runoff.

The main goals of our research were: 1. to quantify the severity of SWR induced by the low-intensity fires, simulated at 300°C in a muffle furnace, utilizing contact angle measurements with an optical goniometer; 2. to analyze the relationship between heat-induced alterations in SWR and subsequent surface runoff, generated by rainfall simulator in laboratory condition. The secondary goal of this study was to develop a novel laboratory approach specifically designed to address the challenges associated with conducting fire experiments in real forest environments. Recognizing the limitations of conducting field experiments due to safety concerns and uncontrollable variables, our aim was to create a replicable and controlled laboratory methodology.

We hypothesized a significant increase in SWR in the soil samples subjected to heating compared to the control group, indicating the presence of hydrophobic substances due to heat exposure. Furthermore, we anticipate that there will be a direct and positive correlation between the heat-induced alterations in SWR and the subsequent increase in surface runoff.

Material and methods

Study site

Soil samples (monoliths) were taken from the study site at Budča village, 6 km southwest of the district town of Zvolen, on the right bank of the Hron River, where the Kremnica Mountains meet the Štiavnica Mountains. The study site (48° 34' 55.2468" N, 19° 3' 15.5592" E; 410 m a. s. l.) is an eastern slope logging site, representing the habitat of the transition from beech to oak-hornbeam forest, covered mainly with scattered European Beech, Common Nettle, Bushgrass and Bugleweed (Fig. 1).

The region has a mildly warm climate. Average annual air temperature ranges from -6.5°C in January to 20.5°C in July, depending on altitude. Average annual rainfall ranges from 530 to 600 mm. The geological bedrock consists of heterogeneous volcanic products, andesite agglomerates and tuffs (Bačíková, 2015). The soils of the site are classified as Cambisols and have a silt loam texture (WRB, 2015). The basic physical and chemical characteristics of the disturbed soil samples are presented in Table 1.

The study site was chosen due to its significant slope, with an average of 14 degrees, which increases the likelihood of induced runoff after disturbances such as wildfires. The site is located in a logging area, making it more susceptible to wildfires. Furthermore, the site has a diverse habitat ranging from beech to oak-hornbeam forest, which allows for an examination of the variability in soil responses across different plant species. The presence of residues on the forest floor acts as potential fuel during wildfires, aggravating the impact of fire on the soil. Additionally, the site has experienced previous runoff events, indicating a history of water movement that has likely altered soil properties.

Table 1. **Characteristics of the topsoil horizon (0–10 cm) of the study site near Budča (Cox = organic carbon content; CA= contact angle). The results are presented as arithmetic mean and standard deviation (SD)**

	Sand [%]	Silt [%]	Clay [%]	Cox [%]	Humus [%]	CA [°]
	mean (SD)	mean (SD)	mean (SD)	mean (SD)	mean (SD)	mean (SD)
Zvolen-Budča	20.72 (1.54)	67.11 (1.08)	12.17 (0.46)	2.10 (0.19)	3.62 (0.33)	16.41 (2.40)

Fig. 1. Study site in September 2023: a) vegetation cover; b) detail of forest floor biomass.

Soil sampling and heating experiment

Soil sampling was conducted in September 2023. We carefully extracted six soil monoliths with forest floor biomass at the study site, measuring 20 cm x 15 cm x 10 cm, using a spade and shovels to disturb the soil structure as little as possible. We placed the soil monoliths in crates and secured them against displacement. In the laboratory, we left the monoliths air-dried in the crates for seven days.

After reaching equilibrium, the monoliths were placed in aluminium containers and weighed. Half of the monoliths were heated in a muffle furnace (LAC, s.r.o., Židlochovice, Czech Republic; Type: LE 15/11) (Fig. 2) at a temperature of 300°C for 20 min. After a given time, we pulled the samples out of the furnace and allowed them to cool to room temperature.

Measurement of soil water repellency

The severity of SWR was estimated by the sessile drop method. This involved placing a water drop on the soil sample's surface and analyzing the static contact angle (CA) by reviewing image recordings taken with the optical goniometer OCA 11 (DataPhysics Instruments GmbH, Filderstadt, Germany). The procedure described by Bachmann et al. (2000) was used to prepare the samples, which involved covering a glass slide with double-sided adhesive tape and pressing soil particles onto the tape for several seconds. The slide was shaken carefully to remove any unglued soil particles, and then a 5 μL drop of deionized water was placed on the sample surface using a 0.91 mm syringe needle. After 1 s when mechanical disruption of the surface was complete after drop placement, CA was evaluated by analyzing the shape of the drop (ellipsoid approximation) and fitting tangents on both sides of the drop using dpiMAX version 1.51.90.75 software (DataPhysics Instruments GmbH, Filderstadt, Germany) according to Goebel et al. (2013). CA of each drop was determined as an arithmetic mean of the CA values on the left and right sides of the drop. The following classes of the severity of SWR can be distinguished: non-water-repellent soil (wettable) (CA < 40°), slightly (40° ≤ CA < 90°), moderately (90° ≤ CA < 110°), strongly and very strongly (110° ≤ CA < 130°), and extremely (CA ≥ 130°)

water repellent soil (Papierowska et al., 2018). CA was estimated with five repetitions for each monolith.

Laboratory runoff experiment

Surface runoff measurements were made using a portable rainfall simulator (Royal Eijkelkamp, Giesbeek, Netherlands) placed on a structure designed for this measurement with an inclined monolith and a space in front for catching runoff (Fig. 2). The runoff area of the rainfall simulator was limited to the surface of prepared monoliths (191 cm^2), and runoff water was captured at the lowest point. The sprinkler unit of the simulator is equipped with 49 glass capillary tubes, each 0.6 mm in diameter and 10 mm in length–only 15 of the capillary tubes were intended to produce simulated rain over the defined runoff area. The soil monoliths were prepared to match the intended area on which the 15 capillaries were designed to drip. This step involved the careful trimming of each monolith using a trimmer to gently remove excess material from the edges of the monoliths. Distilled water was used to simulate rain, with drops weighing 0.106 g falling from an average height of 0.4 m onto the soil monolith surface. Rainfall simulations were conducted on three burned and three unburned monoliths. After the installation of the monoliths, the slope of the drainage area was measured with a digital spirit level (Robert Bosch GmbH, Gerlingen, Germany; Type: GLM50C). A total of 6 rainfall simulations (one simulation on each monolith), with a duration of 4 minutes, were performed. Rainfall intensity, set by the height of the aeration tube (8 cm), varied between 4.28 mm min^{-1} and 4.48 mm min^{-1} (Table 2), with an average value of 4.4 mm min^{-1}.

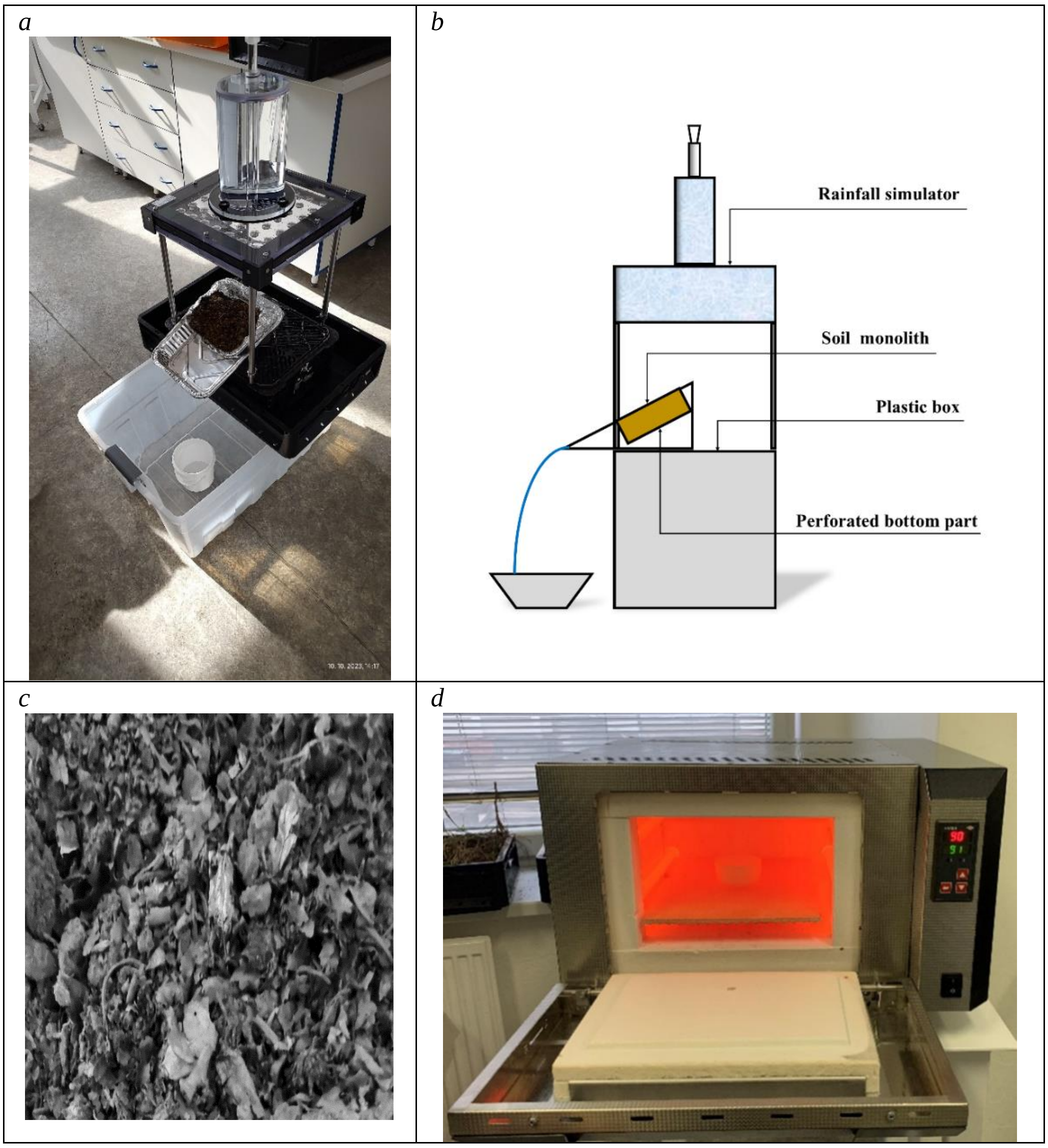

Fig. 2. A laboratory design of rainfall simulator with an inclined monolith: (a) photo and (b) simplified sketch. The burned surface of the monolith (c) and heated muffle furnace (d).

Table 2. **Rainfall simulation parameters for the experiment (rainfall intensity i_r, total rainfall, H_r) and volumetric moisture content w prior to the experiments and the slope of the runoff plots.**

Parameter	Minimum	Maximum	Mean	SD
i_r [mm min^{-1}]	4.28	4.48	4.4	0.09
H_r [mm]	17.12	17.92	17.6	0.35
w [% vol.]	1.3	3.4	2.2	0.51
slope [°]	15.9	19	17.3	1.28

The statistical analysis of rainfall simulation parameters, slope, and soil moisture content showed no significant differences between the burned and unburned monoliths. This uniformity indicates that the experimental conditions were consistent. It is important to note that any differences in measured runoff can be attributed to changes that occurred specifically after the heating process.

Surface runoff from the prepared monoliths was assessed using the surface runoff coefficient (C_r), defined as the proportion of simulated rainfall that is transformed to direct surface runoff (Miyata et al., 2007), and the surface runoff generation time (T_r), defined as the time for the first drop of generated runoff to flow into the prepared container.

Statistical analysis

Comparisons between the burned and unburned treatments (Control) have been performed by t-test. A t-test is a statistical test used to compare the means of two groups. It was used in hypothesis testing to determine whether any treatment has an effect on the population of Control. The null hypothesis (H0) is that the true difference between the Control and burned treatment group means is zero. The alternate hypothesis (Ha) is that the true difference differs from zero. The statistical significance of the analysis was defined at $P < 0.05$. All statistical analyses were performed using the NCSS statistical software (NCSS 12 Statistical Software, 2018).

Results and discussion

The results of our laboratory experiment showed that evident changes occurred in various parameters after heating monoliths from the deciduous forest. Before heating, the contact angle (CA) ranged from a minimum of 14.74° to a maximum of 19.85°, with an average of 16.41°. After heating, the contact angle substantially increased, ranging from 61.84° to 89.91°, with an average of 79.26°. This increase, on average by 62.85°, signifies a remarkable enhancement in soil water repellency following the heating process, confirmed by a significant increase in CA values after heating (Fig. 3a). In our previous studies (Šurda et al., 2023; Hološ et al., 2022), we observed the increase in CA in sandy soil with the heating temperature in an interval from 50°C to 300°C. Also, Samburova et al. (2021) found that sand samples treated with fire emissions showed increased contact angle (CA) between 78° and 87°, while the untreated sand samples showed CA = 48°. Negri et al. (2021) found that with growing temperatures, the Alpine soil samples displayed extremely different wettable behaviour, with or without fire-induced SWR build-up. This happened mainly concerning the content and composition of soil organic material. Carrà et al. (2021) found a moderate SWR in loamy sand soil in chestnut forests and a strong SWR in both pine and oak forests after prescribed fire.

Similarly, the surface runoff coefficient (C_r) displayed notable variations. Before heating, the coefficient ranged from 0.40 to 0.49, with an average of 0.45. Post-heating, the coefficient increased significantly, ranging from 0.57 to 0.73, with an average of 0.63. The increase, on average by 0.18, indicates a higher tendency for surface runoff generation after the heating process, proved by a significant increase in C_r values after heating (Fig. 3b). Previous research proved a strong correlation between fire-induced SWR and increased runoff in various soils. Leighton-Boyce et al. (2007) found that runoff caused by SWR in Eucalyptus plantations with loamy sand and sandy soils increased 16 times. Müller et al. (2018) proved that SWR governed runoff in sandy loam Andosol. Carrà et al. (2021) observed increased runoff in the window of disturbance after fire in loamy sand from oak, chestnut and pine forests. González-Pelayo et al. (2010) observed that surface runoff values in shrubland areas with sandy loam soil treated with low-intensity prescribed fire were 22-fold the values measured in untreated sites. Morales et al. (2000) found an 18-fold increase in runoff one year after the fire in the litosols and rendzins with sandy texture at altitudes above 2500 m a.s.l.

Surface runoff generation time (T_r) also exhibited distinct changes. Before heating, the time ranged from 47 seconds to 52 seconds, with an average of 49.3 seconds. After heating, the range decreased from 25 seconds to 26 seconds, with an average of 25.7 seconds. This reduction, averaging 23.6 seconds, signifies a faster initiation of runoff after the soil is heated, confirmed by a significant decrease in T_r values after heating (Fig. 4a). Müller et al. (2018) observed that the short lag time for runoff initiation, in accordance with the increase in runoff, indicated infiltration excess as the process which is generating runoff.

Furthermore, surface runoff total (H_r) demonstrated significant alterations. Before heating, the total runoff ranged from 5.69 mm to 8.36 mm, averaging 7.02 mm. After heating, the range increased from 10.02 mm to 13.01 mm, averaging 11.28 mm. The change, averaging 4.26 mm, highlights a substantial increase in runoff volume following the heating process, demonstrating a significant increase in Hr values after heating (Fig. 4b). When analyzing the results, we further focused on exploring the relationship between C_r (surface runoff coefficient) and CA (static contact angle) based on a dataset consisting of six observations. Our analysis revealed a robust correlation between these two parameters, with a correlation coefficient of 0.92; we derived a regression equation to represent this relationship quantitatively: C_r = 0.3977 + 0.0031 CA (Fig. 5a). Furthermore, we found a significant R^2 value of 0.8464, which demonstrates that approximately 84.64% of the variation in the surface runoff coefficient (C_r) can be attributed to variations in static contact angle. (CA). This indicates a strong relationship between these two

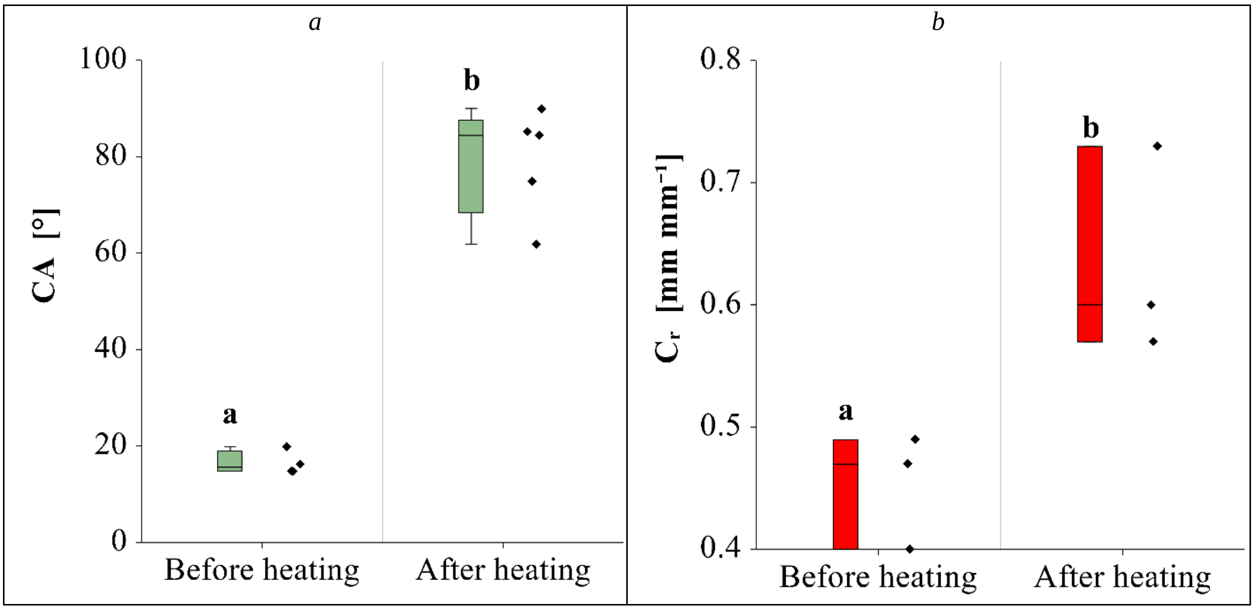

Fig. 3. The measured values of (a) static contact angle (CA) and (b) surface runoff coefficient (C_r). The plot displays individual measurements as points. The whiskers extend to a distance of 1.5 times the interquartile range from the edges of the box. Box plots represented by different letters are significantly different at a 0.05 significance level.

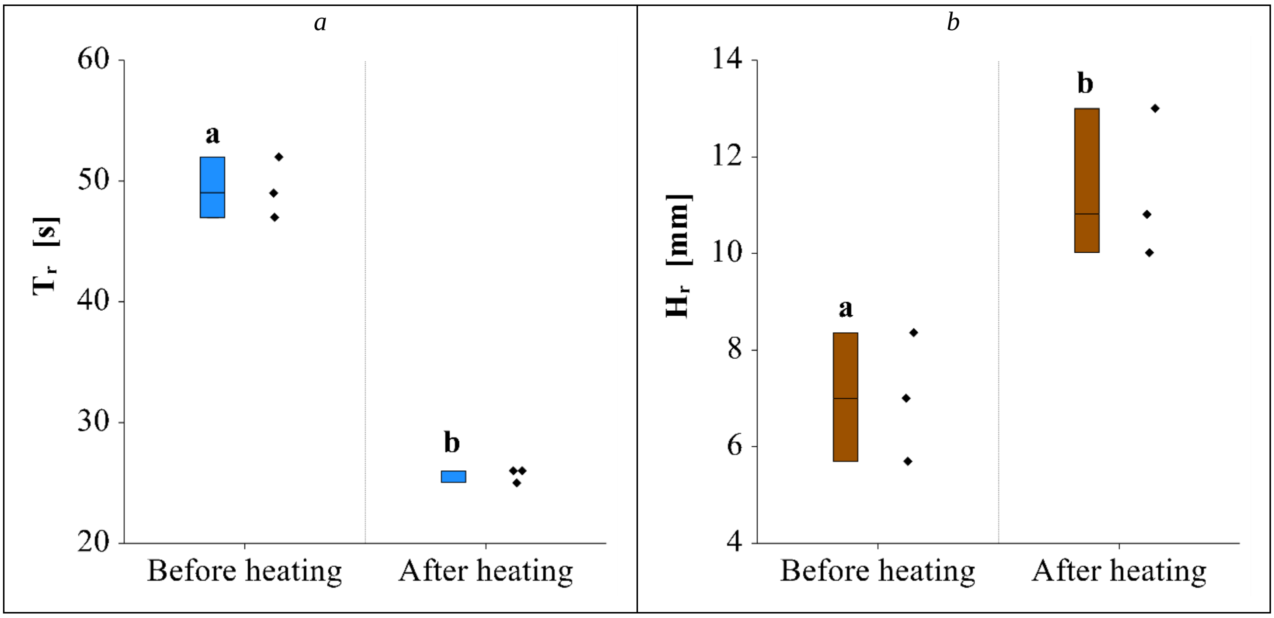

Fig. 4. The measured values of (a) surface runoff generation time (T_r) and (b) surface runoff total (H_r). The plot displays individual measurements as points. The whiskers extend to a distance of 1.5 times the interquartile range from the edges of the box. Box plots represented by different letters are significantly different at a 0.05 significance level.

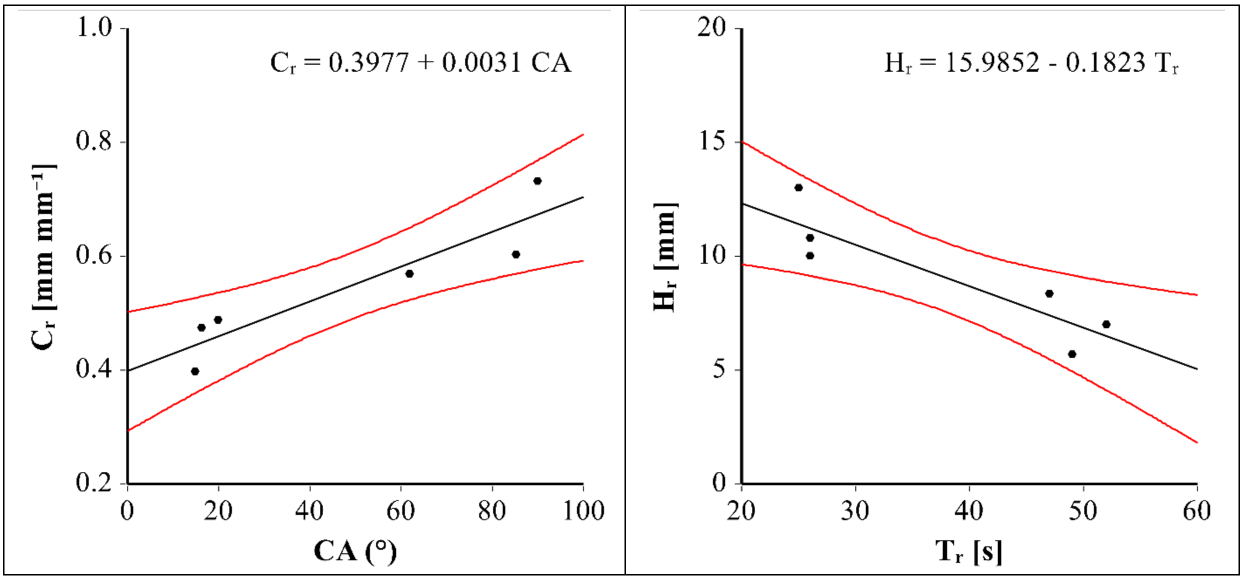

Fig. 5. The derived regression lines and equations of (a) the relationship between surface runoff coefficient (C_r) and static contact angle (CA) and (b) the relationship between simulated precipitation total (H_r) and surface runoff generation time (T_r). The black line displays the regression line, and the red lines represent the confidence limits (the upper and lower boundaries of a confidence interval of the mean at a specific value of X).

variables. The relationship between H_r (simulated precipitation total) and T_r (surface runoff generation time) was investigated using a dataset consisting of 6 observations. The regression equation representing this relationship was derived as follows: H_r = 15.9852 - 0.1823 T_r (Fig. 5b). The R^2 value, which measures the proportion of the variation in Hr explained by variations in T_r, was 0.7983. Our analysis further revealed a strong correlation between H_r and T_r, with a correlation coefficient of -0.89. This negative correlation suggests a robust inverse relationship.

Conclusion

Our study investigated the effects of heat-induced soil water repellency (SWR) on surface runoff through controlled laboratory experiments. We confirmed the hypothesis predicting increased SWR and subsequent surface runoff after heating. Significant changes were observed following soil heating at 300°C. These included a substantial increase in SWR, as indicated by higher contact angle (CA) values; a notable rise in the surface runoff coefficient (C_r), demonstrating a higher tendency for runoff generation; a faster initiation of runoff, as evidenced by reduced surface runoff generation time (T_r); and a considerable increase in total runoff volume (H_r). Moreover, our analysis revealed strong correlations between variables. The relationship between C_r and CA was robust (correlation coefficient = 0.92), leading to the derivation of a regression equation (C_r = 0.3977 + 0.0031 CA). Similarly, the inverse relationship between H_r and T_r was well-established (correlation coefficient = -0.89), represented by the regression equation (H_r = 15.9852 - 0.1823 T_r).

The proposed methodology offers an effective alternative to field experiments by simulating fire-induced SWR and subsequent runoff under controlled conditions. This approach overcomes the limitations of safety concerns and uncontrollable variables associated with working in natural forest environments. Using this method, we can increase the safety and replicability of experiments.

In summary, our findings highlight the impact of heat-induced SWR on surface runoff patterns. These results provide valuable insights for hydrological modelling and environmental management. It emphasizes the importance of considering SWR effects in predicting post-fire runoff processes.

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