



Response of severity and persistence of water repellency to thermal heating parameters in eucalyptus and pine forest soils in Sri Lanka

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Abstract: Soil water repellency (SWR) relates to plant species such as conifers and Eucalyptus with high amounts of hydrophobic substances such as resins, waxes, and other oily substances, and are highly vulnerable to wildfires. The heat generated through fire can influence SWR, although the changes can deviate based on soil, climatic, and environmental conditions. This study aims to examine the impact of heating temperature and duration of exposure to heat on the severity and persistence of SWR in eucalyptus and pine forest soils in Sri Lankan highlands. Soils collected from three depths (0–5, 5–10, 10–15 cm) were air dried, passed through a 2 mm sieve, and exposed to six heating temperatures (50, 70, 100, 150, 200, 250°C) and five durations of exposure (20, 40, 60, 90, 120 min). SWR was determined using water drop penetration time (WDPT) and soil-water contact angle. Both eucalyptus and pine soils showed water repellent conditions at the field and at air-dried conditions. Both soils reached completely wettable level (WDPT < 5 s) with very low contact angles when exposed to 200–250°C for 90–120 min, except for the contact angle of the eucalyptus 0–5 cm layer that decreased to a minimum of 40°. SWR showed fluctuations with increasing temperature between 28 and 150°C at all durations of exposure. SWR showed significant positive linear correlation with soil organic matter (SOM) content, of which the strength was moderate ($R^2 = 0.64$ and 0.50 , respectively, for eucalyptus and pine), indicating that the heat-induced change in SWR was not strongly dependent on SOM content. Contrasting transitions in SOM due to removal via various processes and structural and molecular rearrangements might explain fluctuations of SWR at lower temperatures (28–150°C). The findings would be useful for understanding the impacts of various heating dynamics that might occur during forest fires. Further research considering the other important factors, such as molecular-level variations in organic substances as well as mineralogical and climatic aspects, would be important for a better understanding of hydrological responses on burnt forest floors.

Keywords: Heating duration; Heating temperature; Soil organic matter; Soil water repellency.

1 INTRODUCTION

Soil water repellency (SWR) is a phenomenon that reduces the affinity of soil to water. It reduces the wetting rates in dry soil and is known to interfere with water movement into and within the soil, affecting almost all the hydrophysical properties and processes in soils (Lichner et al., 2012). SWR causes slower infiltration rates, leading to higher overland flow, subsequently triggering soil erosion. It can result in the movement of entrained pollutants to the groundwater through preferential flow pathways, causing pollution (Smettem et al., 2021). SWR is a common phenomenon that has been reported in a wide variety of ecosystems, climates, and soils across all continents except Antarctica (Doerr et al., 2007). Based on the reported findings over the past decades, it appears that nearly all soils exhibit some level of water repellency. Considering the available information on SWR of different soils and ecosystems, it has been suggested that the SWR should be regarded as the norm rather than an exception (Smettem et al., 2021; Wallis et al., 1991). The primary factor responsible for inducing SWR is the accumulation of organic substances that are incorporated into soils through the roots of plants, dead plant material, and soil organisms (Atanassova and Doerr, 2011; Doerr et al., 2000; Franco et al., 1995, 2000). Besides the presence of organic substances, other variables such as soil temperature, texture, soil moisture, soil pH, and heat produced by forest fires are recognized as important in influencing

SWR (Mirbabaei et al., 2013; Roberts and Carbon, 1972; Smettem et al., 2021; Šurda et al., 2023; Zavala et al., 2010).

Since the major proportion of organic compounds that are responsible for developing SWR originates from plants (Doerr et al., 2000; Mao et al., 2014, 2016), its occurrence is generally related to the vegetation that covers the soil. Reported findings in literature indicate that certain specific plant species are more likely to induce SWR because of the higher presence of hydrophobic organic materials such as resins, waxes, and other oily substances that include long-chain organic compounds in their tissues. SWR is usually observed in soils covered by conifers and other similar tree species such as Japanese cypress (*Chamaecyparis obtusa*), Japanese cedar (*Cryptomeria japonica*), eucalyptus (*Eucalyptus grandis*, *E. globulus*), pine (*Pinus caribaea*, *P. pinaster*, *P. sylvestris*), and casuarina (*Casuarina equisetifolia*), which are rich in various types of hydrophobic resins and waxes (Benito et al., 2019; Doerr et al., 1996; Iovino et al., 2018; Kobayashi and Shimizu, 2007; Keizer, et al., 2008; Leelamanie, 2016; Lichner, et al. 2013; Leelamanie et al., 2021). These vegetation-induced SWR conditions are generally associated with chemical compounds such as alkanolic acids, alkanes, and esters (Hansel et al., 2008). SWR in forests under these specific tree species is known to be a natural circumstance rather than being induced by different external aspects. However, due to the waxy or oily nature of their organic substances, the plant debris of these specific plant species, such as conifers and Eucalyptus, is highly flammable, making them vulnerable to wildfires (Bernier

et al., 2016; Scarff and Westoby, 2006). The supply of flash fuels by the waxy flammable litter materials can cause a more rapid heating rate and rise in soil temperature (Bruns et al., 2020). The soil temperature increases to different levels due to the heat generated during a forest fire event (Fajković et al., 2022; Li et al., 2022). The generated heat can cause significant impacts on the SWR (Caltabellotta et al., 2022; García-Corona et al., 2004; Hološ et al., 2022; Plaza-Álvarez et al., 2018; Zavala et al., 2010). Depending on the available evidence, it is noted that the heat generated by wildfire can either increase, decrease, or eliminate the water repellency of the underlying soils (Doerr et al., 2006; Zavala et al., 2010). These impacts on SWR depend on factors such as the intensity and the severity of the fire event that change the peak soil temperature levels as well as the duration of exposure to those temperature peaks (Dao et al., 2022; Doerr et al., 2004, 2006; Zavala et al., 2010). However, the reports on these impacts on SWR are inconsistent. The relationship between the water repellency in soils underlying specific plant species and the impacts of heat on levels of SWR may not always be straightforward because other factors can alter organic substances in soil under natural conditions (Doerr et al., 2000; Majid et al., 2023). Elimination of SWR with increasing heating temperature has been reported in various studies. The temperature levels that eliminate SWR in soils under various plant species are reported as 200°–250°C (Bryant et al., 2005; Perera et al., 2024), 260°–300°C (Doerr et al., 2004, 2005; Perera et al., 2024), and 380° or 400°C (García-Corona et al., 2004; Hološ et al., 2022; Zavala et al., 2010). Reported findings indicate that SWR either increases with increasing temperature at low temperature levels and decreases beyond higher temperature levels, or continuously decreases with temperature, to reach non-repellent conditions with elimination of SWR. Literature reports the ranges of temperatures that cause an increase in SWR as 50–150°C (Dao et al., 2022; Doerr et al., 2005), 100–150° (Zavala et al., 2010; Perera et al., 2024), 25–220°C (García-Corona et al., 2004), or 20–300°C (Lichner et al., 2025). Perera et al. (2024) reported a continuous decrease in SWR in Cedar soil with increasing temperature. These findings indicate that the response of SWR to heat changes with factors such as the type of vegetation, the type and characteristics of soil, and environmental conditions. In addition to inconsistencies in the effect of temperature levels under these different conditions, the evidence regarding the impact of the duration of exposure of soil to the specific temperature levels on their SWR levels is limited in various ways (Doerr et al., 2004, 2005; Perera et al., 2023, 2024). Use of measurement techniques, for example, the molarity of an ethanol droplet (MED) test, with a limited measurement range (contact angles > 90°) restricts the data that can be recorded on SWR (Perera et al., 2024), especially the changes in contact angle that might happen at very low-repellent levels. The objective of this study was to examine the response of both severity and persistence of SWR to heating temperature and duration of exposure to temperature using water-repellent eucalyptus and pine forest soils located in the highlands of Sri Lanka.

2 MATERIALS AND METHODS

2.1 Study area and site characteristics

Two sites with naturally water-repellent soils were selected for the laboratory heating experiments. Site one was a eucalyptus (*Eucalyptus grandis*) forest plantation (06° 47' 45" N 80° 57' 58" E), and the other site was a pine (*Pinus caribaea*) forest plantation (06° 46' 15" N 80° 55' 51" E). Eucalyptus plantation belongs to the IU_{3c} agro ecological region, whereas the pine plantation

belongs to the IU_{3a} and IU_{3b} agro ecological regions, with an average annual precipitation of 1600–1900 mm and a mean annual temperature of 20–22.5°C (National Atlas of Sri Lanka, 2007). The altitude of the locations ranged from 1281 to 1524 m above the mean sea level. The major soil type is Red-Yellow Podzolic, which is categorized under Rhodudults under USDA classification (Soil Survey Staff, 2014). The average litter depth of the two sites was 3.5–4.0 cm. Although Sri Lanka is located in the tropical belt, both study areas are noted as fully humid warm temperate climates with warm summer (Cfb) according to the Köppen-Geiger classification (Kottek et al., 2006). The soils had a loamy sand or sandy loam texture and acidic pH.

2.2 Field sampling and initial preparation

Bulk soil samples and undisturbed core samples (for bulk density determination) were collected from 0–5 cm, 5–10 cm, and 10–15 cm depths in the two study sites for the experiments. Before sampling, the litter and debris on the forest floor were carefully removed. Collected samples were carefully packed in plastic containers and transported to the laboratory for experiments and analysis. In the laboratory, the samples were air dried at room temperature (27 ± 2°C) for three days and passed through a 2 mm mesh before being used for further experiments. After the initial preparation, the basic properties of the soils from the two locations were determined following standard laboratory procedures (in triplicate). The soil texture was determined using the pipette method. The soil organic matter (SOM) content was calculated using the loss on ignition method (Schumacher, 2002). The pH and electrical conductivity (EC) in aqueous suspensions (soil: water 1:2.5 for pH, 1:5 for EC, w/w) were measured using a pH meter and an EC meter, respectively. Table 1 presents the basic soil properties at the two sites.

2.3 Heating treatments

Six heating temperatures (50°C, 70°C, 100°C, 150°C, 200°C, and 250°C) and five durations of exposure (20 min, 40 min, 60 min, 90 min and 120 min) at each temperature were selected for the study. For the heating of soil samples, they were placed in ceramic containers (diameter of 35 mm, height 45 mm) in a layer with a constant thickness of 25 mm. The samples were separately exposed to different levels of temperature and durations of exposure. Up to 200°C temperature experiments were done using a convection drying oven (JEIOTECH, Korea), and the 250°C experiment was done using a muffle furnace (FSE. 500 11 M-Gallencamp, U.K). Since oxygen deprivation influences the thermal transformation of organic materials and SWR (Bryant et al., 2005), the exhaust port of the furnace was kept open to facilitate fresh air circulation and replenish the oxygen supply. After each heat treatment, SOM content, WDPT, and soil-water contact angles were determined.

2.4 Determination of soil water repellency

After heating treatments, the samples were allowed to equilibrate with the laboratory atmospheric conditions (27 ± 2°C and 65–75% Relative humidity) for 24 h prior to testing for SWR. Samples were then tested for the severity and the persistence of potential repellency using the water drop penetration time (WDPT) test (Taumer et al., 2005) and modified sessile drop contact angle methods (Leelamanie, 2016), respectively.

Table 1. Basic soil properties (Mean± standard deviation) of eucalyptus and pine forest soils. WDPT: water drop penetration time.

Soil Property	Eucalyptus			Pine		
	0–5 cm	5–10 cm	10–15 cm	0–5 cm	5–10 cm	10–15 cm
Bulk density (g cm ⁻³)	1.1 ±0.1	1.1 ±0.1	1.1 ±0.1	1.1 ±0.1	1.2 ±0.1	1.2±0.1
Particle density (g cm ⁻³)	2.2 ±0.3	2.4 ±0.1	2.4 ±0.2	2.6 ±0.1	2.9 ±0.1	2.5±0.2
Porosity (%)	51.6	54.7	52.3	56.6	59.5	51.2
Air dried moisture (%)	4.3±0.3	4.1±0.1	5.0 ±0.2	5.1 ±0.2	6.3±0.1	4.4±0.2
Sand %	84.5 ±0.1	77.7 ±1.6	74.1±0.1	75.8 ±2.9	73.6 ±1.3	71.1±1.6
Silt %	4.3±1.5	5.2±0.0	6.0 ±1.5	10.8 ±2.8	10.0±1.6	10.8±2.6
Clay %	11.2 ±1.5	17.2 ±1.6	19.9 ±1.5	13.5 ±2.7	16.4 ±2.6	18.1±3.2
Texture	Loamy sand	sandy loam	sandy loam	sandy loam	sandy loam	sandy loam
Organic matter (%)	14.8±0.2	9.0 ±0.6	6.1 ±0.9	11.1 ±0.4	10.0 ±0.3	9.1 ±0.4
pH	4.8±0.1	5.0±0.0	5.0 ±0.1	4.1 ±0.0	4.3±0.0	4.3±0.0
EC (dS/m)	0.03±0.00	0.02±0.00	0.02±0.00	0.12±0.01	0.09±0.01	0.07±0.01
WDPT (s)	7200±0	364±35	1.9±0.7	6300±26	14.0±1.5	3.5±0.8

2.4.1 Water drop penetration time test

The persistence of SWR was determined using the WDPT test, which measures the time taken for a water drop placed on the soil surface to complete the penetration into the soil. Soil sub-samples in ceramic containers were used for the measurement. One drop of distilled water (50±1 µl) was carefully placed on the soil surface at about 10 mm height from the soil surface using a burette. The time taken for the complete penetration of water drops was recorded using a stopwatch. Ceramic containers were covered to prevent the evaporation of water drops in case of longer penetration times. All measurements below 1 s were taken as 1 s (WDPT ≤ 5 s, non-repellent), and the measurement was terminated after 1 h (WDPT ≥ 3600 s, extremely repellent). The measurements were conducted before and after the heat treatments in triplicate (Leelamanie, 2016).

2.4.2 Soil-water contact angle

The severity of SWR was determined using soil-water contact angles measured by the sessile drop method. For the measurement, soil monolayers were prepared on a double-sided adhesive tape (1.5 cm × 1.5 cm) fixed on a glass slide. After fixing the adhesive tape to the glass slide, a soil monolayer was prepared by sprinkling the soil on the adhesive topside of the tape. Then the samples were pressed to the tape with a 100 g weight for 10 s, and the excess soil was removed by tapping gently. This procedure was repeated twice to ensure the formation of a soil monolayer on the adhesive surface (Leelamanie, 2016).

To determine the soil-water contact angle, a drop of distilled water (10 µL) was placed on the monolayer using a micro pipette (Nichipet EX II J15615241-Nichiriyo, Japan), and a digital micro-photograph of the horizontal view of the water drop was captured within 1 s using a digital microscopic camera (M534S-3100 PC Fujikoden Co. Ltd, Japan). The contact angle of soil was determined using the microphotographs, considering the three-phase (soil-water-air) contact points of the drops on a 2D view. The contact angle of each photograph was measured using screen protractor software. The measurements were conducted before and after the heat treatments in triplicate (Bachmann et al., 2000; Leelamanie, 2016).

2.5 Data analysis

All experiments were conducted in triplicate. Regression analysis was conducted to determine the statistical significance of developed correlations between studied parameters at the 5%

level of significance ($p < 0.05$). The mean values of the measurements were reported, with the error bars in the figures indicating ± standard deviation.

3 RESULTS

Both eucalyptus and pine soils showed water repellent conditions at the field and at air-dried conditions. Figure 1 presents the SWR of two forest soils as measured by the contact angle and WDPT at airdried laboratory conditions (~28°C). Eucalyptus soil showed extreme SWR (WDPT > 3600 s) with soil-water contact angle above 100° on the top layer of soil (0–5 cm) (Fig. 1a). Pine soils showed a lower level of SWR on the topsoil compared with the eucalyptus soil (Fig. 1b). SWR decreased with increasing soil depth in both soils, showing a non-repellent condition (WDPT < 5 s) at the 10–15 cm depth.

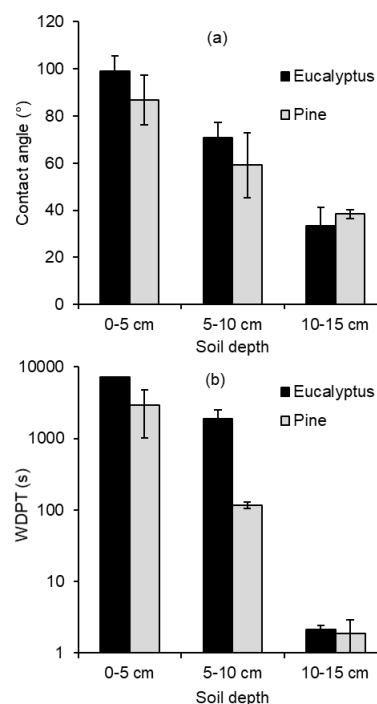


Fig. 1. Initial contact angle and water drop penetration time (WDPT) values for pine and eucalyptus soils. Error bars indicate ± standard deviations.

The laboratory heating experiments revealed specific changes in SWR as influenced by vegetation type, soil depth,

temperature, and duration of exposure to temperature levels. Figure 2 presents the change in WDPT upon exposure to temperature in a range of 28–250°C across exposure periods ranging from 20 to 120 min for the eucalyptus forest soil. In general, the soils reach completely wettable level (negligible WDPT) when exposed to 200–250°C. This is consistent for all three soil layers when exposed to heat for periods of more than 60 min (Fig. 2 c, d, e). With 90–120 min heating duration, complete elimination of SWR with instant wetting occurred at 250°C in the 0–5 and 5–10 cm layers, whereas that in the 10–15 cm layer occurred at 200°C. With shorter heating durations (20, 40 min), the extremely repellent top (0–5 cm) layer showed a distinct form of response to heat, indicating an increase in WDPT with exposure to 250°C. Such an increase was not visible for the less repellent lower layers. Soils showed a slight fluctuation in SWR with increasing temperature between 28 and 100–150°C at all durations of exposure.

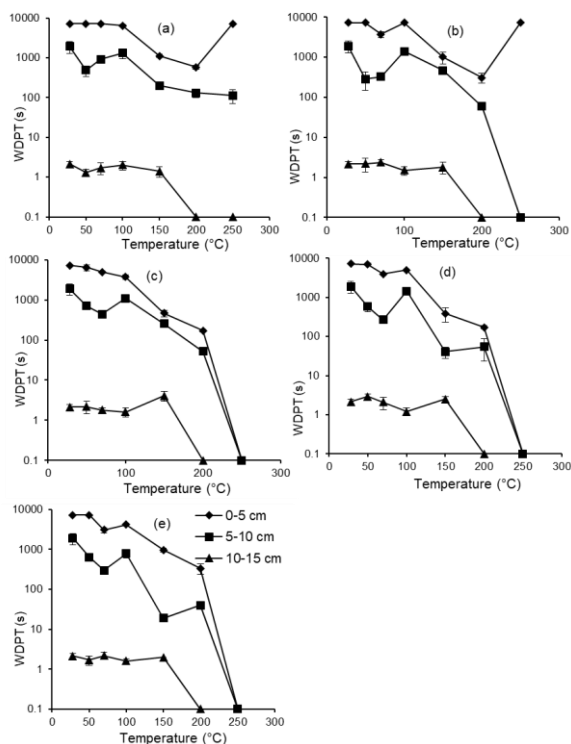


Fig. 2. Water repellency of eucalyptus soil as measured by water drop penetration time (WDPT) exposed to heat for duration of (a) 20 min, (b) 40 min, (c) 60 min, (d) 90 min, and (e) 120 min. Error bars indicate $\pm$ standard deviations.

Figure 3 shows the soil-water contact angle of the tested eucalyptus forest soil upon exposure to temperatures in a range of 28–250°C with heating durations ranging from 20 to 120 min. Contact angle also showed a similar pattern of alterations upon exposure to heat as with WDPT. However, contact angle measurements provided more thorough and refined information on the temperature impact, where the contact angle becomes very low or close to zero at $\sim$ 200–250°C. According to the data, only 5–10 and 10–15 cm soil layers reached zero contact angles with the used temperature treatments. With exposure to heat over 60 min duration, 5–10 and 10–15 cm soil layers showed zero contact angles at 250°C temperature, while the contact angle of the 0–5 cm layer did not decline below 40° with the same treatments (Fig. 3c, d, e). The 10–15 cm soil layer reached zero contact angle with exposure to 250°C for 40 min (Fig. 3b). The contact angle of the extremely-repellent top 0–5 cm layer showed the same pattern as WDPT with shorter heating durations (20, 40 min), indicating a

transient increase with the higher level of temperatures (Fig. 3a, b). Similar to the patterns indicated with WDPT measurements, soils showed a fluctuation in SWR with increasing temperature between 28 and 100–150°C at all durations of exposure.

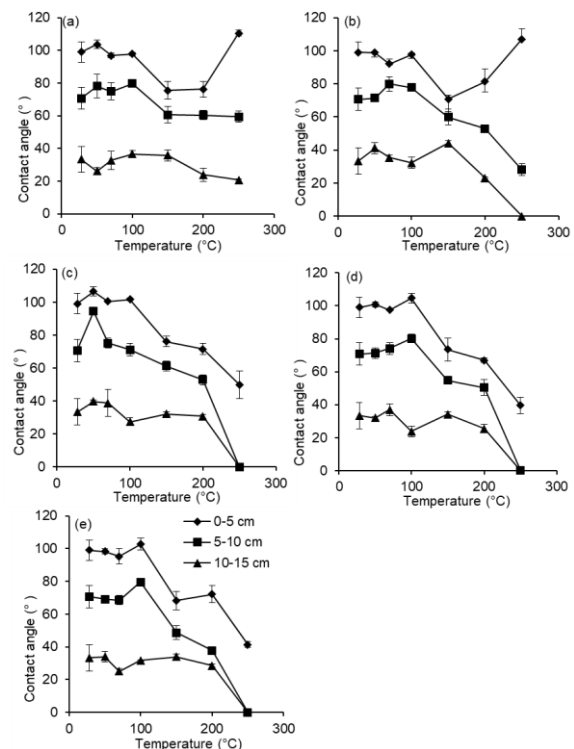


Fig. 3. Water repellency of eucalyptus soil as measured by soil water contact angle exposed to heat for duration of (a) 20 min, (b) 40 min, (c) 60 min, (d) 90 min, and (e) 120 min. Error bars indicate $\pm$ standard deviations.

Figure 4 presents the change in WDPT of the pine forest soil upon exposure to temperature in a range of 28–250°C for durations of exposure ranging from 20 to 120 min. SWR decreased with increasing temperature at all heating durations. Similar to the behavior of the eucalyptus soils, a slight fluctuation in SWR appeared at lower levels of temperatures (50–150°C). Throughout all the heating treatments, pine soils showed a lower level of SWR compared with that of eucalyptus soil. In contrast to the initially extremely repellent top layer of the eucalyptus soils, the top layer of the pine soil reached instant wetting conditions when exposed to 250°C, even with 20- and 40-min heating durations. The lowest tested soil layer (10–15 cm) showed wettable condition (WDPT < 5 s) at all the tested temperature levels and the durations of exposure.

Figure 5 explains the soil-water contact angle of the tested pine forest soil with the exposure to temperature in a range of 28–250°C for heating durations ranging from 20 to 120 min. Contact angle measurements provided more comprehensive and refined information on the temperature impact, especially with low levels of SWR in soils exposed to different heating treatments. The fluctuation in SWR observed with WDPT measurements at lower levels of temperatures (50–150°C) was clearly evident with contact angle measurements. Results showed that only 10–15 cm soil layers reached zero contact angles (250°C with 90- and 120-min heating durations) (Fig. 5d, e). The contact angle of the 0–5 and 5–10 cm layers remained at 75–30° and 57–24°, respectively, with the exposure to 250°C for heating durations ranging from 20–120 min (Fig. 5a–e).

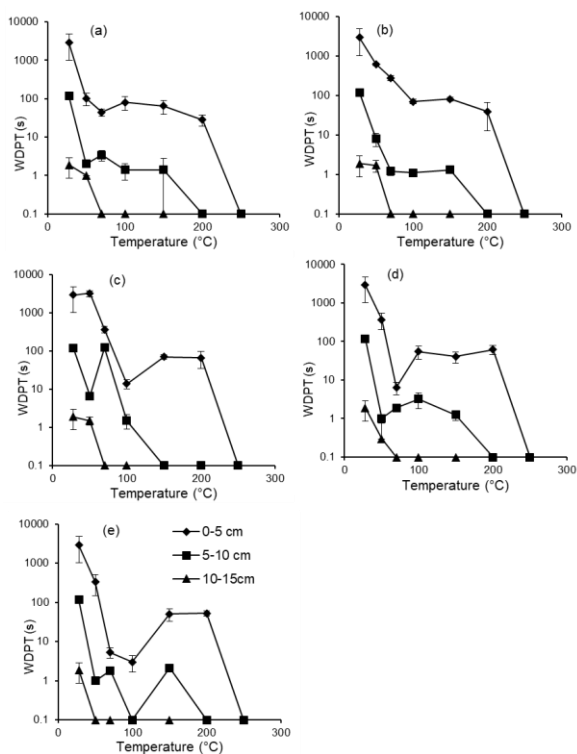


Fig. 4. Water repellency of pine soil as measured by water drop penetration time (WDPT) exposed to heat for duration of (a) 20 min, (b) 40 min, (c) 60 min, (d) 90 min, (e) and 120 min. Error bars indicate $\pm$ standard deviations.

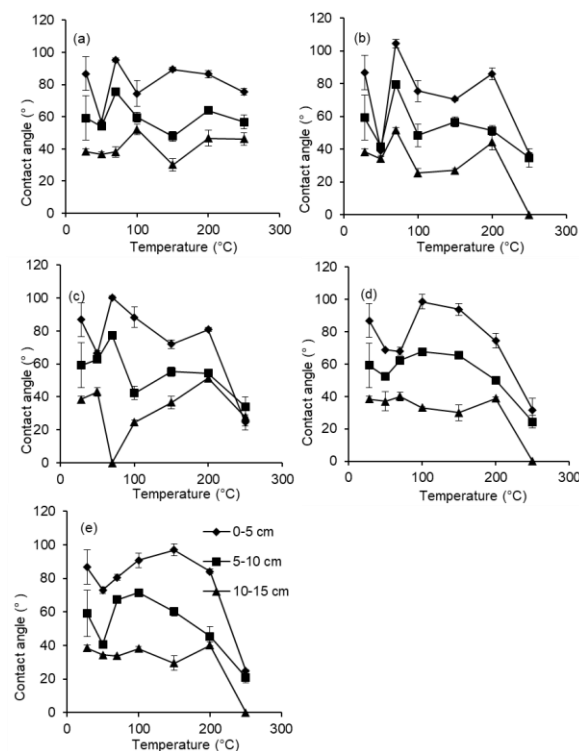


Fig. 5. Water repellency of pine soil as measured by soil water contact angle exposed to heat for duration of (a) 20 min, (b) 40 min, (c) 60 min, (d) 90 min, (e) and 120 min. Error bars indicate $\pm$ standard deviations.

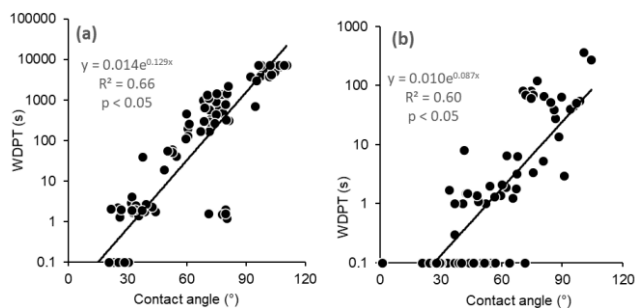


Fig. 6. The correlation between contact angle and water drop penetration time (WDPT) of (a) eucalyptus and (b) pine soils.

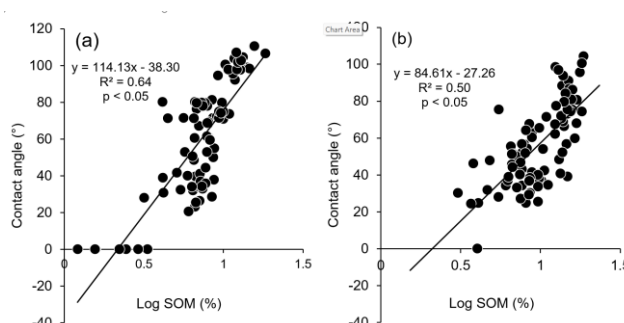


Fig. 7. Correlation between soil organic matter (SOM) content and the soil water repellency as measured by the soil-water contact angle in (a) eucalyptus and (b) pine forest soils.

In the present study, contact angle and WDPT measured for both eucalyptus and pine soils throughout the heating treatments showed similar behaviors. Figure 6 shows the correlation between contact angle and WDPT of eucalyptus and pine soils. In both soils, contact angle showed moderate (R^2 for eucalyptus and pine soils were 0.66 and 0.60, respectively) positive exponential correlation with WDPT. The correlations were statistically significant ($p < 0.05$) according to the regression analysis performed through linearization of the relation with log transformation of WDPT data. Figure 7 presents the correlation between SOM content and the SWR as measured by the soil-water contact angle in eucalyptus and pine forest soils ($n = 93$, each point represents the mean value of 3 replicates). In both soils, contact angle showed moderate positive linear correlation with organic matter content of the soil. The correlation for eucalyptus soil was stronger (the coefficient of determination, $R^2 = 0.64$) than that for the pine soil ($R^2 = 0.50$). Both correlations were statistically significant ($p < 0.05$). The regression equations for eucalyptus and pine soils

were $y = 114.13x - 38.30$ and $y = 84.61x - 27.26$, respectively. The standard errors of the slope and intercept for eucalyptus soil were 9.17 and 8.14, respectively, whereas those for the pine soil were 5.51 and 5.35, respectively. The slope of the regression line for the eucalyptus soil was steeper than that of the pine, indicating a higher sensitivity of SWR for the changes in organic matter content.

4 DISCUSSION

Decrease in SWR with increasing soil depth is a generally reported observation in both burnt and unburnt soils (Keizer et al., 2008; Piyaarwan et al., 2020; Tessler et al., 2008; Woods et al., 2007). The content of SOM is a basic factor that induces SWR under various soil, environmental, and climatic conditions. In general, SWR is acknowledged to be positively related to SOM, while both concentration and composition of SOM are primary components for soil to be water-repellent (Dao et al., 2022;

Leelamanie, 2016; Wu et al., 2020). The decrease in SOM content with increasing soil depth (Table 1) can be considered as the major factor that caused the decrease in SWR with increasing depth.

4.1 Heating impacts on water repellency

Heat generated by fire is one of the factors that induces changes in SWR (Dao et al., 2022; Jordán et al., 2010, 2011; Perera et al., 2023, 2024). The impacts of heat on SWR can be highly variable, as heat can enhance, diminish, or eliminate pre-existing water-repellent conditions in soils (Dao et al., 2022; Jordán et al., 2011; Perera et al., 2023, 2024). In the present study, the range of heating treatments used resulted in various changes in SWR. Still, it was clear that the SWR decreased with exposure to heat, depending on the intensity and duration of heating exposure, where higher intensity and duration resulted in the disappearance of SWR (Figs. 2–5).

Heat-induced changes in SWR are also known to be dependent on the alterations in SOM, either in content or composition (Doerr et al., 2004; Jordan et al., 2010; Perera et al., 2024). Results of the present study indicated a significant positive correlation between SWR, as measured by the soil-water contact angle, and SOM content (Fig. 7), elucidating the crucial role of SOM in the heat-induced changes in SWR. However, the strength of the correlation was moderate, indicating that the behavior of SWR upon exposure to heat treatments was not strongly dependent on the content of SOM. The SOM contents of both tested soils showed a continuous decrease with increasing heating intensity and exposure. Exposure to heat can increase the decomposition of SOM and induce the volatilization of organic substances, reducing the amount of water-repellent organic substances, leading to a decrease in SWR. An increase in heating results in reaching the boiling points of different organic materials gradually, and removes those substances (González-Pérez et al., 2004 and references therein; Jordan et al., 2010). However, there were fluctuations and unexpected increases in SWR at lower levels of temperatures (Fig. 2–5) and shorter (20, 40 min) heating durations (Fig. 2a, b) used in the experiment, which are the reasons that prevented the correlation between SWR and SOM content from being strong.

4.2 Impacts of heating temperature

As explained above, SWR showed fluctuations and unexpected increases at lower temperatures (28–150°C). Since the SOM content decreases with increasing temperature due to increased decomposition rates, volatilization, or reaching the boiling points of organic substances (González-Pérez et al., 2004 and references therein; Jordan et al., 2010), any increase in SWR cannot be considered as caused by an increase in SOM content. The most probable explanation can be the changes in the composition of organic substances when soil is exposed to heat.

Numerous alterations can take place in the structures of organic substances due to the impacts of heat. Reaching melting points allows materials to freely change and then be condensed into different forms once cooled. Jain et al. (2004) explained that C-2 to C-100 carbon chain organic substances, including alkanes, alkanols, alkanic acids, and many other compounds, reach their melting points between the tested temperature ranges in this study. Organic materials are known to transform at temperatures close to their melting points (Koch and Ensikat, 2008) and can then be reorganized into more hydrophobic substances (Dao et al., 2022). Removal of organic substances with increas-

ing temperature due to various reasons such as oxidation and volatilization might cause soil to lower the SWR slightly, while structural and molecular rearrangements of organic substances into more hydrophobic forms can lead soil to increase the SWR. These simultaneous contrasting transitions in soil might be the reason soils show fluctuations in SWR at temperatures ranging from 50 to 150°C.

The present study revealed that elimination of SWR occurred in most of the tested soils at 250°C. These findings are comparable with the similar kinds of studies reported in the literature (Doerr et al., 2005; Negri et al., 2021; Perera et al., 2024). Elimination of SWR at 250°C temperature levels can be a consequence of the combustion of organic substances due to charring of organic matter that initiates at a temperature of about 200°C (González-Pérez et al., 2004). At 250°C, most of the organic substances have exceeded their melting points (Jain et al., 2004), while most of the volatile organic substances have already been removed through volatilization. These removals and changes might cause an increase in the fractions of soil mineral surfaces that are free from organic coatings, enabling the water molecules to freely attach onto those surfaces, leading to lowered WDPT and contact angles (Mayer and Xing, 2001; Negri et al., 2021).

4.3 Impacts of duration of exposure to heat

Results of the present study revealed a clear impact of heat exposure duration on SWR of eucalyptus and pine soils. At lower temperatures, shorter heating durations revealed more fluctuations of SWR. These fluctuations slightly receded at higher temperature levels, indicating a more prominent impact of heating temperature than the duration of exposure. Still, at higher temperatures, the elimination of SWR appeared with longer heating durations. This effect was clearer with contact angle results (Figs. 3, 5). Both soils reached lower contact angles with the increase in duration that the soil is exposed to heat (Ex, 250°C).

According to Marcos et al. (2007), heating of soil for shorter periods of 5 – 15 min would not cause any significant modifications in the SOM content at temperatures below 400°C. This suggests that fluctuations in SWR observed over shorter heating durations at lower temperatures might have resulted from changes in the structure of SOM, rather than its content. The slight changes and fluctuations in contact angle observed in the present study at lower levels of temperature were not observed or reported in a similar experiment with 1 and 2 h heating durations in Perera et al. (2024). This might be due to the use of MED for SWR characterization, which prevents taking measurements of contact angles below 90°. Furthermore, the difference in climatic region pine forest soil (Af, Equatorial rainforest, fully humid Köppen-Geiger climate classification) used in Perera et al. (2024) might also have an impact on the SOM compositional changes.

4.3 Possible impacts on soil organic matter

Heating alters carbohydrates, lipids, and peptides, which contain oxygen functional groups, forming new aromatic structures (Almendros et al., 1997, 2003; Baldock and Smernik, 2002; González-Vila et al., 2001). Furthermore, thermal treatment produces materials with reduced solubility and colloidal properties through removing external oxygen groups (Almendros et al., 1992). Decline in these functional groups changes the soil physicochemical characteristics. A study in Spain showed that the relative abundance of the alkanes (< C₂₅) and fatty acids (< C₂₀) is high in fire-affected pine forest soils, indicating a possible fragmentation of long-chain molecules due to thermal impacts (Dett-

weiler et al., 2003). Fire-mediated transformation of water-soluble SOM fractions into the humic soil fraction is possible through Maillard's reactions as well (Maillard, 1916; González-Pérez et al., 2004), where Maillard's products can be formed through successive reactions occurring at temperatures above 100°C.

Oxygen-bearing functional groups attached to humic macromolecules are susceptible to heat-induced alterations, where part of the humic acid fraction is transformed into more hydrophobic humin with fewer oxygen functionalities (González-Vila and Almendros, 2003). Concurrently, the selective destruction of the less condensed structural substances in soils and related transformations of these forms into those with predominant aliphatic nature can be responsible for the alterations in SWR in burned soils. Accordingly, comparatively hydrophobic surfaces in the humic acid fractions can be formed through dehydration associated with the elimination of oxygen containing functionalities (González-Pérez et al., 2004).

5 CONCLUSIONS

Using laboratory measurements, the present study explored the effect of intensity and duration of exposure to heat on both severity and persistence of SWR in eucalyptus and pine forest soils in the highlands of Sri Lanka. Both the intensity of heating, represented by the heating temperature, and the duration of exposure to heat caused alterations in the severity and persistence of SWR. Low heating temperatures and shorter heating durations caused instabilities in the pattern of SWR in response to heat, which resulted in fluctuations of SWR, showing that mild heating that can be caused by very short-duration flash fire might also make significant changes in SWR. Severity of SWR, as measured by the soil-water contact angle, provided more comprehensive information on these impacts.

Since the present study is a complete laboratory experiment and did not use field soils burned by forest fires, the experimental heating conditions would not precisely represent the impacts of a natural forest fire event. However, the findings would be useful for understanding the impacts of various heating dynamics that can take place in natural fire events. The findings would provide evidence for better estimation and prediction of the transformations in water-repellent conditions of forest soils, which would consequently support the development of appropriate forest floor management strategies. Further research considering the other important factors, such as molecular-level variations in organic substances as well as mineralogical and climatic aspects, would be important for a better understanding of hydrological responses in burnt forest floors.

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