

# Heat-induced alterations in moisture-dependent repellency of water-repellent forest soils: A laboratory approach with Japanese Andosols

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**Abstract:** Soil water repellency (SWR) is a phenomenon that prevents the spontaneous wetting of numerous forest soils. It is a moisture-dependent characteristic, which disappears when soil moisture reaches near saturation. The heat generated during forest fires affects soil characteristics including SWR. The possibility of heat influencing moisture-dependent repellency (MDR) is not well understood. The present study aimed to investigate the effects of different heating temperatures ( $H_T$ ) and exposure durations ( $E_D$ ) on MDR using water-repellent Japanese Cedar (CED) and Japanese Cypress (CYP) forest soils. Soil samples collected from 0–5 cm depth were exposed to heat separately at 50, 100, and 150 °C ( $H_T$ ) for 1 h and 2 h durations ( $E_D$ ). The MDR of heated and non-heated soils was determined using the water drop penetration time (WDPT) test in a drying process. During the drying process of the tested soils, SWR appeared and then increased with drying to reach an extreme level (WDPT  $\geq 3600$  s) that persisted for a range of decreasing moisture contents, and declined to be non-repellent again (WDPT = 0 s). The critical moisture content at which soils become water-repellent with drying (CMC), the highest and the lowest moisture contents when soils showed maximum SWR ( $HMC_{max}$  and  $LMC_{max}$ , respectively), and the integrated area below the MDR curve ( $S_{WR}$ ) decreased with increasing  $H_T$  in both CED and CYP soils. The moisture content at which soils become non-repellent again during drying,  $MC_{NR}$ , was independent of the type of soil and heat treatment. The range of moisture contents between  $HMC_{max}$  and  $LMC_{max}$ , where soils show maximum SWR during drying, decreased with increasing  $H_T$ , from 50 to 150 °C in CED and from 100–150 °C in CYP. The  $S_{WR}$  showed strong positive linear correlations with CMC and  $HMC_{max}$ . The heat generated during wildfires can alter the MDR and all the related repellency parameters of water-repellent forest soils. SWR prevails over a narrower range of moisture contents in heated soil compared with non-heated soils. Further investigations with higher temperature levels using different soil types would be important for a comprehensive understanding of the heat impacts on MDR.

**Keywords:** Forest soils; Japanese Andosols; Laboratory heating; Moisture-dependent repellency; Soil water repellency.

## INTRODUCTION

Soil water repellency (SWR) refers to the resistance of soil to spontaneous wetting, which hinders water infiltration into the soil. Severe topsoil erosion is reported as a common characteristic in water-repellent soils, as the hindered infiltration enhances the overland flow inducing topsoil erosion (Jordán et al., 2013; Wallis and Horne, 1992). SWR is a global phenomenon reported under different land use types in various countries belong to almost all continents on the Earth (Doerr et al., 2006; García-Corona et al., 2004; Iovino et al., 2018; Kobayashi and Shimizu, 2007; Kajiura et al., 2011; Leelamanie et al., 2021; Lichner et al., 2013; Lin et al., 2006).

Organic coatings on mineral particles or intermixed organic materials cause SWR, where both the content and the composition of soil organic matter are vital for the occurrence and the magnitude of SWR (Doerr et al., 2000). SWR is frequently reported in forest soils beneath plant species that are rich in resins and polar waxes such as Japanese cedar (*Cryptomeria japonica*) (Leelamanie and Nishiwaki, 2019), Japanese cypress (*Chamaecyparis obtusa*) (Kobayashi and Shimizu, 2007; Leelamanie and Nishiwaki, 2019; Miyata et al., 2007), Pine (*Pinus densiflora*, *Pinus sylvestris*) (Kawamoto et al., 2007; Lichner et al., 2013), Casuarina (*Casuarina equisetifolia*) (Leelamanie, 2016; Lin et al., 2006), and Eucalyptus (*Eucalyptus sieberi*, *Eucalyptus globulus*, *Eucalyptus globulus*) (Doerr et al., 2006; Walden et al., 2015; Piyaarawan and Leelamanie, 2020).

Among various other factors that influence SWR, soil moisture (Kajiura et al., 2011; Leelamanie and Karube, 2007) and wildfires (DeBano, 2000; Negri et al., 2021) have attracted extensive attention.

As a consequence of climatic changes and anthropogenic activities, wildfires appear with increased frequency in recently past. Frequent wildfires are common in forestlands dominated by the tree species that induce SWR because they produce highly inflammable plant debris (Bernier et al., 2016). During a wildfire, soil temperature increases, influencing various soil characteristics including SWR (Arcenegui et al., 2007; Doerr et al., 2004, 2006; MacDonald and Huffman, 2004; Zavala et al., 2010). Depending on numerous factors, such as the peak soil temperature (Arcenegui et al., 2007; Zavala et al., 2010) and exposure duration of soil heat under specific temperature levels (Doerr et al., 2004), heat can either intensify, subside, or eliminate SWR (Arcenegui et al., 2007; Doerr et al., 2004, 2006; Hubbert et al., 2012; Zavala et al., 2010). Reports indicate that SWR can enhance the runoff causing substantial erosion in forestlands following wildfires leading to severe onsite and off-site impacts (Doerr et al., 2006; Martins et al., 2013).

Soil moisture has a strong influence on the SWR, where the relationship is non-linear. In general, soils are wettable at higher moisture contents near saturation and start to show SWR with drying at a specific marginal moisture content, which is noted as the critical water content (Dekker and Ritsema, 1994). SWR increases with further drying of soil below the critical water

content, to reach a maximum level, and can decline with further drying to an inferior level or to be wettable (Kawamoto et al., 2007; Leelamanie and Karube, 2007, 2011; Regalado and Ritter, 2005), and might increase again showing a second peak (De Jonge et al., 1999). Moisture-dependent repellency (MDR) curves indicate this non-linear behavior of SWR with changing soil moisture content. It shows the range of water content where soils would show water-repellent conditions and related impacts on the land.

Since the heat generated during wildfires alters the SWR, it may also influence the moisture-dependent behavior of SWR, together with various SWR parameters related to the MDR curves. Many laboratory and field studies on the SWR in burned forestlands have focused the attention on actual onsite SWR or the potential air-dried SWR (Doerr et al., 2006; Kajiura et al., 2011, 2012; Negri et al., 2021; Zavala et al., 2010). Some studies report changes in moisture-dependency of SWR after burned conditions, which alters the moisture-range that the forest floor would show SWR (Ex: Caltabellotta et al., 2022). However, the impacts of heat on the MDR behavior are yet to be investigated in detail. The knowledge on heat-induced alterations in MDR and related parameters would be vitally important for erosion estimations and development of overland flow and erosion simulation models in fire-affected forestlands. The main objective of this study is to examine the impact of different heating dynamics (heating temperature and duration of exposure) on MDR behavior using water-repellent Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*) forest soils under laboratory conditions.

## MATERIALS AND METHODS

### Sample collection and preparation

Soil samples (Andosols) were collected from the surface (0–5 cm depth) of Japanese cedar (CED) (35°14'19.34"N 134°2'59.53"E) and Japanese cypress (CYP) (35°14'20.32"N 134°3'2.22"E) forests located in Tsuyama, Okayama, Japan (Figure 1). The climate of the CED and CYP forests belongs to

the warm temperate fully humid category according to the Köppen-Geiger climate classification (Kottek et al., 2006). The soil surfaces of both forests were covered with a thick litter layer (2–5 cm) composed of dry leaves and twigs, which were removed carefully by brushing before collecting the soil samples. Collected samples were air-dried for 48 h under laboratory conditions ( $T = 25 \pm 1$  °C,  $RH = 65 \pm 5\%$ ) and passed through 2 mm sieves. The basic properties of the collected soil samples are presented in Table 1.

### Heat treatments

Combustion of above-ground litter materials and transmission of heat increases the temperature of mineral soils. In the present study, heating temperature ( $H_T$ ) and the duration of exposure of soil samples to heat ( $E_D$ ) were used as the selected heating parameters. During a wildfire, the  $H_T$  represents the strength of the fire, while the  $E_D$  represents the persistence of the particular wildfire. A dry mineral soil behaves as a good insulator, and therefore, the soil temperature around 5 cm depth generally does not exceed  $\sim 150$  °C (DeBano, 2000 and references therein). This study compared  $H_T$  levels ranging from 50 °C to 150 °C with increments of 50 °C. Air-dried soil samples ( $\sim 150$  g) were separately placed on large porcelain containers in triplicates. Samples were exposed separately to six heat treatments consisting of three levels of  $H_T$  (50, 100, 150 °C) and two levels of  $E_D$  (1, 2 h) (Dlapa et al., 2008; Simkovic et al., 2008) using a drying oven (WFO-520, Tokyo Rikakikai Co., Japan). Care was taken to use similar porcelain containers of the same type, to ensure a comparable heat-transferring process in all samples. After exposure to heat, the samples were kept in a desiccator overnight for cooling.

### Moisture-dependent repellency measurement

In general, the MDR behavior, or the change in SWR with soil moisture, is determined through a drying process of pre-wetted soil samples (De Jonge et al., 1999; Leelamanie and Karube, 2011). MDR curves introduce important SWR parameters

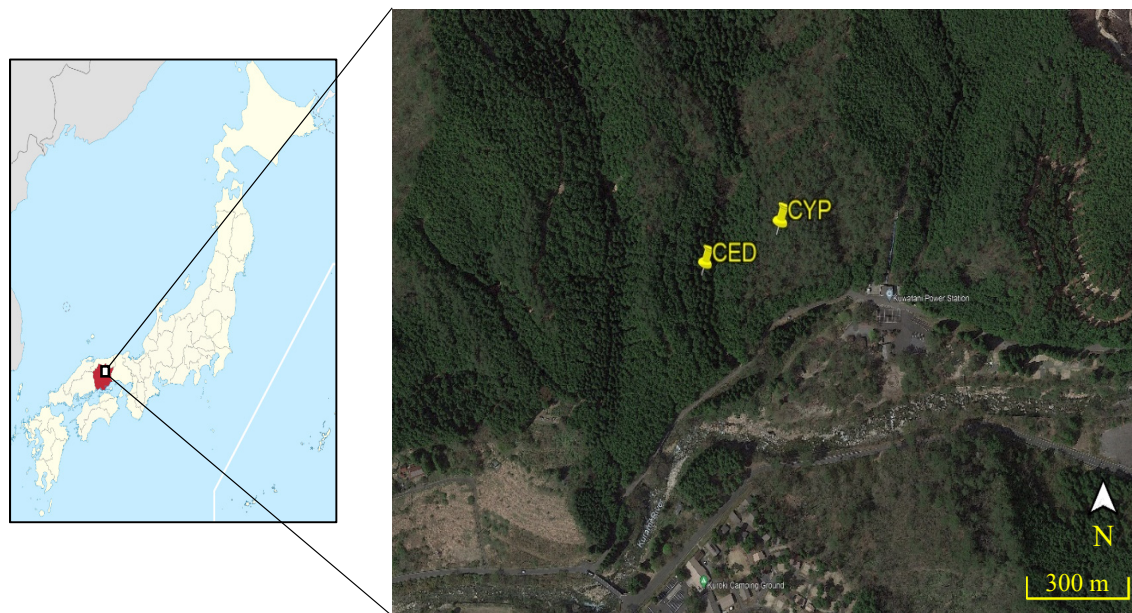


**Fig. 1.** Sampling locations of Japanese cedar (CED) forest (35°14'19.34"N 134°2'59.53"E) and Japanese cypress (CYP) forest (35°14'20.32"N 134°3'2.22"E) located in Tsuyama, Okayama, Japan.

**Table 1.** Basic properties of tested soil.

| Property                               | CED       | CYP       | Method                                              | Reference                      |
|----------------------------------------|-----------|-----------|-----------------------------------------------------|--------------------------------|
| Soil water repellency                  | 3600±0    | 1786±79   | Water drop penetration time (WDPT) test             | Leelamanie et al., 2008        |
| Air-dried moisture (%)                 | 5.7±0.8   | 3.6±0.2   | Gravimetric method                                  | Reynolds, 1970                 |
| Organic matter (%)                     | 20±1      | 17.1±0.9  | Loss on ignition method                             | Schulte and Hopkins, 1996      |
| Sand (%)                               | 36.9±4.3  | 36.2±5.5  | Particle Size Analyzer (SALD-3100, SHIMADZU, Japan) | Faé et al., 2019               |
| Silt (%)                               | 47.3±0.2  | 47.0±1.1  |                                                     |                                |
| Clay (%)                               | 15.7±4.5  | 16.5±4.8  |                                                     |                                |
| Texture                                | Loam      | Loam      |                                                     |                                |
| Bulk density (g cm <sup>-3</sup> )     | 0.78±0.07 | 0.50±0.02 | Undisturbed core method                             | Blake and Hartge, 1986a        |
| Particle density (g cm <sup>-3</sup> ) | 2.5±0.03  | 2.2±0.09  | Pycnometer method                                   | Blake and Hartge, 1986b        |
| Porosity (%)                           | 66±4      | 76±1      | Numerical method                                    | Danielson and Sutherland, 1986 |
| pH                                     | 4.17±0.1  | 4.96±0.3  | pH meter (LAQUAtwin-pH-11, HORIBA, Japan)           | Smith and Doran, 1997          |
| EC (μS cm <sup>-1</sup> )              | 85.7±0.5  | 75.3±0.1  | Conductivity meter (LAQUAtwin-EC-33, HORIBA, Japan) |                                |

such as the critical moisture content at which SWR appears in a particular soil with drying, the highest and the lowest moisture contents at maximum SWR, and the integrated area below the MDR (Regalado and Ritter, 2005).

To determine the MDR curves, the soil samples were pre-wetted using deionized water by sprinkling on the surface of the soil samples subjected to heat and mixed with a spatula until the SWR ceased to exist (WDPT = 0 s). Wet soil samples (Moisture content: ~210 g kg<sup>-1</sup>) were kept sealed overnight to facilitate homogeneous distribution of moisture in the sample before starting the drying process. Non-heated soil samples from CED and CYP forests were used as the control treatments following the same experimental procedure.

Thereafter, the soil samples were air-dried gradually under laboratory conditions ( $T = 28 \pm 2$  °C,  $RH = 65 \pm 5\%$ ). Initial moisture content for each MDR curve is indicated in Table 2. At the final stage of the drying process, where the samples reached a fairly dry level (15–20 g kg<sup>-1</sup>), soil samples were kept in a desiccator to facilitate continuous drying. During the drying process water content was measured gravimetrically (Reynolds, 1970), in triplicates, using subsamples of about 3 g (soil height: 8–10 mm). Samples were thoroughly and carefully mixed during the drying process to maintain a homogenous condition within the samples.

**Table 2.** Initial moisture contents of soils used for each moisture-dependent repellency (MDR) curve.  $H_T$ : heating temperature;  $E_D$ : duration of exposure of soil samples to heat.

| Heat treatment |           | Moisture contents (kg kg <sup>-1</sup> ) |           |
|----------------|-----------|------------------------------------------|-----------|
| $H_T$ (°C)     | $E_D$ (h) | CED                                      | CYP       |
| Control        |           | 0.73±0.01                                | 0.68±0.01 |
|                |           |                                          |           |
| 50             | 1         | 0.62±0.01                                | 0.72±0.01 |
|                | 2         | 0.57±0.01                                | 0.70±0.01 |
| 100            | 1         | 0.53±0.01                                | 0.66±0.01 |
|                | 2         | 0.51±0.01                                | 0.55±0.01 |
| 150            | 1         | 0.46±0.01                                | 0.37±0.01 |
|                | 2         | 0.49±0.01                                | 0.43±0.02 |

Once the moist weights of the subsamples were recorded, the persistency of SWR was measured using the water drop penetration time (WDPT) test (3 replicates). A drop of deionized water (40±1 μL) was placed on the soil surface in containers using a

micropipette (Nichipet EX, K08X08631, Japan) at about 1 cm height to minimize the striking effect of the falling water drop. After placing the water drops on soil surfaces, the containers were covered using glass lids to limit evaporation during the measurement. The time required for the complete penetration of the water drop into the soil was recorded. The average value of three replicates was considered as the WDPT value of a particular sample. The measurement was terminated after 3600 s, and the penetration times exceeding 3600 s were considered as 3600 s. The SWR of samples can be categorized based on the WDPT values, as wettable (WDPT ≤ 1 s), non-repellent (WDPT = 1–5 s), slightly (WDPT = 5–60 s), strongly (WDPT = 60–600 s), severely (WDPT = 600–3600 s), and extremely water-repellent (WDPT = ≥3600 s) (Bisdorn et al., 1993; Perera et al., 2023).

### Data analysis

Linear regression and ANOVA were used to analyze the data statistically at 5% significance level ( $p < 0.05$ ). A Post-hoc test (Tukey's test) was conducted to evaluate the differences between means (Table 3). All the statistical tests were conducted using OriginPro, Version 2023 and Microsoft Excel 2019. Graphs indicate the mean values of three replicates. The error bars in the figures indicate ± standard deviation.

### RESULTS

Figure 2 presents the MDR curves of CYP soil exposed to different  $H_T$  levels separately for 1 h and 2 h  $E_D$ . The curve at 28 °C represents the MDR of the unheated soil. CYP soil exposed to all heat treatments showed single-peak MDR curves, where SWR started to appear, increased to exceed extreme repellency level (WDPT > 3600 s), and decreased to a minimum level to be completely wettable with continuous drying. With both 1 and 2 h  $E_D$  (Figure 2 a, b), CMC and  $HMC_{max}$  of CYP soils heated at 50 °C were higher compared with those of non-heated soil. With the increasing  $H_T$  to 100 and 150 °C, CMC and  $HMC_{max}$  shifted significantly toward lower moisture contents indicating a shrinking of MDR curves. With heating,  $LMC_{max}$  also shifted slightly towards the lower moisture contents. However, since the shift of  $LMC_{max}$  was slight, the range of moisture contents between  $HMC_{max}$  and  $LMC_{max}$  showed a significant decrease with increasing  $H_T$  from 50 and 150 °C. This moisture range did not

**Table 3.** The significant differences in CMC,  $HMC_{max}$ ,  $LMC_{max}$ ,  $MC_{NR}$ , and  $S_{WR}$  values of CYP and CED soils subjected to different heating temperatures ( $H_T$ ) and durations of exposure to heat ( $E_D$ ). Values presented are means  $\pm$  standard deviations. Different Upper case and lower case letters indicate significant differences between different heat treatments in CYP and CED soils, respectively; “\*” indicates the significant differences between CED and CYP soils under each heat treatment, at 95% significance level.

CMC: the critical moisture content at which soils start to show water repellency with drying;  $HMC_{max}$ ,  $LMC_{max}$ : the highest the and the lowest moisture contents, respectively, that soils show maximum water repellency;  $MC_{NR}$ : the driest moisture content at which soils become non-repellent during drying;  $S_{WR}$ : integrated area below the MDR curves.

|     | $H_T$ (°C) | $E_D$ (h) | CMC<br>(kg kg <sup>-1</sup> ) | $HMC_{max}$<br>(kg kg <sup>-1</sup> ) | $LMC_{max}$<br>(kg kg <sup>-1</sup> ) | $MC_{NR}$<br>(kg kg <sup>-1</sup> ) | $S_{WR}$<br>(kg kg <sup>-1</sup> s) |
|-----|------------|-----------|-------------------------------|---------------------------------------|---------------------------------------|-------------------------------------|-------------------------------------|
| CYP | Control    |           | 0.53 $\pm$ 0.01A              | 0.41 $\pm$ 0.00A*                     | 0.14 $\pm$ 0.01A*                     | 0.01 $\pm$ 0.01A*                   | 1417.80 $\pm$ 12.61A*               |
|     | 50         | 1         | 0.58 $\pm$ 0.01B*             | 0.45 $\pm$ 0.01B*                     | 0.19 $\pm$ 0.01B*                     | 0.01 $\pm$ 0.00A                    | 1416.99 $\pm$ 09.89A*               |
|     |            | 2         | 0.63 $\pm$ 0.01C*             | 0.46 $\pm$ 0.01B*                     | 0.12 $\pm$ 0.01C*                     | 0.02 $\pm$ 0.01A*                   | 1652.64 $\pm$ 27.97B*               |
|     | 100        | 1         | 0.44 $\pm$ 0.02D*             | 0.31 $\pm$ 0.00C*                     | 0.11 $\pm$ 0.01C*                     | 0.01 $\pm$ 0.00A                    | 1053.79 $\pm$ 11.08C*               |
|     |            | 2         | 0.42 $\pm$ 0.02D*             | 0.31 $\pm$ 0.00C*                     | 0.05 $\pm$ 0.00D*                     | 0.01 $\pm$ 0.00A                    | 1111.76 $\pm$ 12.75C*               |
|     | 150        | 1         | 0.18 $\pm$ 0.01E              | 0.07 $\pm$ 0.00D                      | 0.05 $\pm$ 0.00D*                     | 0.02 $\pm$ 0.00A*                   | 226.62 $\pm$ 12.83D*                |
|     |            | 2         | 0.17 $\pm$ 0.00E*             | 0.06 $\pm$ 0.00D*                     | 0.04 $\pm$ 0.01D*                     | 0.02 $\pm$ 0.00A*                   | 196.17 $\pm$ 18.08D*                |
|     | Control    |           | 0.53 $\pm$ 0.03a              | 0.39 $\pm$ 0.00a                      | 0.08 $\pm$ 0.01a                      | 0.02 $\pm$ 0.00a                    | 1470.27 $\pm$ 18.21a                |
| CED | 50         | 1         | 0.47 $\pm$ 0.02b              | 0.34 $\pm$ 0.02b                      | 0.05 $\pm$ 0.01b                      | 0.01 $\pm$ 0.00a                    | 1218.87 $\pm$ 20.52b                |
|     |            | 2         | 0.47 $\pm$ 0.00b              | 0.34 $\pm$ 0.01b                      | 0.04 $\pm$ 0.00b                      | 0.01 $\pm$ 0.00a                    | 1319.57 $\pm$ 17.44b                |
|     | 100        | 1         | 0.36 $\pm$ 0.02c              | 0.18 $\pm$ 0.00c                      | 0.03 $\pm$ 0.00b                      | 0.01 $\pm$ 0.00a                    | 729.67 $\pm$ 09.77c                 |
|     |            | 2         | 0.26 $\pm$ 0.02d              | 0.13 $\pm$ 0.01d                      | 0.03 $\pm$ 0.00b                      | 0.01 $\pm$ 0.00a                    | 499.19 $\pm$ 22.32d                 |
|     | 150        | 1         | 0.29 $\pm$ 0.00e              | 0.05 $\pm$ 0.01e                      | 0.03 $\pm$ 0.00b                      | 0.01 $\pm$ 0.00a                    | 266.48 $\pm$ 05.91e                 |
|     |            | 2         | 0.22 $\pm$ 0.03df             | 0.04 $\pm$ 0.00e                      | 0.02 $\pm$ 0.00b                      | 0.01 $\pm$ 0.00a                    | 243.80 $\pm$ 10.01e                 |

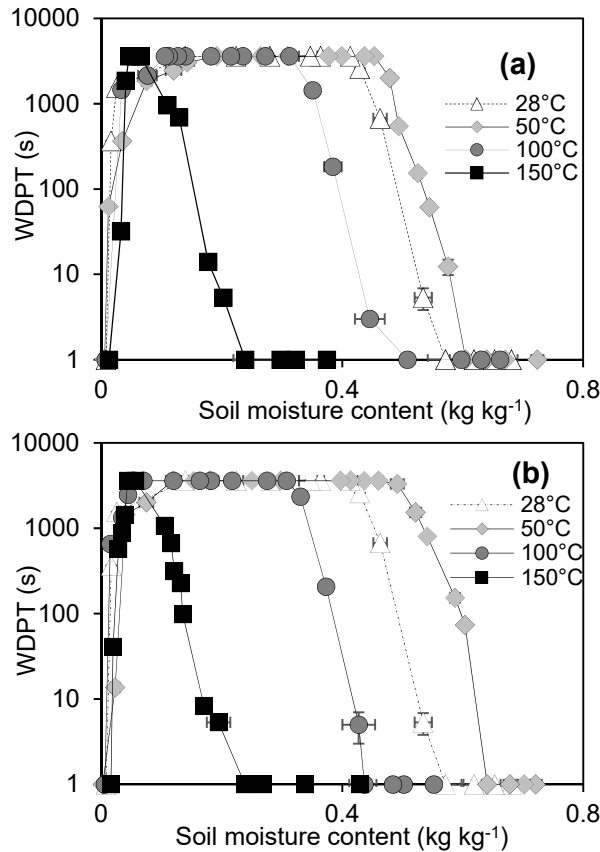


**Fig. 2.** Moisture dependent repellency (MDR) for CYP soil with (a) 1 h and (b) 2 h durations of exposure to 50, 100, and 150 °C temperatures. The curve at 28 °C represents the MDR of the non-heated soil. Error bars indicate  $\pm$  standard deviation.

show a significant difference between unheated samples and samples heated at 50 °C for 1 h of  $E_D$  (Figure 2a). However, this difference was significant under 2 h of  $E_D$  (Figure 2b). The moisture content at which soils show non-repellent conditions with continuous drying ( $MC_{NR}$ ) did not show a significant difference between all samples (Table 3).

Figure 3 presents the MDR curves of CED soils exposed to different  $H_T$  with 1 and 2 h  $E_D$ . Same as in CYP soils, CED soil exposed to all heat treatments showed single-peak MDR curves of the same shape with the drying of pre-wetted soils. All CED soils showed extreme water repellency at the maximum repellent level and continuous drying resulted in showing wettable conditions again. CED soils subjected to all heat treatments, including those heated at 50 °C, CMC, and  $HMC_{max}$  shifted significantly towards lower moisture contents indicating a significant shrinking of MDR curves with increasing temperature with both 1 and 2 h  $E_D$  (Figure 3 a, b). However,  $LMC_{max}$  did not show a shift with a noticeable trend in relation to the  $H_T$ . The range of moisture contents between  $HMC_{max}$  and  $LMC_{max}$ , where the soils remained extremely water-repellent, showed a significant decrease with increasing  $H_T$  from 28 and 150 °C under both 1 and 2 h of  $E_D$  (Figure 3 a, b). The moisture content at which soils show non-repellent conditions with continuous drying ( $MC_{NR}$ ) did not show a significant difference between all CED soils as well (Table 3).

Figure 4 presents the CMC,  $HMC_{max}$ ,  $LMC_{max}$ , and  $MC_{NR}$  of CYP (Figure 4a) and CED (Figure 4b) soils under different  $H_T$  and  $E_D$  levels. The CMC and the  $HMC_{max}$  in both CYP and CED soils dropped sharply with increasing  $H_T$  from 50 to 150 °C. The  $LMC_{max}$  of CYP soil showed a decline with increasing  $H_T$ , whereas that of CED soil did not show significant change (Table 3). The CMC,  $HMC_{max}$ , and  $LMC_{max}$  values between the CYP and CED soils were significantly different, while  $MC_{NR}$  was not under the heat treatments used in the present study (Table 3). The  $MC_{NR}$  showed only a negligible change with increasing  $H_T$  in both CYP and CED soils. Figure 4 reveals that all

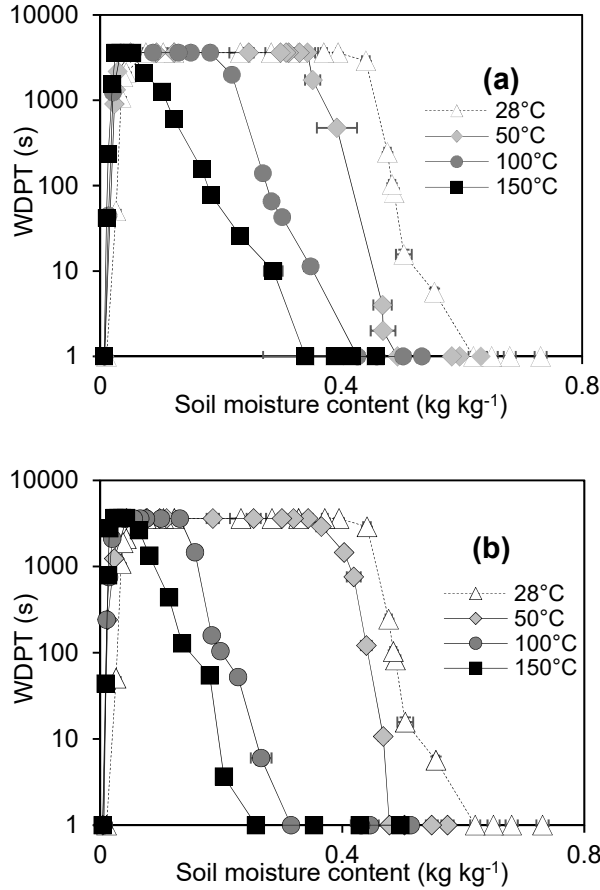


**Fig. 3.** Moisture dependent repellency (MDR) for CED soil with (a) 1 h and (b) 2 h durations of exposure to 50, 100, and 150 °C temperatures. The curve at 28 °C represents the MDR of the non-heated soil. Error bars indicate  $\pm$  standard deviation.

MDR parameters (CMC,  $H_{MC_{max}}$ ,  $LMC_{max}$ , and  $MC_{NR}$ ) did not vary considerably with the change of  $E_D$  (1 h and 2 h) at all temperatures except for CMC at 100 and 150 °C in CED soils, and  $LMC_{max}$  at 50 and 100 °C in CYP soils. The range of moisture contents between the CMC and  $MC_{NR}$  indicates the moisture range at which the soils show water-repellent conditions. Figure 4 further shows that the moisture content range between the CMC and  $MC_{NR}$  decreases with the increasing  $H_T$  in both CYP and CED soils revealing that the moisture range that the soils show water-repellent condition narrows down with increasing  $H_T$ .

Figure 5 presents the heat-induced alterations in the integrated area below the MDR curve ( $S_{WR}$ ) in CYP and CED soils. The  $S_{WR}$  for both CYP (Figure 5a) and CED soils (Figure 5b) showed a progressive decrease with increasing  $H_T$ , except for the slight deviation for CYP at 50 °C  $H_T$  with 2 h  $E_D$ . The  $S_{WR}$  showed a significant difference between CYP and CED soils under both non-heated and heated conditions. In general, the  $E_D$  (1 and 2 h) did not show a significant influence on the  $S_{WR}$  of both CYP and CED soils (Table 3).

Figure 6 indicates the correlation of the  $S_{WR}$  to CMC and  $H_{MC_{max}}$  in CYP and CED soils exposed to heat treatments. The  $S_{WR}$  showed strong positive linear correlations with CMC (Figure 6a;  $R^2 = 0.91$ ) and  $H_{MC_{max}}$  (Figure 6b;  $R^2 = 0.98$ ), where the regression correlations were statistically significant at a 99% confidence interval ( $p < 0.01$ ).

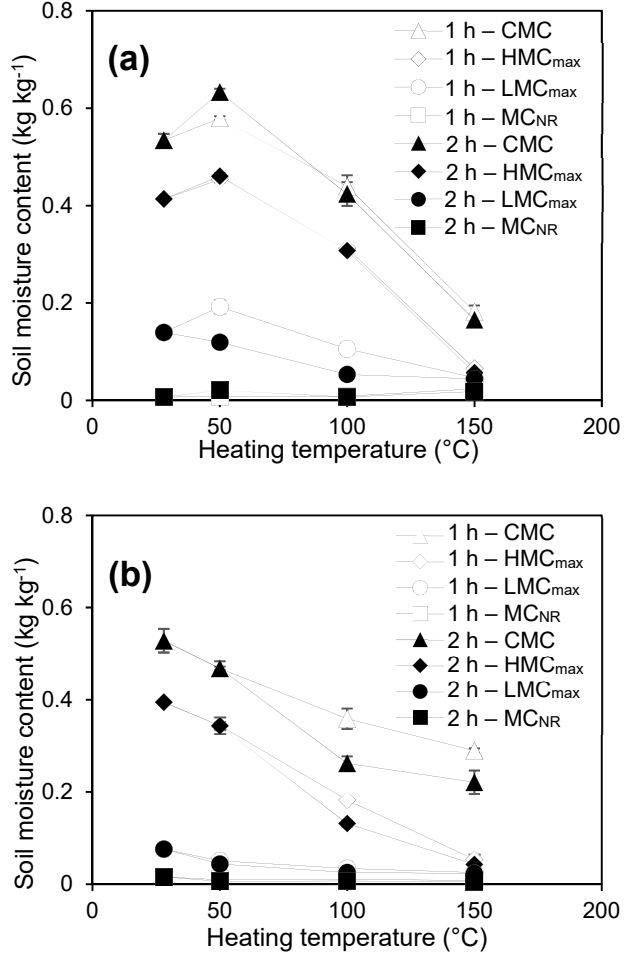


**Fig. 4.** The CMC (the critical moisture content at which soils become water-repellent with drying),  $H_{MC_{max}}$  (the highest moisture contents when soils showed maximum SWR),  $LMC_{max}$  (the lowest moisture contents when soils showed maximum SWR), and  $MC_{NR}$  (the moisture content at which soils become non-repellent again during drying), of (a) CYP and (b) CED soils heated to 50, 100, and 150 °C temperatures with 1 h and 2 h durations of exposure. The values at 28 °C represent the CMC,  $H_{MC_{max}}$ ,  $LMC_{max}$ , and  $MC_{NR}$  of the non-heated soil. Error bars indicate  $\pm$  standard deviation.

## DISCUSSIONS

Water-repellent conditions in soils beneath CYP and CED forests showed non-linear change with decreasing soil moisture under both non-heated and heated conditions (Figures 2, 3). The results for MDR follow a behavior comparable with previously reported findings (De Jonge et al., 1999; Kawamoto et al., 2007; Leelamanie and Karube, 2011). Although this non-linear behavior of SWR with change in soil moisture is yet to be comprehensively identified, several reports (Doerr and Thomas, 2000; Doerr et al., 2002; Goebel et al., 2004; Wallis et al., 1990) propose possible reasons considering conformational changes in water-repellent organic materials. The behavior of water-repellent soils to be wettable at higher moisture contents is explained as owing to the detachment of water-repellent organic molecules from soil particles to expose their non-repellent polar surfaces or molecular level conformational changes with the attraction of abundant moisture (Doerr and Thomas, 2000; Ma'shum and Farmer, 1985). With gradual drying, the mineral grain surfaces

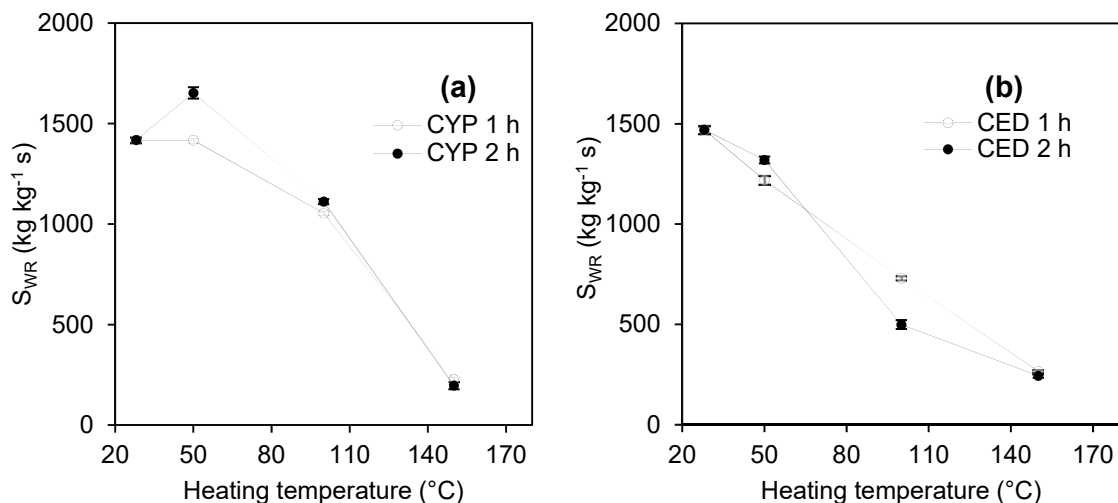


**Fig. 5.** Integrated area below the MDR curves ( $S_{WR}$ ) in (a) CYP and (b) CED soils heated to 50, 100, and 150 °C temperatures with 1 h and 2 h durations of exposure. The values at 28 °C represent the  $S_{WR}$  of the non-heated soil. Error bars indicate  $\pm$  standard deviation.

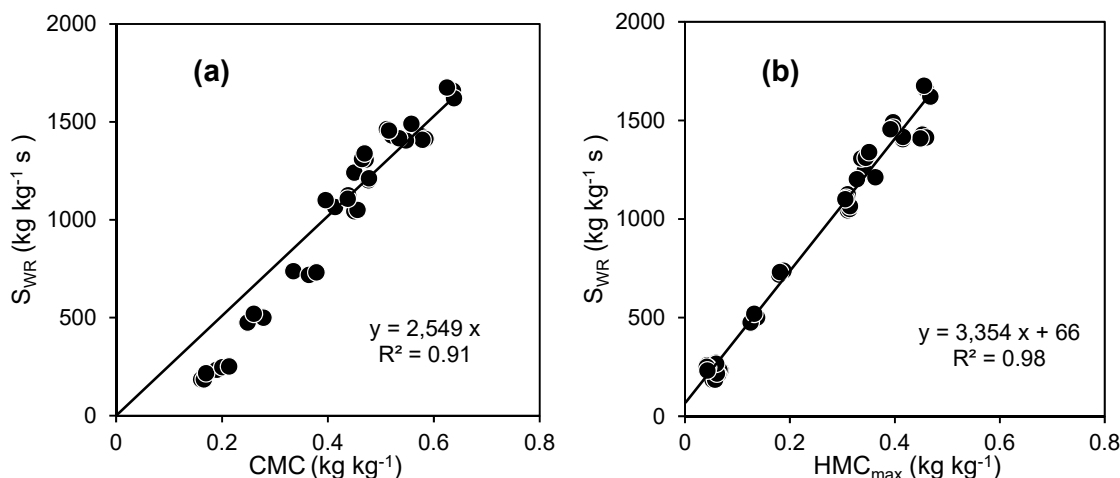


**Fig. 6.** Correlation of the integrated area below the MDR curves ( $S_{WR}$ ) with (a) critical moisture content at which SWR initiated with drying (CMC), and with (b) the highest moisture content at which soils became extremely water-repellent ( $HMC_{max}$ ) in soils under all heat treatments. The standard error of (a) slope: 35.84; (b) slope: 67.70, intercept: 21.16.

re-attract the polar ends of organic molecules exposing hydrophobic surfaces resulting in the occurrence of SWR when soil moisture declines below a CMC. This reattaching process of polar ends of organic molecules to minerals exposing hydrophobic ends can be considered as completed when soils reach a maximum level of repellency. In the present study, the moisture content at which soils reach extreme SWR ( $WDPT > 3600$  s) was considered the maximum level ( $HMC_{max}$ ).

Results showed that CMC and  $HMC_{max}$  of soils declined as the  $H_T$  increased from 50 to 150 °C in CED and 100 to 150 °C in CYP, showing that the initiation as well as reaching of the maximum level of SWR happens at drier soil conditions in heated soils (Figures 2, 3, 4). This shows that the reorientation of organic molecules (due to the attraction of non-repellent polar surfaces towards moisture), which induces wettable condition in soils, happens at drier conditions as the temperature level that the soils were heated ( $H_T$ ) becomes higher. The reattachments of water-repellant organic molecules to mineral soil grains are therefore can be considered delaying until the soils reach relatively lower moisture contents in heated soils, resulting in lower CMC.

Completion of these molecular conformational changes also seemed delaying until the soils reach relatively lower moisture contents with soils exposed to higher  $H_T$ , resulting in lower  $HMC_{max}$  as well. In addition, heating causes a gradual decline in soil organic matter content due to combustion and influences its chemical composition as well (Aedo and Bonilla, 2021). Gradual reduction of organic matter contents along with molecular conformational changes might also contribute to the decrease in CMC with increasing heating temperature.

The trapezoidal integrated area below the MDR curve,  $S_{WR}$ , is an indication of the potential of a particular soil to be water-repellent at a range of soil moisture levels. It is noted as a key index and an optimal parameter for the characterization of SWR because encompasses both moisture dependency of SWR and shows correlation with many other dynamic and static repellency parameters. Furthermore,  $S_{WR}$  is known to show favorable statistical features such as normality and moderate variability (Regalado and Ritter, 2005). Results of the present study reveal that the  $S_{WR}$  and the soil moisture range of which both CYP and CED soils indicate a potential to be water-repellent decreases with

increasing temperature of the heat treatment (Figure 5), except CYP soils heated at 50 °C. Conceptually,  $S_{WR}$  integrates the moisture-dependent characteristics of SWR. However, to estimate the  $S_{WR}$ , it is necessary to determine the whole MDR curve, which would take a difficult and time-consuming experimental process. Correlations of  $S_{WR}$  to other parameters of the MDR curve are helpful in avoiding a lengthy process by providing an approach to extrapolate  $S_{WR}$  from other parameters that can be easily measured (Regalado and Ritter, 2005).

Therefore, the  $S_{WR}$  was plotted against the parameters of the MDR curve, the CMC, and the  $HMC_{max}$  of both CYP and CED soils considering all heat treatments ( $H_T$  and  $E_D$ ) and the correlations were obtained (Figure 6). The results revealed that  $S_{WR}$  shows strong positive linear relations with both CMC and  $HMC_{max}$  indicating comparable findings with previous reports (Leelamanie and Karube, 2011; Regalado and Ritter, 2005). The  $S_{WR}$  showed strong positive linear correlations with CMC and  $HMC_{max}$  (Figure 6 a), indicating that both  $HMC_{max}$  and CMC are decisive and consistent factors that determine the  $S_{WR}$  in soils exposed to heat under different temperature levels for 1–2 h durations. The regression correlations were statistically significant at a 95% confidence interval ( $p < 0.05$ ) with a very low uncertainty level. Therefore, the following equations of the regression lines ( $R^2 = 0.91, 0.98$ ) can be effectively used to estimate  $S_{WR}$  and  $HMC_{max}$  using CMC.

$$S_{WR} = 2549 \times CMC \quad (1)$$

$$S_{WR} = (3354 \times HMC_{max}) + 66 \quad (2)$$

It is possible to determine the CMC easily avoiding prolonged procedures and use the Eq. (1) effectively to calculate  $S_{WR}$ . Once  $S_{WR}$  is determined, it would be possible to predict the moisture content at which SWR would become maximum ( $HMC_{max}$ ) using Eq. (3).

$$HMC_{max} = \frac{S_{WR} - 66}{3354} \quad (3)$$

Interestingly, although the heat altered the CMC,  $HMC_{max}$ , and  $S_{WR}$ , the heat did not influence the  $MC_{NR}$  in tested soils. Following these observations, we can assume that the  $MC_{NR}$  of a particular soil did not depend on the pre-heating, indicating that heat-induced alterations in organic matter content or composition did not influence the  $MC_{NR}$ . The disappearance of water-repellent conditions in drier soils might entirely depend on the moisture variations of particular soil rather than pretreatments like heating. All the heated and non-heated soils became wettable with drying at about a moisture content of 1%. As the soil dries with time, the number of adsorbed water molecules on the surfaces of soil minerals becomes lower leading to smaller contact angles (Goebel et al., 2004). These molecular changes and the attraction of water towards high negative water potential at extremely dry conditions can be considered as the reason for the disappearance of SWR at very dry soils with no relation to the soil type or heating treatments. The differences between the CMC,  $HMC_{max}$ ,  $LMC_{max}$ , and  $S_{WR}$  in CED and CYP soils might happen owing to the intrinsic differences in their organic substances.

## CONCLUSION

The MDR behavior or change in SWR with soil moisture of water-repellent CYP and CED forest soil, which were subjected to different heat treatments ( $H_T$  and  $E_D$ ), were determined under laboratory conditions. All the repellency parameters of the MDR

curve (CMC,  $HMC_{max}$ , and  $LMC_{max}$ ), except  $MC_{NR}$  of both CYP and CED soils decrease as the  $H_T$  increased, except CYP soils heated to 50 °C. Compared with the heating temperature, the duration that the soil is exposed to particular temperature did not show strong influence on the repellency parameter of the MDR curve (CMC,  $HMC_{max}$ ,  $LMC_{max}$ , and  $S_{WR}$ ) obtained for the tested CYP and CED forest soils.

The area under the MDR curve,  $S_{WR}$ , is an effective SWR parameter for both non-heated soils and the soils exposed to heat. It showed strong statistically significant relations with CMC and  $HMC_{max}$  irrespective of the type of the soil and the heating temperature or the duration of heating. Therefore, the most easily measures parameter, CMC, can be used to estimate  $HMC_{max}$  and  $S_{WR}$ , avoiding laborious procedures.

Results revealed that the heat generated during wildfires can alter the MDR and all the related repellency parameters of water-repellent forest soils. SWR prevailed over a narrower range of moisture contents in heated soil compared with non-heated soils, except CYP soils heated to 50 °C, and this range decreased with increasing heat up to 150 °C. This reveals that burned forest soils show repellency in narrower range of moisture contents, and the range gets narrower with increasing temperature that the soil reached. This raises important questions as to whether the water-repellent moisture range can get extremely narrower and disappear when the soils reach higher temperature levels. For a comprehensive understanding, further investigations with higher temperature levels using would be important.

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