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Fire induced water repellency in the forest soil covered with different types of forest floor biomass

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The intensity and severity of a wildfire can influence the persistence of soil water repellency (SWR) in the affected area. The effects of fire on the SWR of forest soils depend on the type of forest vegetation, the quantity of the organic component of the forest soil, the characteristics of the organic matter, the soil type, and its properties.
Three study sites were located in the Borská nížina lowland (southwestern Slovakia). The first site IL1 represents a 100-years-old stand of Scots pine (*Pinus sylvestris*), the second site IL2 is a 30-years-old stand of Scots pine (*Pinus sylvestris*), and the third site LL is a deciduous stand with a predominance of alder (*Alnus glutinosa*). The article aimed to determine the influence of forest floor biomass (FFB) in IL1, IL2 and LL on SWR induced by different heating temperatures. WDPT test was measured on the surface of burned mineral soil samples without FFB, and two series of measurements were carried out in samples covered with FFB. First were carried on the surface of burned FFB and second, under burned FFB on the exposed mineral soil. Our first hypothesis was that heating temperatures would induce higher SWR persistence on soil covered with forest floor biomass compared to bare soil; the second hypothesis was that different forest floor biomass would induce different post-fire SWR persistence.
The differences between the samples covered with FFB and samples without FFB in mean values of SWR induced by different temperatures were not statistically significant for either research site. On the other hand, the highest individual SWR values were measured at or below the forest floor biomass in both deciduous and coniferous forests.
The second hypothesis was not confirmed. We found similar fire-induced SWR in the different types of forest floor biomass and the soil under forest floor biomass.

KEY WORDS: soil water repellency, soil heating, water drop penetration time, forest floor biomass

Introduction

Fire-induced water repellency is a phenomenon that occurs when a wildfire burns through an area, leaving behind a layer of ash and charred debris on the soil surface. This layer can alter the physical and chemical properties of the soil, resulting in increased soil water repellency (SWR) (Zvala et al., 2022).
The intensity and severity of a wildfire can influence the extent, persistence and severity of SWR in the affected area. Higher-intensity fires tend to cause more severe SWR, which can profoundly impact the ecosystem. The water-repellent layer can cause soil erosion, reduce infiltration rates, increase runoff, and alter soil chemistry. The waxy substances produced during combustion can alter the soil's chemistry, making it more acidic (Hološ et al., 2022).
The hydrophobicity induced by wildfires is caused by the combustion of organic matter, such as plant debris and soil organic matter, which produces waxy substances that coat soil particles. Waxes, resins and other organic matter are converted by fire into charred organic residues that release large amounts of hydrophobic organic matter while covering soil particles (DeBano, 2000). The effects of fire on the SWR of forest soils depend on the type of forest vegetation and its density, the content and quantity of the organic component of the forest soil, the characteristics of the organic matter, the soil type, and its properties (Arcenegui et al., 2007; Mataix-Solera et al., 2008; Negri et al., 2021). A forest fire can increase or decrease pre-existing SWR depending on the amount and type of organic matter consumed and the temperature reached (DeBano et al., 1998; Doerr et al., 2004; Certini, 2005; Robichaud and Hungerford, 2000). The composition of organic matter and its interactions with the soil mineral component of the forest soil play an important role in the change in SWR (Lichner et al., 2006). In addition to the redistribution and concentration of hydrophobic substances in the soil, the heat generated by fire is also thought to improve the binding of these substances to soil particles (Savage et al., 1972). Studies of burned stands conducted on forest soils under *Pinus pinaster* and *Pinus halepensis* have found that they are capable of causing extreme SWR (Arcenegui et al.,

2008). Burning non-woody leaves in forest soil organic matter layers can cause SWR in deciduous forests, indicating that this condition is not exclusive to coniferous and dry forests (Chen et al., 2020). The strength of post-fire SWR depends on the severity of the fire. Laboratory experiments have found that heating the soil below 175°C causes slight changes in SWR. Significant increases in SWR were found at temperatures between 175 and 270°C. Micromorphological investigations indicated that high temperatures increased the formation of organic carbon coatings responsible for SWR (Dekker et al., 1998). Temperatures between 270°C and 400°C destroy hydrophobic substances in the soil and suppress SWR (Doerr et al., 2004; Varela et al., 2005; Wu et al., 2020).

Management strategies to reduce the impacts of fire-induced SWR are critical for maintaining ecosystem health and function. One approach is to use fire-retardant materials or chemicals to prevent or reduce the intensity of wildfires. Another method is to use mechanical treatments, such as thinning and prescribed burning, to reduce the fuel load and intensity of fires. In some cases, post-fire rehabilitation, such as the application of mulch and seed, may be necessary to promote vegetation growth and prevent further erosion.

The principal aim of the article was to determine the influence of different types of forest floor biomass on SWR induced by the simulated fire. Our first hypothesis was that heating temperatures would induce higher SWR persistence on soil covered with forest floor biomass compared to bare soil; the second hypothesis was that different forest floor biomass would induce different post-fire SWR persistence.

Material and methods

Research site

Soil samples were taken from the experimental sites IL1, IL2, and LL located at Studienka village with an altitude of 203 m a. s. l. in the Borská nížina lowland (southwestern Slovakia). The region has a temperate climate (Cfb) (Kottek et al., 2006) with a mean annual temperature of 9°C and mean annual precipitation of 600 mm, mainly during the summer months. The soils of the Studienka sites are classified as Arenosol and have a sandy texture (WRB, 2014) (Table 1).

Experimental sites were selected to include different stand ages and types of forest floor biomass (organic surface horizon) under the relatively same site conditions (climate, soil and relief conditions).

The IL1 site is a stand older than 100 years (Fig. 1a); its purpose is to stabilize the sand dune. The herbaceous undergrowth is dominated by grass, especially sheep fescue (*Festuca ovina* agg), and often covered with bushgrass (*Calamagrostis epigejos* (L.) Roth). Other species are rare, such as the wall hawkweed (*Hieracium murorum* L.), the weed species of the black nightshade (*Solanum nigrum* L.) and allochthon species with invasive behaviour, such as the pokeweed (*Phytolacca americana* L.), the black cherry (*Prunus serotina* Ehrh.) and horseweed (*Conyza canadensis* (L.) Cronq.). Rare species here are also red-stemmed feathermoss (*Pleurozium schreberi* (Bird.) Mitt.) and neat feathermoss (*Pseudoscleropodium purum* (Hedw.) M. Fleisch).

The IL2 site represents 30-year-old Scots pine (*Pinus sylvestris*) stand (Fig. 1b). The tree layer is very dense without undergrowth. The soil surface is covered with a few centimetres of coniferous litter. The mechanical site preparation was used for forest restoration, while the surface layer of soil with humus was removed, so the pine trees were planted in the bare sand.

The LL research site represents a younger stand of alder (*Alnus glutinosa*) (30–40 years) in an indistinct terrain depression situated under a sand dune overgrown with monocultures of Scots pine (Pinus sylvestris) in an undergrowth dominated by tall sedges (*Carex elata*) and the presence of other more moisture-loving species (Fig. 1c).

Table 1. Soil parameters of the topsoil horizon (0–10 cm) of study plots IL1, IL2 and LL (Cox = organic carbon content; WDPT = SWR measured before heating). The results are presented in the form of arithmetic mean ± standard deviation. Properties denoted with different letters are significantly different on significance level 0.05.

Parameter	IL1	IL2	LL
Sand [%]	91.82±0.03	92.31±0.02	92.96±0.48
Silt [%]	5.81±0.12	4.96±0.07	3.36±0.33
Clay [%]	2.37±0.09	2.72±0.03	3.68±0.12
$CaCO_3$ [%]	<0.05	<0.05	<0.05
Cox [%]	0.64^a±0.13	0.55^a±0.08	1.43^b±0.37
pH (H_2O)	4.96^a ±0.01	5.33^b ±0.01	4.20^c ±0.01
pH (KCl)	3.99^a ±0.01	4.39^b ±0.01	3.65^c ±0.01
WDPT [s]	16040^a±5828.30	958^b±495.70	146^b±92.15

Soil sampling and heating experiment

The mineral part of the soil from the 2.5 cm depth was sampled into the prepared containers after the organic horizon (0–2.5 cm) was gently removed from the soil surface and sampled separately. After returning to the laboratory, the mineral soil samples were sieved through a 2 mm sieve and dried at 40°C. After reaching equilibrium, the samples were weighed into ceramic dishes. We weighed five ceramic dishes for each temperature. The forest floor biomass (FFB) was air-dried in the laboratory to a constant weight. The dried FFB was processed into 1 to 10 mm material and mixed. For the analysis of the mineral component of the forest soil, we weighed 60 grams of sieved soil sample into ceramic dishes of 70 mm diameter and 35 mm height. To analyze the samples covered with FFB, we first weighed 60 g of the laboratory-prepared mineral component and then weighed 5 g of the FFB (Arcenegui et al., 2007). The samples were heated in a muffle furnace LE 15/11 (Fig. 2) at temperatures of 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850 and 900 ° C for 20 min (a new sample for each temperature). 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 persistence of SWR was assessed by the WDPT test. It involves placing 50 ± 5 μl of a drop of water from a standard dropper or pipette on the soil surface and recording the time of its complete penetration (infiltration) into the soil. A standard drop release height of approximately 10 mm above the soil surface was used to minimize the crater effect on the soil surface (Doerr, 1998; Tinebra et al., 2019). WDPT test was measured on the surface of burned mineral soil samples without FFB (treatment MN). We made two series of measurements for samples covered with FFB; the first was carried on the surface of burned FFB (treatment FFB), and the second under burned FFB on the exposed mineral soil (treatment MNE).
Our experiment's natural background water repellency is represented by the mean value of the persistence of SWR, measured before heating (SWRn). The induced SWR was estimated as the mean of WDPT values measured after heating soil samples at temperatures of 50–900°C (SWRi). SWRmax is the highest value of induced SWR, determined as the highest group average of WDPT measured after heating at a specific temperature. Tmax is the heating temperature that induced SWRmax.

List of abbreviations

Cox	organic carbon content
WDPT	water drop penetration time
SWR	soil water repellency
SWRn	natural background water repellency, measured before heating
SWRi	induced SWR, measured after heating of soil samples at temperatures of 50–900°C
SWRmax	highest value of induced SWR, measured after heating at a specific temperature
Tmax	the heating temperature that induced SWRmax
IL1	100-year-old pine stand
IL2	30-year-old pine stand
LL	30-year-old alder stand
MN	surface of burned mineral soil without FFB (treatment)
MNE	the exposed mineral soil under burned FFB (treatment)
FFB	forest floor biomass

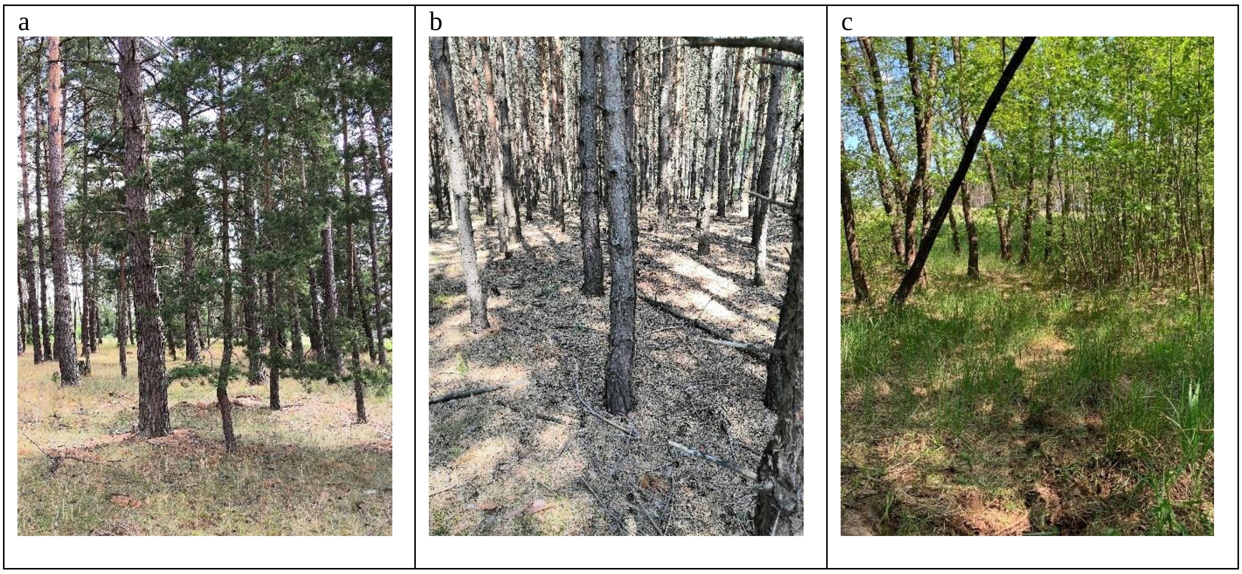

Fig. 1. Research sites: a) IL1 – over 100-year-old Scots pine (Pinus sylvestris L.) plantation; b) IL2 – 30-year-old Scots pine plantation; c) LL – approx. 30-year-old deciduous tree stand.

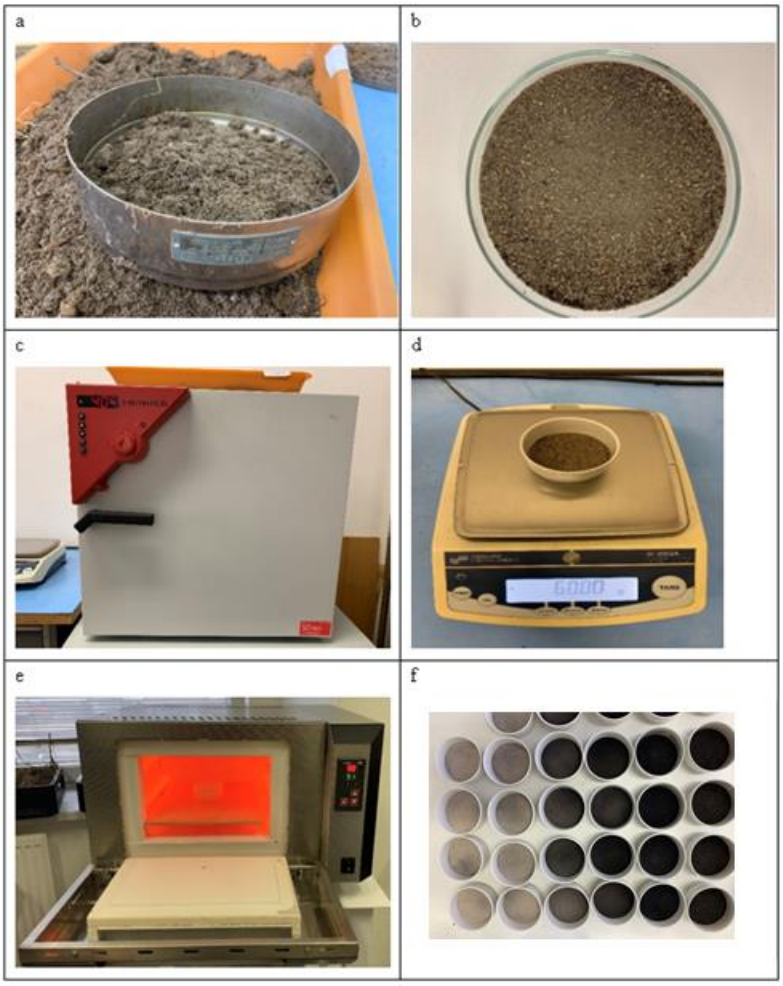

Fig. 2. Sample preparation and heating procedure in the muffle furnace a) sieving through a 2 mm sieve; b) Petri dish; c) BINDER drying oven for drying the samples; d) weighing the samples on a DENVER INSTRUMENT SI-2002A balance; e) burning of the samples in the muffle furnace (LE 15/11); f) soil samples after different temperature heating treatments.

Statistical analysis

The data were first analyzed by the omnibus normality test, which combines the skewness and kurtosis tests into a single measure. After the data had passed the omnibus normality test, differences between the parameters were evaluated using single-factor ANOVA with Tukey's Honest Significant Difference (HSD) post-hoc test. When the assumption of normality was not valid, the nonparametric Kruskal-Wallis test with multiple comparison Kruskal-Wallis Z test was used. It is a distribution-free multiple comparison, meaning that the assumption of normality is unnecessary. It is to be used for testing pairs of medians following the Kruskal-Wallis test. 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 highest mean value of fire-induced SWR (SWRi) in a 100-year-old pine forest was measured in the soil without FFB (MN), followed by exposed soil under FFB (MNE), and the lowest value was measured in the FFB. We did not find statistically significant differences between the mean values of MN and MNE treatment. SWRmax, the highest value of induced SWR, declined in the order MNE>FFB>MN. Based on Fig. 3, it is possible to observe differences in the shape of the line showing the WDPT vs temperature relation. We observed a slight increase in the MN treatment, a relatively long steady state with high SWR, and a subsequent decrease. In the FFB treatment, we observed a steep increase followed by a subsequent decline; interestingly, the steep increase in the MNE treatment occurred only after the SWR decrease in the FFB treatment.
In the 30-year-old pine stand, we measured the highest mean SWRi value in the MNE treatment and a decrease in other treatments in the order FFB > MN (Fig. 4). We found no statistically significant differences between treatments. The highest SWRmax value was measured on the MNE treatment (26 676 s) and decreased in the order of FFB>MN. The shape of the WDPT vs temperature relation in all treatments is similar; the MNE treatment has a higher SWR at low heating temperatures as MN,

while the FFB treatment has a steep rise and fall in SWR. The highest mean value of SWRi in the alder stand was measured in the FFB, followed by MNE, and the lowest value was measured in the MN (which means exactly the opposite of a 100-year-old pine forest). However, this trend has not been statistically confirmed (Fig. 5). SWRmax declined in the order MNE>FFB>MN. The shape of the WDPT vs temperature relation in all alder stand treatments is similar; the MNE treatment has a similar SWR at 100–250°C as MN, while the FFB treatment has a higher SWR.

We did not find a statistically significant difference between the research sites (IL1, IL2, LL) in the SWRi measured below FFB. The shape of the WDPT vs temperature relation in research sites IL1 and IL2 is very similar. The difference is in the lower SWR measured in

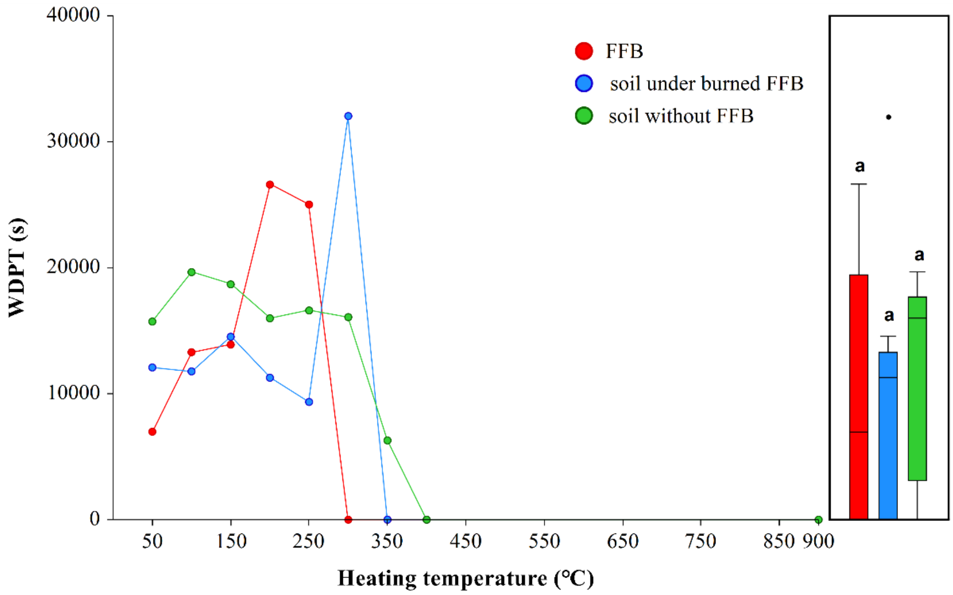

Fig. 3. Persistence of SWR induced by increasing temperature in soil from research site IL1, measured in forest floor biomass (FFB), in soil under FFB and soil without FFB. Box plots denoted with different letters are significantly different on significance level 0.05. The whiskers in the border plot show minima and maxima, and points represent outliers.

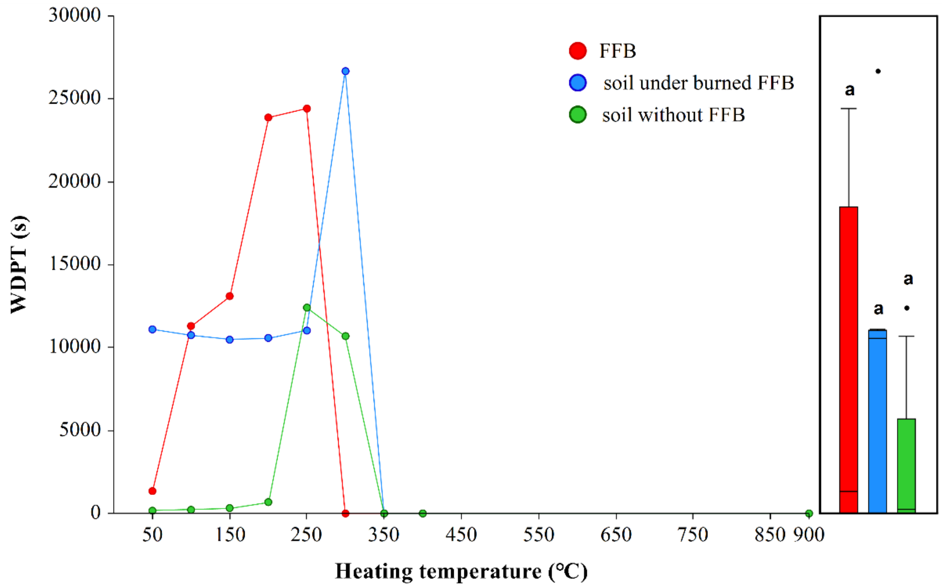

Fig. 4. Persistence of SWR induced by increasing temperature in soil from research site IL2, measured in forest floor biomass (FFB), in soil under FFB and soil without FFB. Box plots denoted with different letters are significantly different on significance level 0.05. The whiskers in the border plot show minima and maxima, and points represent outliers.

the LL site (Fig. 6). The highest mean for SWRi was measured on research site IL1, followed by IL2 with a minimal difference and the lowest value was measured on LL. SWRmax was very similar, 32 040 s, 26 676 s resp. 27 888 s, for sites IL1, IL2 resp. LL measured at 300°C.
The highest mean SWRi of FFB was measured on research site IL1, followed by LL with a very small difference and the lowest value was measured in IL2 (Fig. 7). However, this trend has not been statistically confirmed. SWRmax was very similar in all research sites, with the highest value measured in IL1 at 200°C, followed by LL and IL2 at 250°C. The shape of the WDPT vs temperature relation in all research sites is very similar. Differences are in the SWR measured at 50°C (for all sites) and shift in SWRmax in IL1 (Fig. 7).

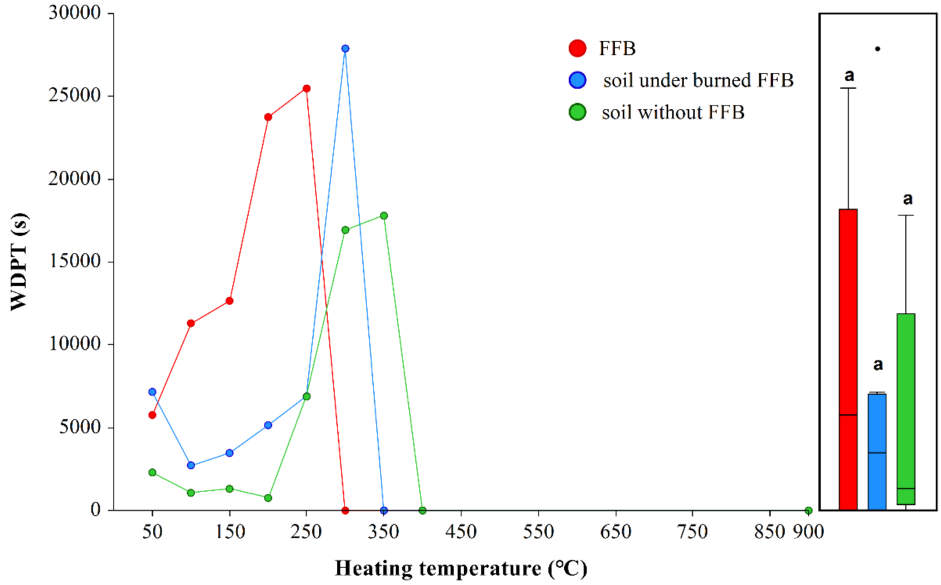

Fig. 5. Persistence of SWR induced by increasing temperature in soil from research site LL, measured in forest floor biomass (FFB), in soil under FFB and soil without FFB. Box plots denoted with different letters are significantly different on significance level 0.05. The whiskers in the border plot show minima and maxima, and points represent outliers.

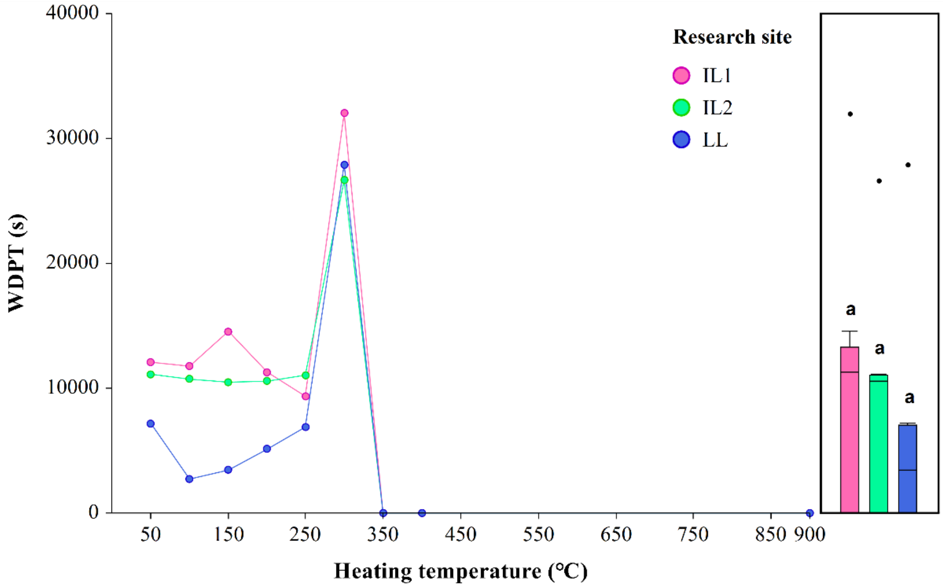

Fig. 6. Persistence of SWR induced by increasing temperature in soil under FFB for all research sites. Box plots denoted with different letters are significantly different on significance level 0.05. The whiskers in the border plot show minima and maxima, and points represent outliers.

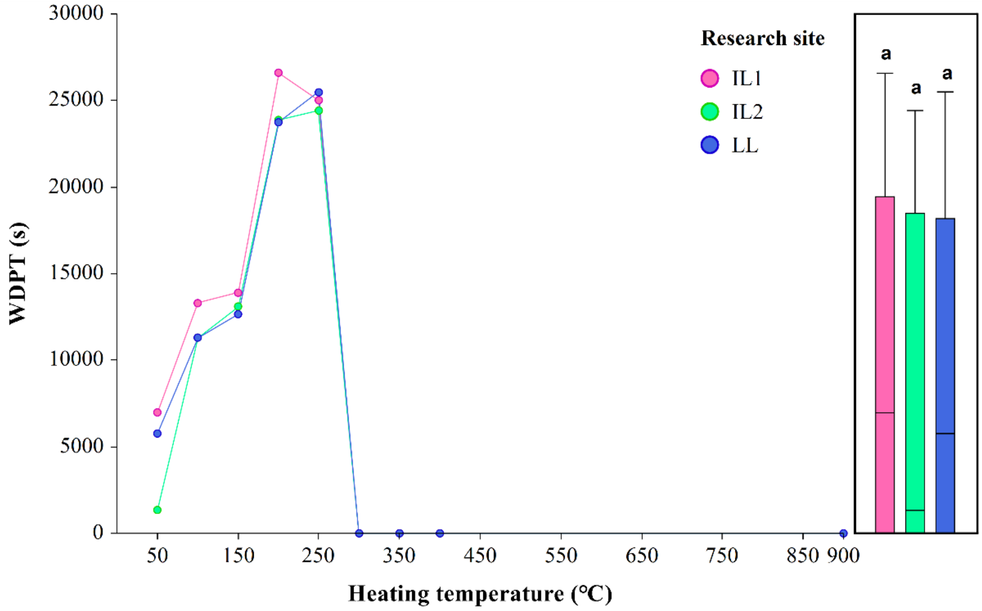

Fig. 7. Persistence of SWR induced by increasing temperature in the FFB for all research sites. Box plots denoted with different letters are significantly different on significance level 0.05. The whiskers in the border plot show minima and maxima, and points represent outliers.

Conclusion

In our study, we found the changes in fire-induced SWR that may be attributed to the different types of forest floor biomass (FFB); however, none of the observed differences was statistically confirmed.
Our first hypothesis that heating temperatures would induce higher SWR in soil covered with FFB compared to bare soil was partially confirmed. The highest SWRmax values were measured at or below the FFB in deciduous and coniferous forests. Higher SWR can cause reduced infiltration, increased runoff and erosion, greater soil moisture variability and alter nutrient cycling. Removing dead biomass reduces the fuel load and can help mitigate SWR and fire risk in forest plantations. It's important to note that deadwood and biomass play significant ecological roles in forest ecosystems, providing habitat for numerous organisms, contributing to nutrient cycling, and promoting biodiversity. Therefore, deadwood removal should be carefully considered, and sustainable management practices should aim to balance the removal of dead biomass with the conservation of ecosystem functions and biodiversity.
The second hypothesis that different forest floor biomass would induce different post-fire SWR persistence was not confirmed. We found similar fire-induced SWR in the different types of forest floor biomass and the soil under forest floor biomass.

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