DOI: 10.31577/ahs-2022-0023.01.0015

ACTA HYDROLOGICA SLOVACA

Volume 23, No. 1, 2022, 140 – 146

The effect of different fire temperatures on the water repellency parameters of forest sandy soil under different types of vegetation

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Soil under specific tree forest species (e.g. pines) can be naturally water repellent. Forest fire can strengthen or destroy soil water repellency (SWR). Fire induced SWR have many direct or indirect effects, including increased preferential flow rate and risk of ground water contamination, increased surface runoff and soil erosion, increased amount of carbon stored in soil, reduced levels of seed germination and plant growth. Understanding the post-fire hydrologic response of forest soil is paramount for effective risk management and mitigation of post-fire hydrologic hazards.
Three experimental sites were located in the Borská nížina lowland (southwestern Slovakia). Eolian (wind-blown) sand dunes form the central part of the Borská nížina lowland, which make it a specific region within Central Europe. Pines have been planted here for sand dune stabilization since the 18th century and today cover a huge part of the lowland. The first site IL1 represent 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 disturbed mineral soil samples were taken from 2.5–5.0 cm depth of soil horizon. The organic horizon (0–2.5 cm) was sampled separately before mineral soil. In the laboratory, the samples from each site in 5 replicates were placed into a muffle furnace and exposed to a temperature from 50 to 900°C. The persistence of SWR in soil samples was measured using the water drop penetration time (WDPT) test.
Our goal was to quantify the changes of SWR of the naturally water repellent soil induced by different fire temperatures under age and species different forest stands. Forest stands were selected to include different vegetation age and type of litter (surface organic horizon) under the relatively same site conditions (climate, soil and relief conditions).
The measured values of natural background water repellency decreased in order IL1>IL2>LL. The highest value of induced SWR ($WDPT_{max}$) was measured at IL1 and further declined in the order LL>IL2; however increase of SWR after heating, estimated as a difference between maximal induced and natural SWR had different trend (LL>IL2>IL1). Mean value of parameter $WDPT_{max}$-$WDPT_n$ at IL1 was statistically different from values estimated at sites IL2 resp. LL.
The changes in natural and induced SWR that we have found may be attributed partially to the quantity and to the origin of organic material (litter of the plant communities with different age and composition of the species).

KEY WORDS: soil water repellency, soil heating, water drop penetration time, forests

Introduction

Wildfire activity, number of fires, area burned, and fire severity, has increased in many areas of the world in recent decades (Abatzoglou et al., 2013; Reilly et al., 2017; Hološ and Šurda, 2021). These rising trends are projected to continue in some regions due to climate change, increasing population, and fire suppression activities (Flannigan et al., 2013; Moritz et al., 2012; Novák, 2021).
Soil water repellency (SWR) is a natural phenomenon occurring under relatively dry conditions in soils with a wide range of land uses and climatic conditions, which can be intensified by heating the soil during wildfires. In fact, fire creates SWR in previously hydrophilic soils and also maintains or even increases it in previously repellent soils, depending on the specific pre-fire conditions and its severity. Various preceding studies reported that fires can create or increase SWR on forest soils (Certini, 2005; Doerr et al., 2004). An increase in the SWR of the soil due to fire may increase preferential flow rate and risk of ground water contamination, make the soil incapable of infiltrating water and being more susceptible to erosion (DeBano and Krammes, 1966). SWR is considered important for post-fire hydrology, causing reduced infiltration and increased surface runoff and erosion, especially after a fire when vegetation has been removed (Certini, 2005, DeBano, 1981; DeBano, 2000; Doerr et al., 2004, Kettridge et al., 2014).
SWR is induced by the hydrophobic and amphiphilic components of soil organic matter. Some authors (e.g., Buczko et al., 2005; Hrabovský et al., 2020; Zavala et al., 2009) found positive correlation between SWR and soil organic matter; other authors shown that quantity of soil

organic matter alone could not fully explain the changes of SWR (Zema et al., 2021). Dinel et al. (1990) found that the concentration of hydrophobic lipid compounds decreases with increasing efficiency of organic matter decomposition and Cesarano et al. (2016) shown that litter incorporated into the soil can produce a variety of effects on SWR, ranging from a dramatic increase to a null effect depending on the considered litter type.

The increase in forest soil temperature during combustion is significantly influenced by the intensity and duration of the fire, which depends on the quality and humidity of the burning fuel, air temperature and humidity, wind speed and terrain topography (Robichaud and Hungerford, 2000; Campbell et al., 1995). At low fire intensities, forest soil temperatures range from 250°C to 450°C (Janzen and Tobin-Janzen, 2008; Franklin et al., 1997). In the presence of a good amount of fuel, the intensity of the fire increases, the forest soil temperature rises from 500°C to 700°C (DeBano et al., 1998), however fire sites with a recorded forest soil temperature of 850°C have been observed (DeBano, 2000). Some laboratory experiments have revealed that heating the soil below 175°C causes slight changes in SWR. A significant increase in SWR was found at temperatures from 175 to 270°C. Temperatures in the range of 270°C to 400°C destroy hydrophobic substances in the soil and, as a result, suppress SWR (DeBano et al., 1976; Doerr et al., 2004; Varela et al., 2005). The effects of fire on SWR depend on other factors, including the type of plants present and their density, organic matter characteristics, soil structure or the mineralogical composition of the clay fraction (Arcenegui et al., 2007; Mataix-Solera et al., 2008; Sándor et al., 2021). Micromorphological studies have suggested that high temperatures have resulted in increased formation of organic carbon coatings responsible for SWR (Dekker et al., 1998).

Main goal of our study was to quantify the changes of SWR of the naturally water repellent soil induced by different fire temperatures under age and species different forest stands. Our hypothesis was that the effect of fire temperature on SWR depends on initial organic carbon content (existence of positive correlation between C_{ox} and hydrophobic components of soil organic matter) and/or on the origin of organic material (different composition of the litter incorporated into the soil can produce either increase or null effect on SWR). Experimental sites were selected to include relatively high natural background SWR (sandy soils of Borská nížina lowland), different stand age and type of litter (surface organic horizon) under the relatively same site conditions (climate, soil and relief conditions). The locality was also chosen due to the close proximity of three age- and species-different stands.

Material and methods

Research site

The research was conducted near the village of Studienka (48° 31.733' N, 17° 07.315' E) in the Borská nížina lowland (southwestern Slovakia). Most of the area is located on Eolithic sands. The soils of the research sites are classified as Arenosol (WRB, 2014) and have a sandy texture (Soil Science Division Staff., 2017). The climate is mild with mild humidity and winter. The average annual temperature in this area is 9–10°C and the average annual rainfall in the Borská nížina lowland is 600–650 mm (Atlas of the Slovak Republic, 2002). Despite Scots pine is being proven to be a native species here, its current large stands are intensively managed human established plantations with specific undergrowth. Pines have been planted here for sand dune stabilization since the 18th century.

Experimental sites were selected to include relatively high natural background SWR, different stand age and type of litter (surface organic horizon) under the relatively same site conditions (climate, soil and relief conditions). The locality was also chosen due to the close proximity of three age- and species-different stands. Within the group of forest stands, 3 research sites were set aside: a 30-year-old (IL2) and a 100-year-old coniferous tree stand (IL1) and 40-year-old deciduous tree stand (LL) (Fig. 1).

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.

The IL2 site represent 30 years old Scots pine (*Pinus sylvestris*) stand. The tree layer is very dense without undergrowth. The soil surface is covered with a few centimeters 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 IL1 site is a stand older than 100 years; 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 allochton species with invasive behavior, 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).

Soil sampling, determination of basic soil characteristics 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. Basic soil properties were determined with three replications in the ISO Certified Laboratory of the Soil Science and Protection Research Institute in Bratislava.

In the laboratory of IH SAS, the 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 5 ceramic dishes for each temperature. The weight of the mineral part of the soil was 60 g. 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 given time, we pulled the samples out of the oven and allowed to cool to room temperature.

Measurement of soil water repellency

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 et al., 1998; Tinebra, 2019).

The natural background water repellency in our experiment is represented by the mean value of the persistence of SWR, measured without heating ($WDPT_n$). The induced SWR was estimated as mean of WDPT values measured at 20°C (without heating) and after heating of soil samples at temperatures of 50–900°C ($WDPT_i$). $WDPT_{max}$ is the highest value of induced SWR, determined as the highest group average of WDPT measured after heating at a certain temperature. T_{max} is the combustion temperature that induced $WDPT_{max}$.

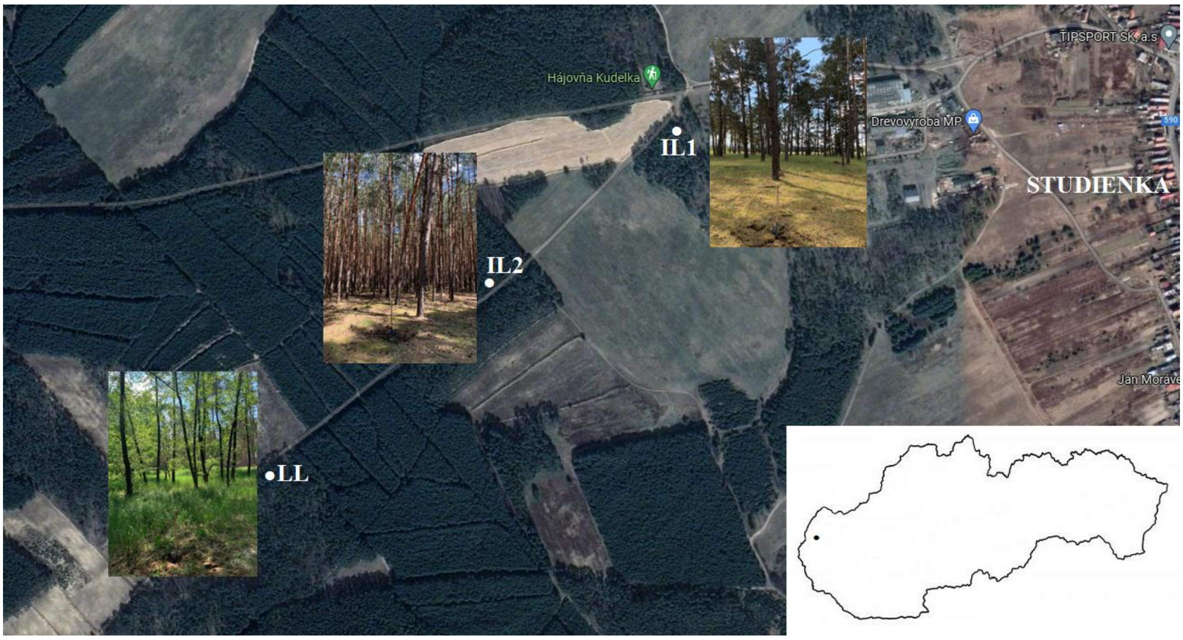

Fig. 1. Map of the experimental area with marked research sites IL1 – 100 years old coniferous forest, IL2 – 30 years old coniferous forest, LL – deciduous forest.

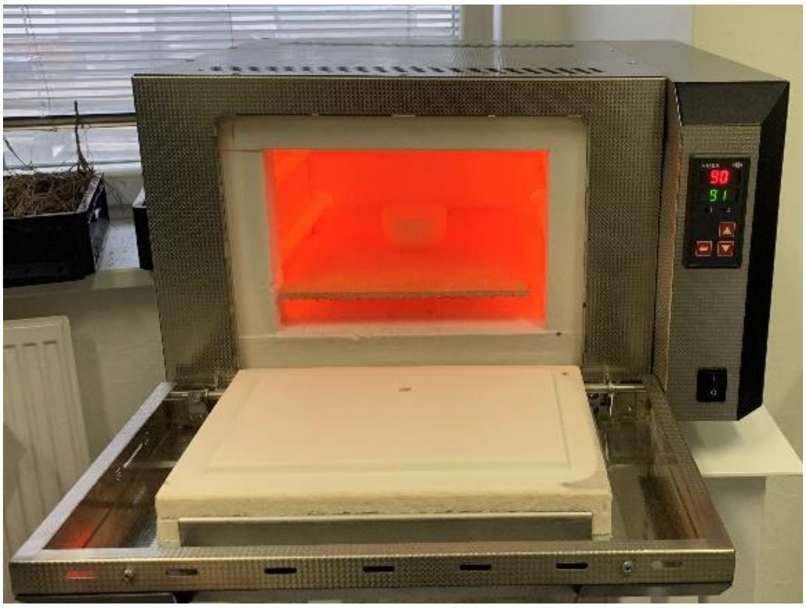

Fig. 2. Heated muffle furnace (LAC LE 15/11).

Statistical analysis

Differences between the parameters estimated in different sites were evaluated using single factor ANOVA with Tukey's Honest Significant Difference (HSD) post-hoc test. The Tukey-Kramer method (also known as Tukey's HSD method) uses the Studentized Range distribution to compute the adjustment to the critical value. The Tukey-Kramer method achieves the exact alpha level (and simultaneous confidence level $(1 - \alpha)$) if the group sample sizes are equal and is conservative if the sample sizes are unequal. The statistical significance in the analysis was defined at $P < 0.05$.

Results and discussion

The basic physical and chemical properties of the upper part of soil horizon at the studied forest stands are in Table 1. The lowest sand fraction was determined at the IL1, which represents a higher stage of succession (100-year-old forest stand) compared to IL2 (approximately 30 years) and LL (approximately 40 years). The older age of the stand is related to the accumulation of plant residues on the soil surface, the decomposition of which increases the proportion of organic carbon and finer grain fraction. The high content of organic carbon per LL, which does not correlate with the age of the stand, may be due to the different composition of the litter - carbon content, C: N ratio (needles vs. leaves).

The water repellency parameters, which were used for analysis of the fire temperature impact on the persistence of SWR at sites LL, IL1 and IL2, are shown in Fig. 3. The natural background water repellency in our experiment is represented by the mean value of the persistence of SWR, measured without heating at 20°C ($WDPT_n$). $WDPT_{max}$ is the highest value of SWR (natural + induced), determined as the highest group average of WDPT measured after heating at a certain temperature. T_{max} is the combustion temperature that induced $WDPT_{max}$. The absolute increase of SWR after heating was estimated as $WDPT_{max}$-$WDPT_n$.

The highest value of $WDPT_n$ was measured on IL1,

Table 1. Physical and chemical properties of the upper part of the soil horizon at the experimental sites IL2, IL1 resp. LL (a 100-year-old and 30-year-old coniferous tree stand, resp. 40-year-old deciduous tree stand). (Cox = organic carbon content)

Attribute	Experimental site		
	IL1	IL2	LL
Sand [%]	89.82	92.31	92.96
Silt [%]	5.81	4.96	3.36
Clay [%]	2.37	2.72	3.68
$CaCO_3$ [%]	<0.05	<0.05	<0.05
Cox [%]	0.75	0.61	1.35

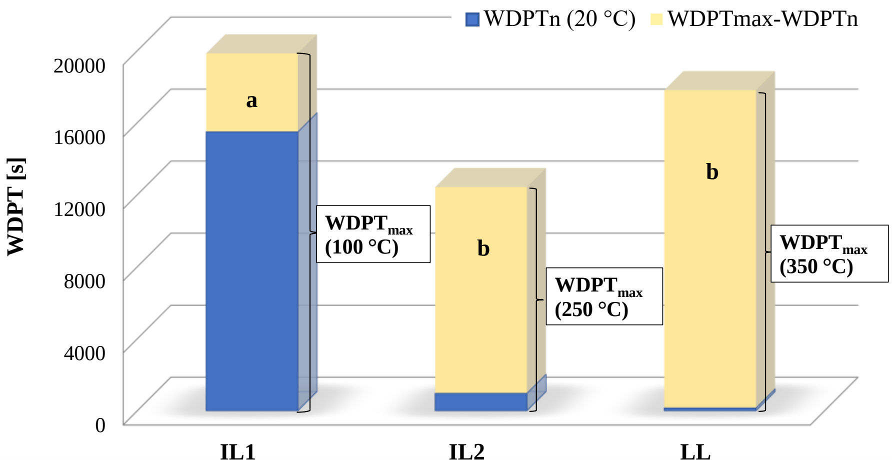

Fig. 3. Water repellency parameters (persistence of SWR at 20°C – $WDPT_n$; highest value of induced SWR, determined as the highest group average of WDPT at a certain temperature – $WDPT_{max}$ at T_{max}, increase of induced SWR as the difference of $WDPT_{max}$ - $WDPT_n$) on the experimental sites IL1 – 100-year-old coniferous forest, IL2 – 30-year-old coniferous forest, LL – 40-year-old deciduous forest. Parameters with the same letter are not significantly different from each other (Tukey's HSD test, $P < 0.05$).

which was caused by the composition of coniferous litter and vegetation cover (especially grasses). The lower value of $WDPT_n$ on IL2 is probably due to the absence of vegetation cover and the lowest value on LL due to the absence of coniferous litter.

The parameter $WDPT_{max}$ decreases in the order of IL1>LL>IL2. Since the proportion of coarse-grained fraction at all the sites is approximately the same and the $WDPT_{max}$ values are not related with C_{ox}, differences in $WDPT_{max}$ can be probably attributed to the different composition of litter.

A different trend was found in the analysis of SWR increase, estimated as a difference between maximal induced SWR and natural SWR. The highest value of $WDPT_{max}$-$WDPT_n$ was measured at site LL and decreased in order IL2>IL1. Mean value of $WDPT_{max}$-$WDPT_n$ at IL1 was statistically different from values estimated at sites IL2 resp. LL.

T_{max} parameter decreases in the order LL>IL2>IL1, which appears to be the same trend as $WDPT_{max}$-$WDPT_n$. The graphical representation of the natural and induced persistence of SWR as a function of temperature (Fig. 4) shows a large degree of variability.

The highest mean value of natural SWR – $WDPT_n$ (15480 s) was measured at the IL1 research site. The heating at 100°C increased the WDPT value to 19650 s. The further increase in heating temperature reduced persistence of SWR and at a temperature of 400°C SWR disappears and does not occur up to the investigated temperature of 900°C. The extreme (natural and induced) SWR of the forest soil from the IL1 site can be caused by the specific type of litter accumulated during 100 years.

The $WDPT_n$ value at the IL2 site was 958 s. The heating to 50°C reduced the WDPT value to 164 s, but further temperature increase to 200°C increased also the WDPT value. We found then a rapid increase in WDPT values in the temperature range from 200°C to 250°C. From 250°C we recorded a decrease in WDPT and at a temperature of 350°C water repellency disappears. The soil remained wettable up to the investigated temperature of 900°C. Site IL2 was covered by a younger forest stand than IL1, which means a shorter accumulation time of litter and the associated lower increase in organic matter content. Induced and natural SWR is also lower than at site IL1. The obtained values of WDPT and T_{max} are in line with results from the study of Novak et al. (2009), who investigated the effect of heating on the persistence of SWR, saturated hydraulic conductivity and soil retention at forest and meadow localities of Borská nížina lowland. Dlapa et al. (2007) at the same locality observed a significant increase in persistence of SWR when the samples were heated for 20 minutes at 150 and 200°C. Water repellency disappeared after heating to 250, resp. 300°C in subsurface and topsoil horizons due to the decomposition of organic matter.

The measured value of $WDPT_n$ at the LL site was 146 s. The heating at 50°C caused an increase in WDPT to 2294 s. We did not measure significant WDPT changes up to heating temperature of 200°C. In the temperature range from 200°C to 350°C, we measured an increase in WDPT to a maximum value of 17796 s. At a temperature of 375°C, water repellency disappears and the soil is wettable up to the last examined temperature of 900°C. The low value of natural background SWR ($WDPT_n$) at LL site was caused by a different type of litter; however, the heating of soil at specific temperature was able to induce extreme SWR – comparable with SWR the site IL1 with the strong natural background SWR. This results are in line with the study of Arcenegui et al. (2007), who investigated the effect of burning temperature (200–500°C), vegetation type (*Rosmarinus officinalis*, *Pinus halepensis* and *Brachypodium retusum*) in two calcareous soils (regosol and luvisol), representing the forest areas of south-eastern Spain. They observed the maximum WDPT values after heating the samples to 300–350°C, while above this temperature the SWR was

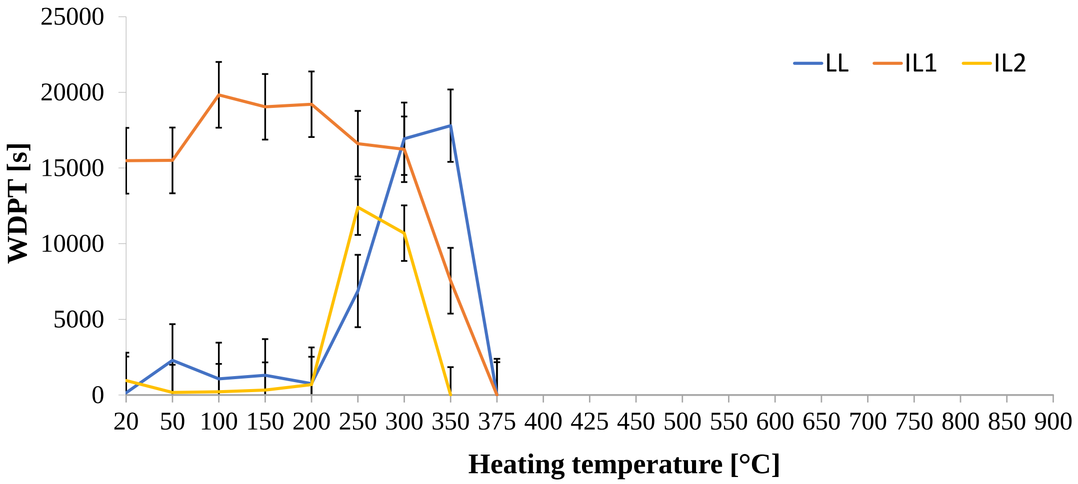

Fig. 4. Persistence of water repellency (as results of WDPT test); natural at 20°C and induced after heating to 50–900 at experimental sites: IL1 – 100-year-old coniferous forest, IL2 – 30-year-old coniferous forest, LL – 40-year-old deciduous forest (bars at each measuring point show the standard deviation).

eliminated. These results show that water repellency caused by combustion can be significantly influenced by environmental factors, such as vegetation type and the amount and properties of litter, and that soil type and its properties also play a crucial role.

Conclusion

Quantity and chemical composition of organic matter from vegetation cover and tree litter affect the natural background SWR. The highest values of natural SWR were measured at site with a 100-year-old Scots pine stand (IL1) and decreased in the order of IL2 (30-year-old Scots pine stand) >LL (40-year-old deciduous forest), which may be due to a longer accumulation of organic matter from coniferous litter and cover vegetation. The highest increase in induced SWR was determined at the LL site and decreased in the order of IL2>IL1, as well as the heating temperature that induced maximal SWR. SWR disappeared at heating temperatures 375, 350 and 400°C at sites LL, IL2 resp. IL1.

Our study did not confirm the positive relation between organic carbon content (C_{ox}) and the maximal value of SWR ($WDPT_{max}$), i.e. value of $WDPT_{max}$ did not increase in same order as value of C_{ox} at study sites. This relation can be applied only for the same vegetation type (IL1 and IL2) – i.e. SWR increases with increasing age and degree of succession only under the same vegetation type (in our study - the Scots pine stand). We found also that with increasing age (succession stage) of the forest stand the proportion of natural background SWR is raising.

The role of the origin of organic material (composition of litter) can be partially confirmed in the conditions of our experiment. The high organic carbon content at LL, which does not correlate with the age of the stand, may be attributed to the different composition of the litter and C:N ratio (needles vs. leaves). However, the highest C_{ox} at LL (compared to IL1 and IL2) did not induce the maximal value of SWR ($WDPT_{max}$), which we assume may be the influence of the different origin of the organic material. The proportion of natural/induced SWR at LL was similar to that at IL2 (parameters were not significantly different from each other), which can be attributed to the similar age of sites. Further research is needed to determine and qualitatively analyze the chemical composition of organic litter at experimental sites.

Acknowledgement

This contribution was supported by the Scientific Grant Agency VEGA Project No. 2/0150/20 „Impact of climate change on rainfall–runoff relationships“ and Project EIG JC2019-074 “Soil Eco-Technology to Recover Water Storage in disturbed Forests”.

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