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Fire-induced changes in soil properties depend on age and type of forests

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Abstract: Wildfires affect different physical, chemical, and hydraulic soil properties, and the magnitude of their effects varies depending on intrinsic soil properties and wildfire characteristics. The objectives of this study are: to estimate the impact of heating temperature (50–900°C) on the properties of sandy soil (Arenosol) taken in 1) coniferous forests (Scots pine *Pinus sylvestris*) of different ages (30 and 100 years); and 2) coniferous (Scots pine *Pinus sylvestris*) and deciduous (alder *Alnus glutinosa*) forests of the same age (30 years). The forests are located in the central part of the Borská nížina lowland (western Slovakia), and the properties treated were soil organic carbon content (SOC), pH, and soil water repellency (measured in terms of water drop penetration time, WDPT). It was found that the impact of heating temperature on the properties of sandy soil is great and depends on both the age and type of forest. The SOC value decreased unevenly with temperature in all three soils, and it was higher in the 30-year-old deciduous forest soil than in the 30-year-old coniferous forest soil. The value of pH increased monotonously with temperature from 200 °C, and it was higher in 30-year-old coniferous forest soil than in the 100-year-old coniferous forest soil. SOC and WDPT in the 100-year-old coniferous forest soil were higher than SOC and WDPT in the 30-year-old coniferous forest soil. Results obtained (decrease in SOC, disappearance of SWR after heating to 400 °C, and increase in pH from heating temperature 200 °C) bring important information for post-fire vegetation restoration and post-fire management of Central European forests established on sandy soil.

Keywords: Sandy soil; Soil water repellency; Soil heating; Soil organic carbon; pH; Water drop penetration time.

Abbreviations: SOC = soil organic carbon; SWR = soil water repellency; WDPT = water drop penetration time; HA = humic acids; FA = fulvic acids; RIm = modified repellency index; IL30 = 30-year-old pine forest; IL100 = 100-year-old coniferous forest; LL = approx. 30-year-old deciduous tree stand; HSD test = honest significant difference test;

INTRODUCTION

Roughly 3% of the Earth's land surface burns annually, with subsequent profound impacts on the Earth system (Archibald et al., 2018). Depending on its severity, wildfire can remove some or all vegetation and litter cover, thereby altering key variables in the hydrological cycle (Shakesby and Doerr, 2006). Fire-induced soil surface temperatures may reach 845 °C, but the temperature gradient is steep and temperatures decrease rapidly with depth because dry soil is a poor conductor of heat. At 50 mm depth, the temperature is not likely to exceed 150 °C except with long heating times that occur during smoldering fires (Robichaud and Hungerford, 2000). Wildfires affect different physical, chemical, and hydraulic soil properties, and the magnitude of their effects varies depending on intrinsic soil properties and wildfire characteristics (Martínez et al., 2022).

During burning, plant cover and litter layers are consumed, and the mineral soil is heated, resulting in changes to soil bulk density, porosity, texture, colour, pH, organic carbon content, water content, soil water repellency (SWR), and permeability. Physical property trends did depend on initial burn severity, whereas hydraulic property trends did not, according to Ebel et al. (2022).

González-Pérez et al. (2004) reviewed the effect of forest fires on the most stable pool of soil C; i.e., that having a large residence time, composed of free lipids, colloidal fractions, including humic acids (HA) and fulvic acids (FA), and other resilient forms. The main transformations exerted by fire on soil humus include the accumulation of new particulate C forms highly resistant to oxidation and biological degradation, including the so-called "black carbon".

The heat produced by the combustion of the litter layer on the soil surface vaporizes organic substances, which are then moved downward in the soil along the steep temperature gradients until they reach the cooler underlying soil layers, where they condense. The final result is a water-repellent layer underneath the burnt area that runs parallel to the soil surface (DeBano, 2000). At typical wildfire soil profile temperatures and when the soil was dry, SWR occurred at shallow depths (<20 mm). With wet soils, i.e., conditions that commonly occur during a prescribed fire, SWR was less pronounced and occurred deeper in the soil profile (Robichaud and Hungerford, 2000).

SWR is one of the soil's properties most affected by fire (Arcenegui et al., 2007). It has significant repercussions on plant growth (Doerr et al., 2000), reduces evaporation (Rye and Smettem, 2017), retards infiltration, thereby enhancing overland flow/surface runoff and erosion (Ebel, 2020; Müller et al., 2018). SWR characteristics are influenced by soil water content (Leelamanie and Nishiwaki, 2019), soil water retention (Czachor et al., 2020), soil texture (Benito et al., 2019), soil pH (Diehl et al., 2010), SOC content and structure of humic substances (Mielnik et al., 2021), and clay (mainly kaolinite) content (Lichner et al., 2006). SWR is temporally and spatially

variable (Täumer et at., 2006) and varies with depth (Sepehrnia et al., 2017; Turski et al., 2022). SWR can be reduced or eliminated after prolonged and/or heavy precipitation (Doerr et al., 2000). It can also be reduced by the use of surfactants (Kostka, 2000), inoculation with wax-degrading bacteria (Roper, 2006), and the addition of clay (mainly kaolinite) to topsoil (Lichner et al., 2006; McKissock et al., 2002).

Vegetation and its burning can induce, increase, reduce or destroy SWR. Arcenegui et al. (2007) estimated the impact of heating temperature (200–500 °C), vegetation type (pine tree *Pinus halepensis*, shrub *Rosmarinus officinalis*, and grass *Brachypodium retusum*), the quantity of vegetation litter (control, low and high) and type of calcareous soil (Regosol and Luvisol) to SWR. They found that the order of increasing SWR was *Brachypodium* < *Pinus* < *Rosmarinus*, and larger amounts of litter induced greater SWR. Most of the maximum values of SWR classified as severe (901–3600 s) were found in the range of 300–350 °C, whereas SWR disappeared beyond this temperature.

Novák et al. (2009) estimated the impact of heating temperature (20–300 °C) on the hydrophysical (SWR, water retention, and saturated hydraulic conductivity) properties of sandy soil sampled under 30-year-old Scots pine trees (*Pinus sylvestris*) and grasses (*Festuca rupicola*, *F. vaginata*, *Carex supina*, *Potentilla arenaria*, *Rumex acetosella*, *Armeria maritima*, *Eryngium campestre*, *Euphorbia cyparissias*, *Veronica dillenii*, and *Teucrium chamaedrys*). SWR initially decreased with temperature (20–50 °C), followed by its increase (50–150 °C) and drop (150–250 °C). The impact of heating temperature on the saturated hydraulic conductivity of soil was small. It was found for both the drying and wetting branches of soil water retention curves that an increase in soil water repellency resulted in a drop in soil water content at the same matric potential.

Martínez et al. (2022) estimated the impact of heating temperature (300, 500, 700, and 900 °C for two hours) on the saturated and unsaturated hydraulic conductivity, pH, electrical conductivity, wet aggregate stability, soil water repellency measured in the terms of modified repellency index, RIm, and soil organic matter content were measured in six laboratory heated soils with loam, sandy loam, and sandy clay loam texture. The results showed that wet aggregate stability exhibited a U-shaped trend, opposite to pH and electrical conductivity. The saturated and unsaturated hydraulic conductivity (negative tension of −3 cm) tended to increase with temperature, reaching a maximum of 1.27×10^{-4} m/s and 5.62×10^{-5} m/s at 900 °C, respectively. RIm was highly dependent on texture; loam soils had an average minimum and maximum of 1.84 and 2.73 at 900 and 300 °C, respectively, while sandy loam soils had an average minimum and maximum of 1.29 and 2.08 at 300 and 900 °C, respectively. Finally, the parameters that provided laboratory variation and a temperature range consistent with the results observed in naturally heated soils were wet aggregate stability, RIm, pH, and electrical conductivity.

Motivation for our study was the increased wildfire activity, number of fires, area burned, and fire severity, in many areas of the world in recent decades (Abatzoglou et al., 2013; Holos et al., 2021; Reilly et al., 2017). 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). The study area is during the summer period repeatedly threatened by an increased risk of fire, declared by the District Headquarters of the Rescue and Fire Brigade, due to high tourist traffic and flammable pine monocultures. Research about soil hydrology after a wildfire is essential to enable the appropriate postfire management strategies.

Experimental sites were selected to include relatively high natural background SWR (sandy soils of Borská nížina lowland), different age and type of forest vegetation with the relatively same site conditions (climate, soil and relief conditions). The influence of plant age and forests type on soil hydrology and its driving parameters have been less explored, particularly in the ecosystems of the central European forests. Thus, the objectives of this study are to estimate the impact of heating temperature on the properties of 1) sandy soil taken in coniferous forests (Scots pine *Pinus sylvestris*) of different ages (30 and 100 years), and 2) soil taken in coniferous (Scots pine *Pinus sylvestris*) and deciduous (alder *Alnus glutinosa*) forests of the same age (30 years).

MATERIAL AND METHODS

Site description

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 (Ditzler et al., 2017). According to the Köppen-Geiger climate classification, the region has a temperate climate without a dry season and warm summer (Cfb) (Kottek et al., 2006). 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).

Experimental sites were selected to include different stand ages and types of litter (organic surface horizon) under relatively equal conditions (climate, soil, and relief). Within the group of forest stands, three research sites were set aside: a 30-year-old (IL30) and a 100-year-old coniferous tree stand (IL100) and approx. 30-year-old deciduous tree stand (LL) (Fig. 1). The LL research site represents a younger (about 30 years) stand of alder (*Alnus glutinosa*) in an indistinct terrain depression situated under a 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 IL30 site represents 30-year-old Scots pine (*Pinus sylvestris*) stand. 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 IL100 site is a stand older than 100 years; its purpose is to stabilize the dune. The herbaceous undergrowth is dominated by grass, especially sheep fescue (*Festuca ovina* agg), and often covered with bush grass (*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 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 and heating experiment

The mineral part of the soil (ca. 6 kg) from the area 200 cm × 200 cm and 2.5 cm depth was sampled into the prepared plastic containers (60 cm × 40 cm × 22 cm) after the organic horizon (0–2.5 cm) was gently removed from the soil surface.

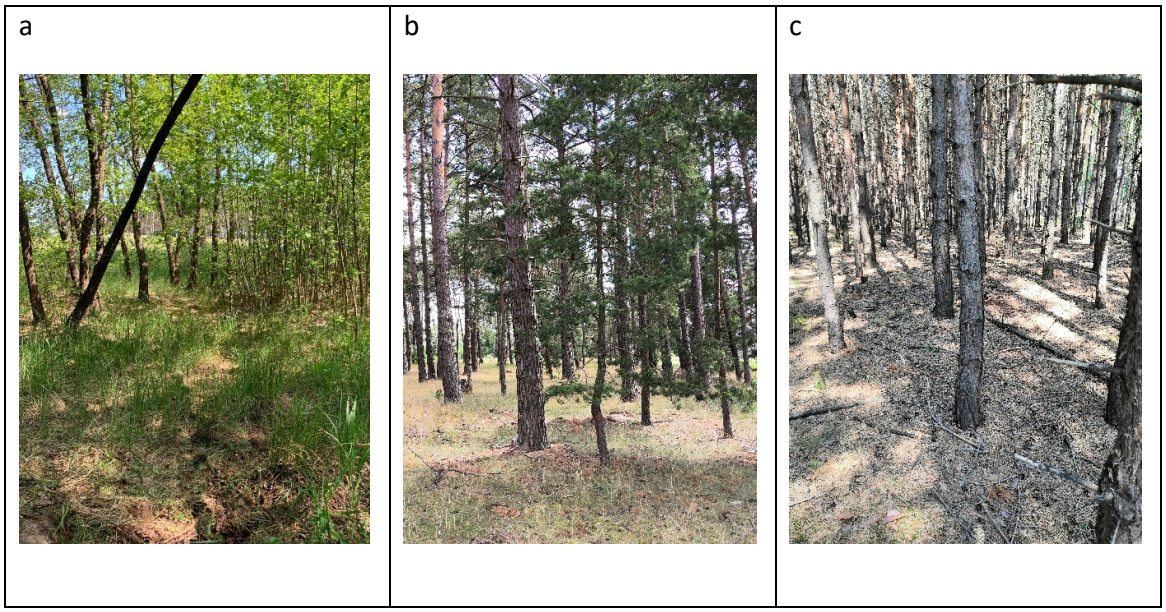


Fig. 1. Research sites: a) LL – approx. 30-year-old deciduous tree stand; b) IL100 – over 100-year-old Scots pine (*Pinus sylvestris* L.) plantation; c) IL30 – 30-year-old Scots pine plantation.

After returning to the laboratory, the soil mineral material was sieved through a 2 mm sieve, homogenized and dried at 40 °C. After reaching equilibrium, the mineral soil material was weighed into ceramic dishes. We weighed five 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 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 (one sample was used for one temperature only). Once the samples were removed from the muffle, they were cooled down to room temperature.

Measurement of soil properties

Basic soil properties were determined on disturbed samples in the ISO Certified Laboratory of the Soil Science and Protection Research Institute in Bratislava. Particle size distribution was determined by sieving and sedimentation according to ISO 11277 (2009), pH(KCl) and pH(H_2O) were measured according to ISO 10390 (2005), SOC content was determined by oxidation with $K_2Cr_2O_7$-H_2SO_4 and titration of non-reduced dichromate according to ISO 10694 (1995), and carbonate content was determined from the volume of CO_2, produced during the decomposition of carbonates with about 10% hydrochloric acid, according to ISO 10693 (1995).

The water drop penetration time (WDPT) test assessed the persistence of SWR. 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. An average 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). The following classes of the persistence of SWR were then distinguished: wettable or non-water-repellent soil (WDPT < 5 s), slightly (WDPT = 5–60 s), strongly (WDPT = 60–600 s), severely (WDPT = 600–3600 s), and extremely (WDPT > 3600 s) water repellent soil (Bisdom et al., 1993).

Statistical analysis

After the analysed groups of data have passed the skewness normality test, differences between the three group means were evaluated using Tukey's Honest Significant Difference (HSD) posthoc test. The Tukey-Kramer method (also known as Tukey's HSD) 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 – α)) if the group sample sizes are equal and is conservative if the sample sizes are unequal. The statistical significance of the analysis was defined at $P < 0.05$.

Differences between the two group means estimated in different sites were evaluated using Welch's t-test. The unequal variances t-test is a two-sample location test used to test the hypothesis that two populations have equal means. It is named for its creator, Bernard Lewis Welch, and is an adaptation of the Student's t-test and is more reliable when the two samples have unequal variances and/or unequal sample sizes. These tests are often referred to as unpaired t-tests, as they are typically applied when the statistical units underlying the two samples being compared are non-overlapping.

Welch's t-test defines the statistic t by the following equation:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}$$

where $\bar{X}$, s, and N are the sample mean, sample variance, and sample size, respectively.

All statistical analyses were performed through the use of statistical software NCSS (NCSS 12 Statistical Software, 2018).

RESULTS AND DISCUSSION

Soil sampling results

Basic soil-physical and chemical properties of the sampled soils are presented in Table 1. The sand/silt/clay content in the soil samples does not differ much, and they all have a sandy texture (Soil Science Division Staff, 2017). SOC in deciduous forest soil is low and significantly different from SOC in both coniferous forest soils (very low SOC). pH in all three soils is extremely acidic, and the means are significantly different from each other.

Impact of heating on soil properties

The effect of the laboratory heating on SOC, pH, and WDPT in 270 samples of 3 different soils is shown in Figures 2–4. Part A in each Figure shows the parameter's absolute value at each temperature for every soil. Part B in each Figure shows the density plot, i.e., the smoothed distribution of the values along the numeric axis (the peaks of the density plot are at the locations with the highest concentration of points). Part C in each Figure shows means, standard deviations and ranges of the variability of parameters, as well as the statistical significance of the difference in mean for different soils.

For all heating temperatures, SOC was in the order IL30 < IL100 < LL. SOC decreased unevenly with temperature in all three soils (Fig. 2), and the mean SOC in the deciduous forest soil was significantly different from the mean SOC in the soils of coniferous forests. SOC decrease with temperature was registered by Certini et al. (2011), Garcia-Corona et al. (2004), and Martínez et al. (2022). Badía et al. (2017) found that burning depleted 50% of the SOC content in the air-dried soil and 25% in the wet soil at the upper centimetre.

For the heating temperatures from 50 °C to 400 °C, pH was in the order LL < IL100 < IL30, and for the temperatures from 400 °C to 800 °C, pH was in the order IL100 < LL < IL30. pH increased monotonously with temperature from 200 °C to 700 °C in the soil of the 30-year-old coniferous forest, to 800 °C in the soil of the 100-year-old coniferous forest, and to 900 °C in the soil of the 30-year-old deciduous forest, and the mean pH in the soils was not significantly different (Fig. 3). Martínez et al. (2022) presented that most soils showed an initial increase in pH between 300 °C and 500 °C and a subsequent decrease between 700 °C and 900 °C, which is in agreement with our results.

Table 1. Physical and chemical properties of the top (0–2.5 cm) soils were taken from the experimental sites IL100, IL30, and LL near Studienka. Chemical properties were measured in duplicate and results in the form of arithmetic mean ± standard deviation are presented here. Arithmetic means with the same letter are not significantly different from each other (Tukey's HSD test, $P < 0.05$). (SOC – soil organic carbon content).

Site	Sand (%)	Silt (%)	Clay (%)	SOC (%)	$CaCO_3$ (%)	pH (H_2O)	pH (KCl)
IL100	91.82±0.03	5.81±0.12	2.37±0.09	0.64^{a}±0.13	<0.05	4.96^{a} ±0.01	3.99^{a} ±0.01
	texture class: sand			very low		extremely acidic	
IL30	92.31±0.02	4.96±0.07	2.72±0.03	0.55^{a}±0.08	<0.05	5.33^{b} ±0.01	4.39^{b} ±0.01
	texture class: sand			very low		extremely acidic	
LL	92.96±0.48	3.36±0.33	3.68±0.12	1.43^{b}±0.37	<0.05	4.20^{c} ±0.01	3.65^{c} ±0.01
	texture class: sand			low		extremely acidic	

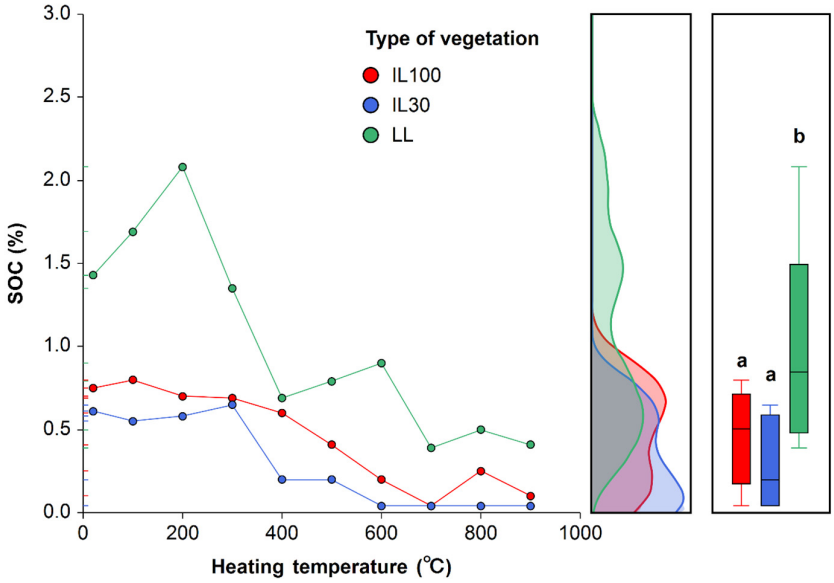


Fig. 2. The effect of laboratory heating on soil organic carbon (SOC) content (scatter plot). The density plot shows the smoothed distribution of the SOC values along the numeric axis (the peaks of the density plot are at the locations with the highest concentration of points). Box plots denoted with different letters are significantly different on significance level 0.05 (the whiskers boundaries are determined according to the inter-quartile range).

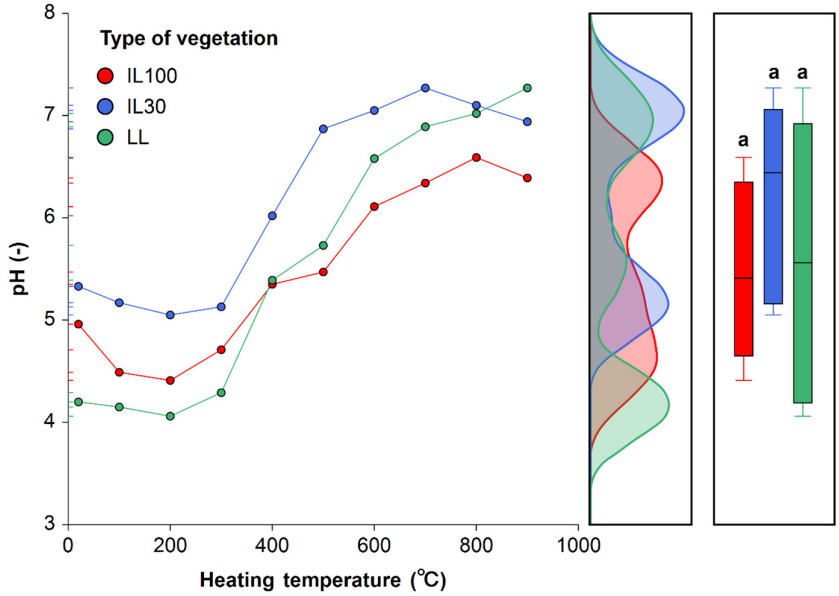


Fig. 3. The effect of laboratory heating on soil pH. The density plot shows the smoothed distribution of the pH values along the numeric axis (the peaks of the density plot are at the locations with the highest concentration of points). Box plots denoted with different letters are significantly different on significance level 0.05 (the whiskers boundaries are determined according to the inter-quartile range).

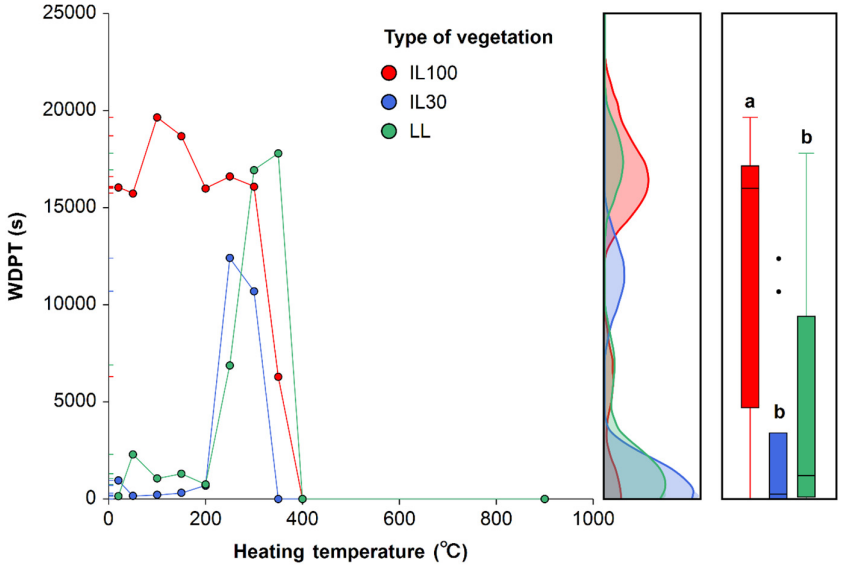


Fig. 4. The effect of laboratory heating on the water drop penetration time (WDPT) of the soils. The density plot shows the smoothed distribution of the WDPT values along the numeric axis (the peaks of the density plot are at the locations with the highest concentration of points). Box plots denoted with different letters are significantly different on significance level 0.05 (the whiskers boundaries are determined according to the inter-quartile range, and black points outside the whisker boundaries are considered outliers).

Terefe et al. (2008) explained a substantial increase in the pH when soils are exposed to heating over 200 °C, by the complete oxidation of the organic matter, which releases a substantial number of cations or due to the loss of organic acids.

The influence of the heating temperature on the change in soil pH is great. A lower pH of the examined soils with a comparatively high organic carbon content indicates a poorer quality of organic matter with a high concentration of fulvic acids. When the soil is heated to around 300 °C, decarboxylation of humic and fulvic acids occurs, which reduces the acidic character of soil organic matter (Schnitzer and Hoffman, 1964). At higher temperatures, complete combustion of soil organic matter occurs, releasing oxides of alkaline metals and alkaline earth metals, which exhibit a strongly alkaline reaction when in contact with the aqueous environment (Gray and Dighton, 2006; Úbeda et al., 2009). We assume that the presence of alkaline cations in sandy soils is relatively small, and therefore, the pH after burning the sample did not exceed 7.5.

The effect of laboratory heating on WDPT of the studied soils is shown in Fig. 4. The persistence of SWR of the soil from a 100-year-old coniferous forest was extreme even in the unheated state (mean value of WDPT = 16040 s) and after heating to a temperature of 50–350 °C. WDPT decreased unevenly with temperature for temperatures greater than 100 °C and disappeared at 400 °C. The persistence of SWR of the soil from a 30-year-old coniferous forest was severe (mean value of WDPT = 958 s) in the unheated state, strong for the temperature of 50–150 °C, severe for 200 °C, extreme for temperatures of 250–300 °C, and it disappeared at 350 °C. The persistence of SWR of the soil from a 30-year-old deciduous forest was strong (mean value of WDPT = 146 s) in the unheated state, severe for temperatures of 50–200 °C, extreme for temperatures of 250–350 °C and it disappeared at 375 °C. Martínez et al. (2022) state that fires at 100 and 200 °C do not considerably affect repellency and SOC was not fulfilled because significant changes in WDPT with temperatures between 20 and 200 °C were registered in all three soils. It should be mentioned that deadwood can increase the persistence of SWR (measured in terms of WDPT) depending on the species and rate of decomposition (Blonska et al., 2018).

Garcia-Corona et al. (2004) found that WDPT increased for temperatures of 25–220 °C and disappeared at 380 °C in Leptic Regosols and Leptic Umbrisols with *Pinus pinaster* cover. Doerr et al. (2004) quantified the temperature of SWR destruction for Australian topsoil material sampled under three sites with contrasting eucalypt cover (Site 1: sandy soil + *Eucalyptus sieberi*, extreme SWR; Site 2: sandy soil + *E. ovata*, strong SWR; and Site 3: sandy loam soil + *E. baxteri*, strong SWR). Strong to extreme SWR was present prior to heating in all samples, increased during heating, and was abruptly eliminated at a specific temperature between 260 and 340 °C.

Badía et al. (2017) found that burning decreased significantly the persistence of SWR (measured in terms of WDPT) at the first, second, and third centimetre of the Ah horizon. The main changes were found in the first centimetre (with a maximum temperature of 427 °C), where the severe SWR in air-dried unburned soil (WDPT = 923 s) disappeared after burning. The severe repellency of the second (with a maximum temperature of 235 °C) and third centimetre (with a maximum temperature of 131 °C) decreased to strong repellency.

The maximum SOC was measured at 100 °C in the soil of a 100-year-old coniferous forest, at 200 °C in the soil of a 30-year-old deciduous forest, at 300 °C in the soil of a 30-year-old coniferous forest, and then, SOC decreased with an increase in temperature. Maximum WDPT was measured at 100 °C in the soil of a 100-year-old coniferous forest, at 250 °C in a 30-year-old coniferous forest, and at 350 °C in the soil of a 30-year-old deciduous forest. It is in agreement with the findings of McKissock et al. (1998) that SWR (measured in terms of water drop penetration time, WDPT) is positively related to SOC in the soil from the given site.

Impact of forest age on heating effects

Pine forest age significantly influenced the effects of heating on the properties of sandy soil. Both SOC and WDPT in the soil from the 100-year-old coniferous forest were higher than those from the 30-year-old coniferous forest for all temperatures. On the other hand, pH in the soil of the 30-year-old coniferous forest was higher than soil pH in the soil of the 100-year-old coniferous forest for all temperatures. It could result from the different components of soil organic matter in younger (30-year-old) forests compared to that in older (100-year-old) forests.

Statistical characteristics of soil properties (namely organic carbon content SOC (%), pH (–), and water drop penetration time, WDPT (s)) measured in the soil samples from the 30-year-old (IL30) and 100-year-old coniferous forest (IL100) before and after heating in a muffle furnace are presented in Table 2. Arithmetic means of pH and WDPT estimated in a 100-year-old deciduous forest were significantly different from those estimated in the soil of a 30-year-old deciduous forest. Arithmetic means of SOC were not significantly different.

It should be mentioned that the decisive influence on SOC in the forest soil has the annual fallout deposited on the soil's surface in the form of forest litter and the root system, which ensures the renewal of finer roots. Beneath the conifer forest, under conditions of biological activity, an acidic layer of organic matter is formed, the transformation of which is mainly carried out by acidophilic micromycetes. In the older forest with a longer-term undisturbed process of accumulation and conversion of organic waste, the SOC content is higher (Tobiašová et al., 2016).

Impact of forest type on heating effects

SOC in the 30-year-old deciduous forest was higher than SOC in the 30-year-old coniferous forest. Soil pH in the 30-year-old coniferous forest was higher than soil pH in the 30-year-old deciduous forest for all but one (maximum = 900 °C) temperature. WDPT in the 30-year-old deciduous forest was higher than soil pH in the 30-year-old coniferous forest for all but two (20 and 250 °C) temperatures.

Statistical characteristics of soil properties (namely organic carbon content SOC (%), pH (–), and water drop penetration time, WDPT (s)) of the soil samples from the 30-year-old deciduous forest (LL), and 30-year-old coniferous forest (IL30) before and after heating in a muffle furnace are presented in Table 3. The arithmetic mean of SOC estimated in the soil of the 30-year-old coniferous forest was significantly different from the ones from the 30-year-old deciduous forest. Arithmetic means of pH and WDPT were not significantly different among different types and ages of the forests.

Table 2. Statistical characteristics of soil properties (namely organic carbon content SOC (%), pH (–), and water drop penetration time, WDPT (s)) estimated in soil samples from the sites IL100 and IL30 before and after heating in a muffle furnace. Arithmetic means with the same letter are not significantly different (unequal variances t-test at $\alpha = 0.05$). (N = number of replicates).

Site	Attribute	Minimum	Maximum	Arithmetic mean	Standard deviation	N
IL100	SOC (%)	0.040	0.793	0.458[a]	0.268	22
	pH(H_2O) (–)	4.4	6.59	5.48[a]	0.809	20
	WDPT (s)	0	27300	6547[a]	8700	95
IL30	SOC (%)	0.040	0.672	0.303[a]	0.247	22
	pH(H_2O) (–)	5.04	7.28	6.19 [b]	0.918	20
	WDPT (s)	0	21420	1340[b]	4312	95

Table 3. Statistical characteristics of soil properties (namely organic carbon content SOC (%), pH (–), and water drop penetration time, WDPT (s)) of the soil samples from the 30-year-old deciduous forest (LL) and 30-year-old coniferous forest (IL30) before and after heating in a muffle furnace. Arithmetic means with the same letter are not significantly different (unequal variances t-test at α = 0.05). (N = number of replicates).

	Attribute	Minimum	Maximum	Arithmetic mean	Standard deviation	N
LL	SOC (%)	0.392	2.170	1.053[a]	0.572	22
	pH(H_2O) (–)	4.05	7.28	5.55[a]	1.283	20
	WDPT (s)	0	22440	2482[a]	5491	95
IL30	SOC (%)	0.040	0.672	0.303[b]	0.247	22
	pH(H_2O) (–)	5.04	7.28	6.19[a]	0.918	20
	WDPT (s)	0	21420	1340[a]	4312	95

CONCLUSIONS

This study has shown that initial value of SOC was highest in the deciduous forest, lowest in young pine forest and decreased unevenly with temperature in all three studied forest soils in the order IL30 < IL100 < LL. There was significant decrease in SOC after heating to 400 °C in all 3 forest soils.

The SWR completely disappeared after heating to 400 °C in all forest soils. The highest values of WDPT were measured in the IL100 soil for the heating temperatures from 50 °C to 250 °C and LL soil for the heating temperatures from 300 °C to 350 °C, which was in line with fact that higher SOC is characterised by higher SWR.

The pH values increased monotonously with temperatures from 200 °C in all 3 forest soils; pH was in the order LL < IL100 < IL30 for the heating temperatures from 50 °C to 400 °C, and in the order IL100 < LL < IL30 for the temperatures from 400 °C to 800 °C.

It can be concluded that the impact of heating temperature (50–900°C) on the properties (namely SOC, pH and WDPT) of sandy soil is great and depends on both the age and type of forest vegetation. Results obtained (decrease in SOC, disappearance of SWR after heating to 400 °C, and increase in pH from heating temperature 200 °C) bring important information for post-fire vegetation restoration and post-fire management of Central European forests established on sandy soil.

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