



Heating affects properties of forest soils with different texture: 1. Physical and chemical properties

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Abstract: Wildland fires affect physical and chemical properties of forest soils, and the magnitude of their effects depends on the soil temperature achieved during a fire. Laboratory heating of soil samples in muffle furnace was used to simulate a natural fire heating of forest soils, although it does not completely reproduce natural fire conditions. The effect of heating temperature of 100–900°C on particle size distribution, soil water repellency (SWR), soil organic carbon content (SOC) and pH was estimated in three soils differing in texture (sandy soil, silty-clay soil, and clay soil) sampled in coniferous and deciduous forests at Gbely (Areni-Gleyic Umbrisol), Hviezdoslavov (Fluvisol) and Gabčíkovo (Fluvisol), respectively. Decrease in the clay content and increase in the sand content was large in silty-clay and clay soils, but not as large in sandy soils. Surprisingly, heating the soil to 100°C, commonly used in soil moisture measurement, caused a decrease in clay content by half (the average value for all soils). This finding should be confirmed by further measurements on the soils from other regions, because the degree of aggregation depends also on the type of clay and other minerals. The persistence of SWR gradually increased in the heating temperature range 100–300°C in all three soils from coniferous forests and sandy soil from deciduous forest, and was absent in the remaining two soils. The SOC decreased and pH increased with increasing heating temperature.

Keywords: Heating; Temperature; Particle size distribution; Soil water repellency; Soil organic carbon; pH.

1 INTRODUCTION

Wildland fires are considered among the most dangerous natural disasters to human societies, and their probability and severity are increasing as a consequence of global climate change (Doerr and Santin, 2016). The most serious hydrological consequences of wildfires include surface runoff and soil erosion, which depend on plant species covering the soil (Cerdeja et al., 2021), as well as water pollution with ash and debris from fire (Santín et al., 2015). Wildfires also affect basic soil properties, and the magnitude of their effects depends on wildfire characteristics. Basic soil properties include particle size distribution, initial water content, chemical properties, water repellency, wet aggregate stability, and soil organic carbon content (SOC), while the main wildfire properties are temperature and duration (Martínez et al., 2022). The best-known metric for estimating the degree of soil heating and its consequences is the soil temperature achieved during a fire. Some temperature thresholds and ranges associated with various fire effects on soil properties are 40–160°C (notable biological damage, i.e., plant tissue, seed, bacteria and fungi death), 60–100°C (water loss), 350–450°C (organic matter charring), and 400–900°C (decomposition of clay minerals) (Massman et al., 2010; Sun et al., 2016). The thresholds presented by Doerr et al. (2025) are 60°C (notable biological damage), 100°C (vaporisation of soil water) and 300°C (organic matter combustion becomes prevalent). Most fires heated only the uppermost centimetres of the soil, rarely exceeding 300°C below 0.5 cm depth (DeBano, 2000; Doerr et al., 2025) and 100°C below 5 cm depth (Badía et al., 2017), although more than 1500°C has been instantaneously recorded on the ground surface where high loads of heavy fuel are present (Badía-Villas et al., 2014). Laboratory heating of soil samples in muffle furnaces is often

used to simulate a natural fire heating. Heating (to more than 500°C) can produce a finer texture due to the kaolin fine sand decomposition into the silt-sized feldspar pseudomorphs, but also to a coarser texture due to the aggregation of clay particles into stable sand-sized particles (Ulery and Graham, 1993). Among the components of soil texture, clay is the most sensitive to temperature changes, when clay hydration and lattice structure start to collapse at soil temperatures of around 400°C, and the complete destruction of internal clay structure can occur at temperatures of 700 to 900°C (Al-Khayri and Khan, 2024). Soil water repellency (SWR) is one of the soil physical properties most affected by fire. Wildfire can induce, enhance, or destroy natural SWR depending mostly on soil burnt severity, soil and vegetation types, soil organic matter content and type, soil texture, peak soil temperature and remaining time and, antecedent soil moisture content (Hewelke et al., 2018; Martins et al., 2020, 2024). Different measuring methods may yield different results, e.g., heating in the lab to 50–900°C resulted in the higher contact angle (CA; the measure of SWR severity) in the birch forest soil in comparison with the pine forest soil for all the heating temperatures, but in the higher water drop penetration time (WDPT; the measure of SWR persistence) in the pine forest soil in comparison with the birch forest soil for all but three (200, 250, and 300°C) heating temperatures (Lichner et al., 2025). Badía-Villas et al. (2020) found that the SOC decrease in 0–1-cm depth of sandy-loam soil from 52.3 to 47.3 g/kg resulted in the WDPT decrease from 1335 s to 7.4 s and in the unsaturated hydraulic conductivity increase from 1.2 to 7.7 mm/h as a consequence of a shrubland prescribed burn. Hewelke et al. (2020) found that the severe fire and subsequent increase in the richness of the succession of non-forest species contributed to the elimination of SWR. Hološ et al. (2022) found that the fire-induced changes in soil

properties depend on age and type of forests. Temperatures $>300^{\circ}\text{C}$ or longer than 10 min heating duration at 300°C lead to elimination of water repellency (Atanassova and Doerr, 2010; Doerr et al., 2004). Fire and heat cause selective destruction of aliphatic domains in soil organic matter, accompanied by input of lipid compounds from necromass ($100\text{--}200^{\circ}\text{C}$), or production of specific hydrophobic compounds of aromatic nature during heating at greater temperatures (about 300°C) through input of lignin, carbohydrate, lipids and amino acids derived degradation products (Gonzalez-Perez, 2008). Changes in soil properties during heating are closely related to changes in organic carbon concentrations and composition in soil and are associated with the formation of fatty acid signature to members $< \text{C}_{20}$ and an increase of total content of aromatic compounds (in O_2 atmosphere) and benzaldehydes, unsaturated amides and organophosphate esters (in N_2 atmosphere). The temperatures most critical to carbon loss and alteration were found to be 250°C , where charring of organic matter starts and caused the carbon reduction of approximately 15%–20%, and 450°C where approximately 90% of the carbon is combusted (Badía-Villas et al., 2014). Jiménez-Morillo et al. (2020) found that fire leads to a depletion of organic matter in the whole soil and its coarse fraction, resulting from losses of volatile compounds. On the contrary, the concentration of organic matter in the fine soil fraction increased to some extent, at the expense of pyrogenic material from the combustion of the organic matter in coarser fractions. 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 of clay-loam soil. Šurda et al. (2023) found that a small (0.1–0.7%) SOC content was recorded even in soils heated to $600\text{--}900^{\circ}\text{C}$, due to the incomplete combustion of SOC. The increase in soil pH at $300\text{--}500^{\circ}\text{C}$ was attributed to the denaturation of organic acids and to the increase in Na and K oxides, carbonates and hydroxides (Francos et al., 2023), and the increase in soil pH at $500\text{--}900^{\circ}\text{C}$ to the decomposition of clay minerals (Aryanpour et al., 2023). The objective of this study was to estimate the effect of heating temperature on the selected properties (particle size distribution, WDPT, SOC, pH) of three soils with different texture (sandy soil, silty-clay soil, and clay soil) in coniferous and deciduous forests. We hypothesized that heating would lead to alterations in sand, silt and clay contents, WDPT, SOC, and pH, and these changes would differ between coniferous and deciduous forest soils.

2 MATERIALS AND METHODS

2.1 Research site description

To determine the effect of heating on the properties of soils with different textures, three locations (each with 2 sites) were selected in southwestern Slovakia (Fig. 1). The names of research sites were 1c, 1d, 2c, 2d, 3c, and 3d, where 1 means sandy soil, 2 silty-clay soil, 3 clay soil, c coniferous forest, and d deciduous forest. The first pair of research sites, 1c ($48^{\circ}42'52.0''\text{N}$, $17^{\circ}02'15.6''\text{E}$) and 1d ($48^{\circ}42'50.3''\text{N}$, $17^{\circ}02'13.2''\text{E}$), was located at Gbely in the Borská Lowland, and the distance between research sites is 300 meters. According to the Köppen-Geiger climate classification, the region has a temperate climate without dry season, warm summer (Cfb) (Kottek et al., 2006), with a mean annual temperature of 9°C and mean annual precipitation of 600 mm, mainly during summer. The second pair of research sites, 2c ($48^{\circ}04'56.3''\text{N}$, $17^{\circ}20'25.5''\text{E}$) and 2d ($48^{\circ}04'50.1''\text{N}$, $17^{\circ}20'19.4''\text{E}$), was located at Hviezdoslavov in the Danubian Lowland, and the distance between research sites is 500 meters. According to the Köppen-Geiger climate classification, the region has a temperate climate without dry season, warm summer

(Cfb) (Kottek et al., 2006), with a mean annual temperature of 11°C and mean annual precipitation of 600 mm, mainly during summer. The third pair of research sites, 3c ($47^{\circ}53'37.3''\text{N}$, $17^{\circ}36'18.5''\text{E}$) and 3d ($47^{\circ}53'30.4''\text{N}$, $17^{\circ}36'24.1''\text{E}$), was located at Gabčíkovo in the Danubian Lowland, and the distance between research sites is 300 meters. According to the Köppen-Geiger climate classification, the region has a temperate climate without dry season, warm summer (Cfb) (Kottek et al., 2006), with a mean annual temperature of 11°C and mean annual precipitation of 600 mm, mainly during summer.



Fig. 1. Location of the research sites 1c, 1d (Gbely, Borská Lowland), 2c, 2d (Hviezdoslavov, Danubian Lowland), 3c and 3d (Gabčíkovo, Danubian Lowland) in southwestern Slovakia.

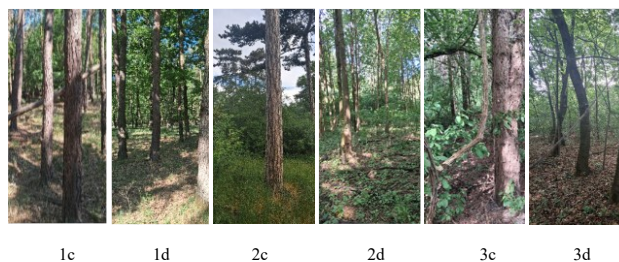


Fig. 2. Images of the research site 1c – sandy soil under coniferous forest (b); research site 1d – sandy soil under deciduous forest (c); research site 2c – silty-clay soil under coniferous forest (d); research site 2d – silty-clay soil under deciduous forest (e); research site 3c – clay soil under coniferous forest (f); and research site 3d – silty-clay soil under deciduous forest (g).

2.2 Vegetation and ecological site description

The sampling sites in Gbely are located in a forest complex situated on the old Morava River terrace. The area was extensively drained in the 1960s and now represents a mosaic of remnants of original deciduous forest dominated by pedunculate oak (*Quercus robur*) and Scots pine (*Pinus sylvestris*) plantations. The soil is classified as Areni-Gleyic Umbrisol.

2.2.1 Site 1c (coniferous forest)

A Scots pine (*Pinus sylvestris*) monoculture established on the site of subcontinental thermophilous oak forest described below as site 1d. As a result of secondary regression succession, species composition is similar, but it is poorer in species and herb layer cover.

2.2.2 Site 1d (deciduous forest)

A species-rich pedunculate oak (*Quercus robur*) stand representing subcontinental thermophilous oak forest on sandy, intermittently waterlogged soils. Species composition is rich in species and indicates long forest continuity. The sampling sites in

Hviezdoslavov are located in small forest complex established in the period after 1950s. The soil is Fluvisol.

2.2.3 Site 2c (coniferous forest)

A sparse, approximately 60–70-year-old monoculture stand of Austrian pine (*Pinus nigra*). Due to the high light availability caused by the open canopy of the tree layer, the shrub layer is very dense. In this part of the stand, the herb layer is dominated mainly by nitrophilous shadow-tolerant species. In places, however, there are also shrub-free patches with grass-herb vegetation.

2.2.4 Site 2d (deciduous forest)

A young, approximately 30–40-year-old homogeneous plantation dominated by Norway maple (*Acer platanoides*), located in the immediate vicinity of site 1. Due to the dense canopy cover, the shrub and herb layers are only weakly developed and are poor in species. The sampling sites in Gabčíkovo are situated in the former Danube River inundation. The soil is Fluvisol.

2.2.5 Site 3c (coniferous forest)

A homogeneous, approximately 40-year-old monoculture stand of Austrian pine (*Pinus nigra*). Species composition is poor in species and partially resembles hardwood floodplain forest.

2.2.6 Site 3d (deciduous forest)

A young, approximately 20–30-year-old plantation dominated by sycamore maple (*Acer pseudoplatanus*), planted in a regular spacing pattern. Species composition correspond with that described in site 3d. It includes species indicating hardwood floodplain forests and ecological generalists. Images of all the research sites are presented in Fig. 2.

2.3 Laboratory heating and measurement of soil properties

Soil samples were collected from the surface layer (0–2.5 cm) of soils at the research sites 1c, 1d, 2c, 2d, 3c, and 3d, air-dried at 20°C to equilibrium weight and passed through a 2-mm sieve. The 220 mL porcelain incinerating dishes were filled with the 60-g samples of sieved soil and placed in a preheated muffle furnace and heated at temperatures of 100, 200, 300, 400, 500, 600, 700, 800, and 900°C for 20 minutes. After removal from the furnace, they were left to equilibrate at 20°C and subjected to the measurement of soil properties.

It should be noted that the laboratory heating in a muffle furnace is useful and controlled, but it does not completely reproduce natural fire conditions, where heating duration, oxygen availability, soil moisture, heat transfer and fuel load vary strongly. As a result, the transferability of the results taken in the laboratory to field conditions is problematic.

Basic soil properties were determined on unheated and heated samples in the ISO-Certified Laboratory of the Soil Science and Protection Research Institute in Bratislava. Particle size distribution (sand/silt/clay contents) was determined by sieving and sedimentation according to ISO 11277 (2009). Soil texture class was determined using the World Reference Base for Soil Resources (WRB, 2015).

The persistence of SWR was assessed by the WDPT test. It involved placing a 50±5 µL water drop from a medicine dropper from the height of 10 mm on the soil surface and recording the time of its complete penetration (Doerr, 1998). WDPT determines how long water repellency persists in the contact area of a water droplet (Doerr et al., 2000), and the following classes of

the persistence of SWR were 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 (Bisdorn et al., 1993). The SOC was determined by the Walkley–Black titration method based on the oxidation of organic matter by potassium dichromate (K₂Cr₂O₇)-sulfuric acid mixture followed by back titration of the excessive dichromate by ferrous ammonium sulfate (Fe(NH₄)₂(SO₄)₂×6H₂O). The pH of soil was determined by suspending a sieved soil sample in deionized water at a 1:2.5 soil-to-water ratio and using a pH meter to measure the pH of suspension according to ISO 10390 (2005). The sand, silt and clay contents were measured with 1 replicate for each study site and temperature. SOC and pH were measured with 2 replicates for each study site and temperature. The WDPT was measured with 3 replicates for each study site and temperature. The values of sand, silt and clay contents, soil texture, and the average values of SOC and pH of unheated soils, collected from the surface layer (0–2.5 cm) of soils at research sites 1c, 1d, 2c, 2d, 3c and 3d, are presented in Table 1. The values of sand, silt and clay contents, and the average values of WDPT, SOC, and pH of unheated and heated soils, collected from the surface layer (0–2.5 cm) of soils at research sites 1c, 1d, 2c, 2d, 3c and 3d, are presented in Tables S1–S6.

Table 1. The average values of sand, silt and clay contents, soil organic carbon content (SOC), pH, and soil texture of unheated soils, collected from the surface layer (0–2.5 cm) of soils at research sites 1c, 1d, 2c, 2d, 3c and 3d, where 1 means sandy soil, 2 silty-clay soil, 3 clay soil, c coniferous forest, and d deciduous forest.

Measured quantity	Research site					
	1c	1d	2c	2d	3c	3d
Sand (%)	88.14	82.44	38.18	34.34	26.81	27.14
Silt (%)	4.98	9.48	29.41	33.38	25.28	25.84
Clay (%)	6.87	8.07	32.41	32.29	47.90	48.62
Soil texture	Sand	Sand	Silty clay	Silty clay	Clay	Clay
SOC (%)	2.45	1.60	7.89	7.20	10.00	7.83
CaCO ₃ (%)	0.1	0.05	0.1	1.9	21.0	20.0
pH	3.89	4.23	5.21	7.58	7.88	7.55

3 RESULTS

Heating 6 studied soils to temperatures of 100–900°C for 20 minutes led to changes in their properties compared to unheated soils, as it is shown in Tables S1–S6. Particle-size shift was registered in all the soils after heating. Surprisingly, heating the soil to 100°C, commonly used in soil moisture measurement, caused a decrease in clay content by half (the average value for all soils). Moreover, drying the soil in an oven at 105°C when measuring soil moisture takes at least 24 hours, and heating in our case took only 20 minutes. The sand content of silty-clay and clay soils remained almost unchanged at heating temperatures of 20–300°C, increased approximately 3 times in the heating temperature range 300–600°C, and then remained almost unchanged at heating temperatures of 600–900°C. The sand content of sandy soils remained almost the same for all the heating temperatures (Fig. 3).

The silt content of silty-clay and clay soils increased approximately 2 times compared to unheated soils in the heating temperature range 100–300°C, then gradually decreased in the heating temperature range 300–900°C, and fell below the silt content of unheated soils in the heating temperature range 400–900°C.

The silt content of sandy soils remained almost the same for all the heating temperatures (Fig. 4).

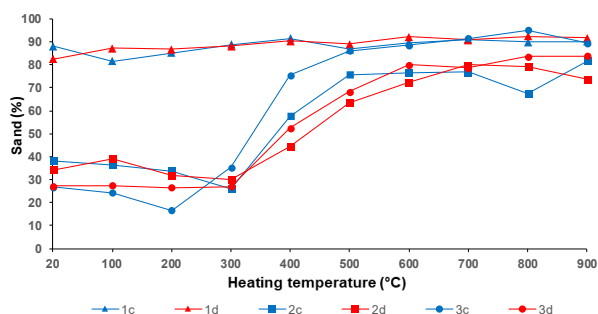


Fig. 3. The effect of heating temperature on sand content of the surface layer (0–2.5 cm) of soils collected from research sites 1c, 1d, 2c, 2d, 3c and 3d.

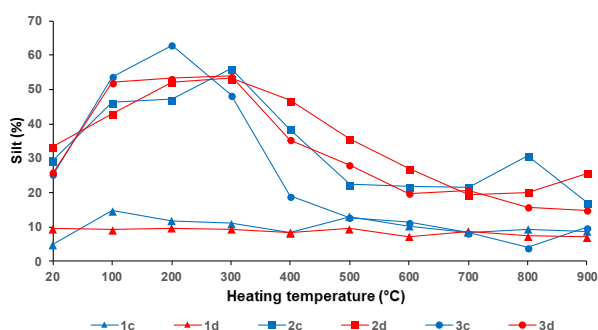


Fig. 4. The effect of heating temperature on silt content of the surface layer (0–2.5 cm) of soils collected from research sites 1c, 1d, 2c, 2d, 3c and 3d.

The clay content of silty-clay and clay soils decreased compared to unheated soils in the heating temperature range 20–100°C and 300–500°C, and remained almost unchanged in the heating temperature range 100–300°C and 500–900°C. The clay content of sandy soils decreased compared to unheated soils in the heating temperature range 20–300°C, and then remained almost the same in the heating temperature range 300–900°C (Fig. 5).

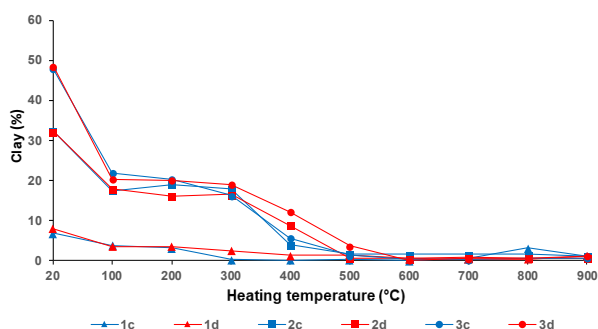


Fig. 5. The effect of heating temperature on clay content of the surface layer (0–2.5 cm) of soils collected from research sites 1c, 1d, 2c, 2d, 3c and 3d.

The persistence of SWR was extreme for unheated soil collected from research site 1c, and it gradually increased in the heating temperature range 100–300°C. Then it decreased (but remained extreme) after heating to temperature of 400°C, and the absence of SWR was registered in the heating temperature range 500–900°C. The persistence of SWR was slight for unheated soil

collected from research site 1d, it gradually increased in the heating temperature range 100–300°C, and it was extreme after heating to temperature of 300°C. Then it decreased, and the absence of SWR was registered in the heating temperature range 400–900°C. The persistence of SWR was slight for unheated soil collected from research site 2c, it gradually increased in the heating temperature range 100–300°C, and it was strong after heating to temperature of 300°C. Then it decreased, and the absence of SWR was registered in the heating temperature range 400–900°C. The non-water-repellent soil collected from research site 3c remained wettable after heating to temperature of 100°C. The persistence of SWR was slight after heating to temperature of 200°C and 300°C, and the absence of SWR was registered in the heating temperature range 400–900°C. The soils collected from research sites 2d and 3d were non-water-repellent for all the heating temperatures (Fig. 6).

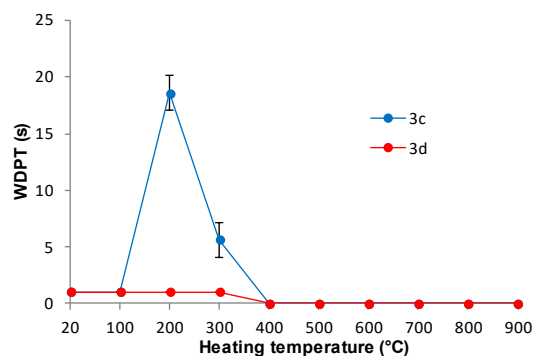
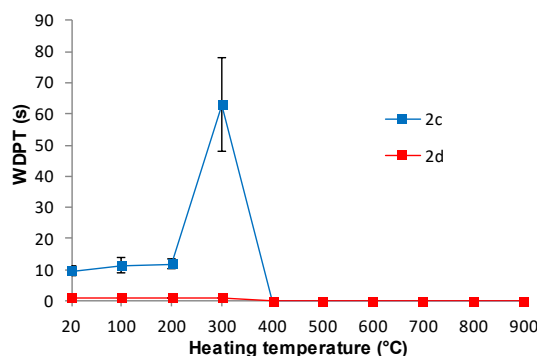
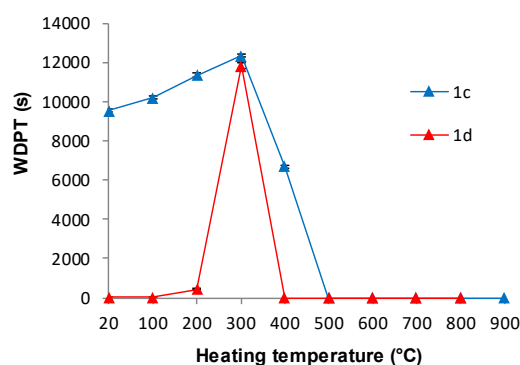


Fig. 6. The effect of heating temperature on water drop penetration time (WDPT) of the surface layer (0–2.5 cm) of soils collected from research sites 1c, 1d, 2c, 2d, 3c and 3d.

The effect of heating temperature on SOC of studied soils is presented in Fig. 7. Only average SOC values are presented, as standard deviation values would not be visible. SOC remained almost unchanged at heating temperatures of 20–300°C. In sandy soils with lower initial SOC levels (approximately 2%), SOC was reduced to almost zero at 500°C. In silty-clay and clay soils

SOC decreased with increasing heating temperature in the range of 300–700°C and did not change at temperatures of 700–900°C. and amounted to 2–4%, which could be a consequence of pyrolysis of naturally occurring organic matter in clay (Johnson et al., 1988). For the heating temperatures from 100 to 400°C, SOC was in the order $1d < 1c < 2d < 2c < 3c$, and for the temperatures from 500 to 900°C, SOC was in the order $1d < 1c < 2d < 2c < 3d < 3c$.

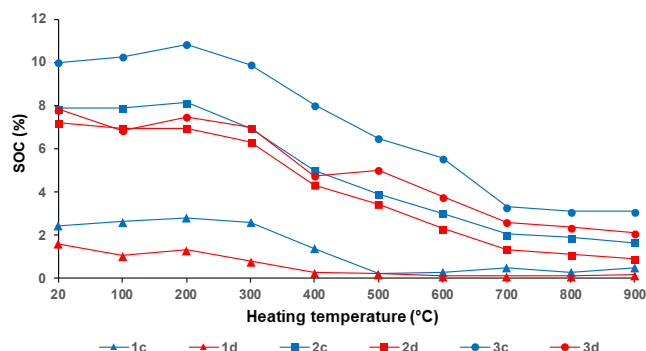


Fig. 7. The effect of heating temperature on soil organic carbon content (SOC) of the surface layer (0–2.5 cm) of soils collected from research sites 1c, 1d, 2c, 2d, 3c and 3d.

The effect of laboratory heating on pH of the studied soils is shown in Fig. 8. Only average pH values are presented, as standard deviation values would not be visible. The pH remained almost unchanged at temperatures of 20–300°C, and then increased with increasing temperature in all soils. An increase in soil pH occurred primarily at temperatures of 300–500°C in all soils, which could be a consequence of denaturation of organic acids and the increase in Na and K oxides, carbonates and hydroxides (Franco et al., 2023). However, the pH in soils from sites 2d, 3c and 3d (silty-clay and clay soils) also increased at temperatures of 700–900°C and reached a value of about pH 12.

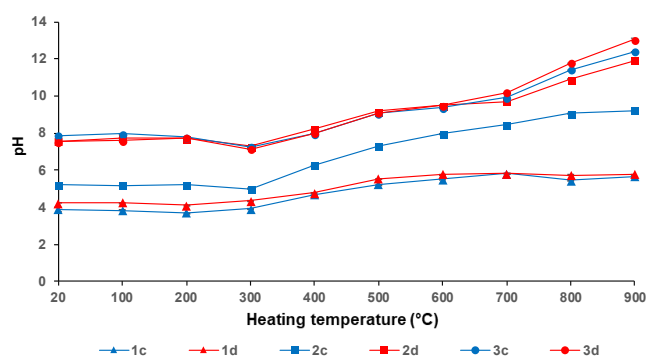


Fig. 8. The effect of heating temperature on pH of the surface layer (0–2.5 cm) of soils collected from research sites 1c, 1d, 2c, 2d, 3c and 3d.

4 DISCUSSION

In this study, the silt content of silty-clay soils increased by approximately half and the silt content of clay soils increased approximately 2 times in the heating temperature range 100–300°C. The larger aggregates that might be determined as silt during the texture analysis, may form after the loss of adsorbed and hydration water in the interlayer spaces of clay minerals, which may cause flocculation of soil colloids, when electrostatic attraction overcomes repulsive forces and the colloids flocculate.

The sand content of silty-clay and clay soils increased approximately 3 times in the heating temperature range 300–600°C. The observed decrease in clay content and increase in sand or silt content may partly reflect aggregation (depending on the type of clay and other minerals), thermal alteration and methodological effects during particle-size analysis, rather than a direct loss of primary clay particles. Similar decrease in the clay content and increase in the sand content of silty-clay and clay soils was attributed to the thermal fusion of clay minerals (Ulery and Graham, 1993). The resulting stable silt-sized and sand-sized secondary particles may be even more resistant to the disrupting action of water than the original clay-sized particles (Giovannini and Lucchesi, 1997). Ulery and Graham (1993) registered a similar particle-size shift in the reddened layers of loamy soils in coniferous forests that had been burned in wildfires. Increase in the sand content and decrease in the clay content (from 37% to 1%) was similarly by observed Kabubo et al. (2017) after heating the clay-loam soil at 600°C for 2 hours. Giraldo et al. (2024) found that the clay content of the soils from Valdivian Temperate Forests decreased from 19 to 10% after heating at 300°C for 2 hours. Guo et al. (2025) found that the sand content in silt-loam soil increased by 65.63% after heating at 210°C for 15 seconds compared to the no heating treatment.

During heating to 100°C (resulting in the decrease in clay content by half), mainly physical rather than chemical alterations occur, generally resulting in the desorption of water from the interlayer spaces of clay minerals, and a slight decrease in clay content due to aggregation and coarsening of soil texture, where fine clay particles are converted into larger aggregate structures (Abu-Zreig et al. (2001). This surprising effect should be taken into account when measuring soil moisture, which is commonly performed at this temperature.

The persistence of SWR was registered in soil from site 1c up to the heating temperature of 400°C, in the other 5 soils up to 300°C. Perera et al. (2024) observed the persistence of SWR in sandy-loam and loam soils up to 150–200°C. Sandy soil from coniferous forest was extremely repellent before heating and after heating to 100–400°C. Sandy soil from deciduous forest was extremely repellent after heating to 300°C. These soils can generate ponding and runoff very quickly during intense thunderstorms, which does not necessarily reflect on a larger scale if permeable zones beneath other plant species and macropores allow infiltration (Popovic and Cerda, 2023). The absence of SWR after heating the soils to higher temperature is primarily due to complete destruction and combustion of the soil organic matter that acts as the hydrophobic coating on soil particles.

Atanassova and Doerr (2010, 2011) based on in-depth analysis of the total solvent extracts in iso-propanol/ NH_3 and iso-propanol suggested putative mechanisms of soil water repellency expression. A number of compounds, such as aromatics, saccharides, glycosides and polar low-molecular-weight (PLMW) compounds such as oxo- and (di)hydroxyacids (C_3 – C_4), and alcohols participate in stabilizing hydrophobic interactions in unheated water repellent soils, while in water repellent soils after heating hydroxy- and hydroxymethoxypyridine appear to be involved in the development of soil water repellency. Data obtained on WDPTs of the selected sandy, silty-clay and clay soil (Fig. 5) in this study confirm previously described mechanisms of the chemical and physico-chemical processes of water repellency expression in soils of different texture and mineralogy (Atanassova and Doerr, 2010). We can speculate that in the sandy soils the sorption of these compounds is different from that in silty-clay and clay (hydrophilic) soils. The sandy soils are mainly composed of quartz possessing less hydrophilic and more

hydrophobic surfaces, and less clay (sesquioxides and clay minerals) than the silty-clay and clay soils. In addition, the negatively charged sand grains (SiO_2) will cause horizontal sorption of the backbone of hydrophobic compounds (fatty acids, alcohols, alkanes) attracted to the less charged siloxane Si-O-Si surfaces, thus covering a larger surface area. The hydrophobic organic compounds coatings on the surfaces of silty clay and clay soils are different from those present on quartz dominated sandy soils, because they possess more polar sites (COOH and OH groups negatively charged on clay minerals), which can affect the adsorption and conformation of the organic molecules causing water repellency. The SOC in clay soils was 63–67% lower after heating at 700°C compared to that at 20°C, which is a greater decrease than the 20% recorded by Thomaz and Fachin (2014) after heating clay soil to 650°C. The decrease in SOC in our sandy (88–94%) and silty-clay (74–82%) soils after heating at 700°C was even greater. Garcia-Corona et al. (2004) observed a SOS decrease of 82–92% in sandy-loam and silty-loam soils after heating at 460°C. The pH increases in soils from sites 2d, 3c and 3d (silty-clay and clay soils) at temperatures of 700–900°C is consistent with findings of Aryanpour et al. (2023), who observed a steep increase in pH of clay soil (with a maximum value of 12.3 close to our values) at temperatures of 500–900°C. On the other hand, Martinez et al. (2022) registered a decrease in pH of sandy-loam and loam soils with increasing heating temperature in the range of 500–900°C.

5 CONCLUSIONS

In the first part of our paper, we assessed how the heating affected physical and chemical properties of forest soils with different texture. The presented conclusions are based on laboratory results and cannot be considered as field-scale conclusions for post-fire soil behaviour. We found that the decrease in the clay content was large in silty-clay and clay soils, but not as large in sandy soils. Surprisingly, heating the soil to 100°C, commonly used in soil moisture measurement, caused a decrease in clay content by half (the average value for all soils). This finding should be confirmed by further measurements on the soils from other regions, because the degree of aggregation depends also on the type of clay and other minerals. Decrease in the clay content was offset by an increase in the silt content after heating to 100–200°C and an increase in the sand content after heating to 300–500°C. The changes in grain size distribution of the studied soils could have been caused by thermal fusion of clay minerals, resulting in the aggregation of clay-sized particles into stable silt-sized and sand-sized secondary particles. The persistence of SWR gradually increased in the heating temperature range 100–300°C in soils from coniferous forests and sandy soil from deciduous forest, and was absent in the remaining two soils. The SOC decreased and pH increased with increasing heating temperature. In the second part of our paper, we will present how these changes in physical and chemical properties will affect the infiltration and retention characteristics of forest soils with different texture.

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REFERENCES

- Abu-Zreig, M.M., Al-Akhras, N.M., Attom, M.F., 2001. Influence of heat treatment on the behavior of clayey soils. *Appl. Clay Sci.*, 20, 3, 129–135. [https://doi.org/10.1016/S0169-1317\(01\)00066-7](https://doi.org/10.1016/S0169-1317(01)00066-7)
- Al-Khayri, J.M., Khan, T., 2024. Impacts of forest fires on soil: Exploring the effects on biotic and abiotic components. *Sylwan*, 168, 601–614. <https://doi.org/10.26202/sylwan.2024031>
- Aryanpour, M., Falamaki, A., Vakili, A.H., 2023. Effects of elevated temperature on mineralogical/microstructural changes and mechanical responses of clay soil. *Phys. Chem. Earth, Parts A/B/C*, 132, 103493. <https://doi.org/10.1016/j.pce.2023.103493>
- Atanassova, I., Doerr, S., 2010. Organic compounds of different extractability in total solvent extracts from soils of contrasting water repellency. *Eur. J. Soil Sci.*, 61, 298–313. <https://doi.org/10.1111/j.1365-2389.2009.01224.x>
- Atanassova, I., Doerr, S.H., 2011. Changes in soil organic compound composition associated with heat-induced increases in soil water repellency. *Eur. J. Soil Sci.*, 62, 516–532. <https://doi.org/10.1111/j.1365-2389.2011.01350.x>
- Badía, D., López-García, S., Martí, C., Ortíz-Perpiñá, O., Girona-García, A., Casanova-Gascón, J., 2017. Burn effects on soil properties associated to heat transfer under contrasting moisture content. *Sci. Total Env.*, 601–602, 1119–1128. <https://doi.org/10.1016/j.scitotenv.2017.05.254>
- Badía-Villas, D., González-Pérez, J.A., Aznar, J., Arjona-Gracia, B., Martí-Dalmau, C., 2014. Changes in water repellency, aggregation and organic matter of a mollic horizon burned in laboratory: Soil depth affected by fire. *Geoderma*, 213, 400–407. <http://dx.doi.org/10.1016/j.geoderma.2013.08.038>
- Badía-Villas, D., Esteban-Piñero, J., Girona-García, A., Ortiz-Perpiñá, O., Poch, R.M., 2020. Topsoil microstructure changes after a shrubland prescribed burn (Central Pyrenees, NE Spain). *Sci. Total Env.*, 748, 141253. <https://doi.org/10.1016/j.scitotenv.2020.141253>
- Bisdorf, E.B.A., Dekker, L.W., Schoute, J.F.T., 1993. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *Geoderma*, 56, 105–118. [https://doi.org/10.1016/0016-7061\(93\)90103-R](https://doi.org/10.1016/0016-7061(93)90103-R)
- Cerda, A., Lucas-Borja, M.-E., Franch-Pardo, I., Úbeda, X., Novara, A., López-Vicente, M., Popovic, Z., Pulido, M., 2021. The role of plant species on runoff and soil erosion in a Mediterranean shrubland. *Sci. Total Environ.*, 799, 149218. <https://doi.org/10.1016/j.scitotenv.2021.149218>
- DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. *J. Hydrol.*, 231–232, 195–206. [https://doi.org/10.1016/S0022-1694\(00\)00194-3](https://doi.org/10.1016/S0022-1694(00)00194-3)
- Doerr, S.H., 1998. On standardizing the "Water Drop Penetration Time" and the "Molarity of an Ethanol Droplet" techniques to classify soil hydrophobicity: a case study using medium textured soils. *Earth Surf. Process. Landf.*, 23, 663–668. [https://doi.org/10.1002/\(SICI\)1096-9837\(199807\)23:7<663::AID-ESP909>3.0.CO;2-6](https://doi.org/10.1002/(SICI)1096-9837(199807)23:7<663::AID-ESP909>3.0.CO;2-6)
- Doerr, S.H., Santin, C., 2016. Global trends in wildfire and its impacts: Perceptions versus realities in a changing world. *Phil. Trans. R. Soc. B*, 371, 20150345. <https://doi.org/10.1098/rstb.2015.0345>
- Doerr, S.H., Shakesby, R.A., Walsh, R., 2000. Soil water repellency: Its causes, characteristics and hydrogeomorphological significance. *Earth Sci. Rev.*, 51, 33–65. [https://doi.org/10.1016/S0012-8252\(00\)00011-8](https://doi.org/10.1016/S0012-8252(00)00011-8)
- Doerr, S.H., Blake, W.H., Shakesby, R.A., Stagnitti, F., Vuurens, S.H., Humphreys, G.S., Wallbrink, P., 2004. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil

- temperatures. *Int. J. Wildland Fire*, 13, 2, 157–163. <https://doi.org/10.1071/WF03051>
- Doerr, S.H., Girona-García, A., Sánchez-García, C., Badía-Villas, D., Bryant, R., Dickinson, M.B., Hsieh, R., Mataix-Solera, J., Miesel, J.R., Robichaud, P.R., Stoof, C.R., Santín, C., 2025. Soil heating during wildfires and prescribed burns: a global evaluation. *Int. J. Wildland Fire*, 34, WF25103. <https://doi.org/10.1071/WF25103>
- Francos, M., Vieira, A., Bento-Gonçalves, A., Úbeda, X., Zema, D.A., Lucas-Borja, M.E., 2023. Effects of wildfire, torrential rainfall and straw mulching on the physicochemical soil properties in a Mediterranean forest. *Ecol. Eng.*, 192, 106987. <https://doi.org/10.1016/j.ecoleng.2023.106987>
- García-Corona, R., Benito, E., de Blas, E., Varela, M.E., 2004. Effects of heating on some soil physical properties related to its hydrological behaviour in two north-western Spanish soils. *Int. J. Wildland Fire*, 13, 195–199. <https://doi.org/10.1071/WF03068>
- Giovannini, G., Lucchesi, S., 1997. Modifications induced in soil physico-chemical parameters by experimental fires at different intensities. *Soil Sci.*, 162, 479–486. <https://doi.org/10.1097/00010694-199707000-00003>
- Giraldo, C.V., Acevedo, S.E., Contreras, C.P., Santibáñez, F., Sáez, E., Calderón, F.J., Bonilla, C.A., 2024. Effects of soil heating changes on soil hydraulic properties in Central Chile. *Geoderma*, 449, 117013.
- González-Perez, J.A., González-Vila, F.J., González-Vázquez, R., Arias, M.E., Rodríguez, J., Knicker, H., 2008. Use of multiple biogeochemical parameters to monitor the recovery of soils after forest fires. *Org. Geochem.*, 39, 940–944. <https://doi.org/10.1016/j.orggeochem.2008.03.014>
- Guo, Z., Han, J., Zhang, Y., Zhuang, H., 2025. Effects of temperature and time treatment on soil characteristics and wheat growth. *Front. Sustain. Food Syst.*, 9, 1499224. <https://doi.org/10.3389/fsufs.2025.1499224>
- Hewelke, E., Oktaba, L., Gozdowski, D., Kondras, M., Olejniczak, I., Górská, E.B., 2018. Intensity and persistence of soil water repellency in pine forest soil in a temperate continental climate under drought conditions. *Water*, 10, 1121. <https://doi.org/10.3390/w10091121>
- Hewelke, E., Górská, E.B., Gozdowski, D., Korc, M., Olejniczak, I., Prędecka, A., 2020. Soil functional responses to natural ecosystem restoration of a pine forest *Peucedano-Pinetum* after a fire. *Forests*, 11, 286. <https://doi.org/10.3390/fl1030286>
- Hološ, S., Šurda, P., Lichner, E., Zvala, A., Píš, V., 2022. Fire-induced changes in soil properties depend on age and type of forests. *J. Hydrol. Hydromech.*, 70, 442–449. <https://doi.org/10.2478/johh-2022-0034>
- ISO 10390, 2005. Soil quality. Determination of pH. International Organization of Standardization, Geneva. <https://www.iso.org/standard/40879.html>
- ISO 11274, 2019. Soil quality. Determination of the water-retention characteristic – Laboratory methods. Geneva. <https://www.iso.org/standard/68256.html>
- ISO 11277, 2009. Soil quality. Determination of particle size distribution in mineral soil material. Method by sieving and sedimentation. International Organization of Standardization, Geneva. <https://www.iso.org/standard/54151.html>
- Jiménez-Morillo, N.T., Almendros, G., De la Rosa, J.M., Jordán, A., Zvala, L.M., Granged, A.J.P., González-Pérez, J.A., 2020. Effect of a wildfire and of post-fire restoration actions in the organic matter structure in soil fractions. *Sci. Total Env.*, 728, 138715. <https://doi.org/10.1016/j.scitotenv.2020.138715>
- Johnson, J.S., Clark, J., Miller-Antonio, S., Robins, D., Schiffer, M.B., Skibo, J.M., 1988. Effects of firing temperature on the fate of naturally occurring organic matter in clays. *J. Archaeol. Sci.*, 15, 403–414. [https://doi.org/10.1016/0305-4403\(88\)90038-6](https://doi.org/10.1016/0305-4403(88)90038-6)
- Kabubo, C.K., Mwea, S.K., Abuodha, S.O., Gariy, Z.A., 2017. The effect of heat on the properties of expansive clay soil. *Int. J. Sci. Res.*, 6, 464–469. <https://doi.org/10.21275/28121602>
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, 15, 259–263. <https://doi.org/10.1127/0941-2948/2006/0130>
- Lichner, E., Šurda, P., Zvala, A., Kollár, J., Šimanský, V., 2025. Impact of heating on properties of sandy soil under pine and birch trees. *Biologia*, 80, 1195–1206. <https://doi.org/10.1007/s11756-025-01903-w>
- Martínez, S.I., Contreras, C.P., Acevedo, S.E., Bonilla, C.A., 2022. Unveiling soil temperature reached during a wildfire event using ex-post chemical and hydraulic soil analysis. *Sci. Total Env.*, 822, 153654. <https://doi.org/10.1016/j.scitotenv.2022.153654>
- Martins, M.A.S., Verheijen, F.G.A., Malvar, M.C., Serpa, D., Gonzalez-Pelayo, O., Keizer, J.J., 2020. Do wildfire and slope aspect affect soil water repellency in eucalypt plantations? – A two-year high resolution temporal dataset. *Catena*, 189, 104471. <https://doi.org/10.1016/j.catena.2020.104471>
- Martins, M.A.S., Prats, S.A., Keizer, J.J., Verheijen, F.G.A., 2024. Post-fire soil water repellency under stones and forest residue mulch versus of bare soil. *J. Hydrol. Hydromech.*, 72, 413–421. <https://doi.org/10.2478/johh-2024-0024>
- Massman, W.J., Frank, J.M., Mooney, S.J., 2010. Advancing investigation and physical modeling of first-order fire effects in soils. *Fire Ecol.*, 6, 36–54. <https://doi.org/10.4996/fireecology.0601036>
- Perera, H.T.M., Leelamanie, D.A.L., Mori, Y., Maeda, M., 2024. Heat-induced alterations in water repellency of tropical and temperate soils: A laboratory experiment using Ultisols and Andosols. *Catena*, 243, 108230. <https://doi.org/10.1016/j.catena.2024.108230>
- Popovic, Z., Cerda, A., 2023. Soil water repellency and plant cover: A state-of-knowledge review. *Catena*, 229, 107213. <https://doi.org/10.1016/j.catena.2023.107213>
- Santín, C., Doerr, S.H., Otero, X.L., Chafer, C.J., 2015. Quantity, composition and water contamination potential of ash produced under different wildfire severities. *Environ. Res.*, 142, 297–308. <http://dx.doi.org/10.1016/j.envres.2015.06.041>
- Sun, Q., Zhang, W., Qian, H., 2016. Effects of high temperature thermal treatment on the physical properties of clay. *Environ. Earth Sci.*, 75, 610. <https://doi.org/10.1007/s12665-016-5402-2>
- Šurda, P., Lichner, E., Iovino, M., Hološ, S., Zvala, A., 2023. The effect of heating on properties of sandy soils. *Land*, 12, 9, 1752. <https://doi.org/10.3390/land12091752>
- Thomaz, E.L., Fachin, P.A., 2014. Effects of heating on soil physical properties by using realistic peak temperature gradients. *Geoderma*, 230–231, 243–249. <http://dx.doi.org/10.1016/j.geoderma.2014.04.025>
- Ulery, A.L., Graham, R.C., 1993. Forest fire effects on soil color and texture. *Soil Sci. Soc. Am. J.*, 57, 135–140. <https://doi.org/10.2136/sssaj1993.03615995005700010026x>

WRB, 2015. World Reference Base for Soil Resources 2014.
Update 2015. World Soil Resources Reports No. 106. FAO,
Rome, 192 p.
<https://openknowledge.fao.org/items/80a86a87-e01b-4cda-a8d7-09be79a127e5>

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Supplementary data

Table S1. Impact of heating temperature on the average values of sand, silt and clay contents, water drop penetration time (WDPT), soil organic carbon content (SOC), and pH of soils, collected from the surface layer (0–2.5 cm) of soil at research site 1c (sandy soil under coniferous forest).

Heating temperature (°C)	Sand (%)	Silt (%)	Clay (%)	WDPT (s)	SOC (%)	pH (–)
20	88.14	4.98	6.87	9564	2.45	3.89
100	81.50	14.72	3.83	10224	2.62	3.84
200	85.10	11.77	3.22	11376	2.81	3.70
300	88.70	10.97	0.32	12372	2.59	3.92
400	91.50	8.39	0.16	6696	1.39	4.70
500	86.80	12.95	0.24	0	0.20	5.23
600	89.70	10.31	0.04	0	0.30	5.52
700	91.00	8.45	0.56	0	0.50	5.81
800	89.90	9.42	3.21	0	0.30	5.45
900	90.04	8.72	1.24	0	0.50	5.66

Table S2. Impact of heating temperature on the average values of sand, silt and clay contents, water drop penetration time (WDPT), soil organic carbon content (SOC), and pH of soils, collected from the surface layer (0–2.5 cm) of soil at research site 1d (sandy soil under deciduous forest).

Heating temperature (°C)	Sand (%)	Silt (%)	Clay (%)	WDPT (s)	SOC (%)	pH (–)
20	82.44	9.48	8.07	10.6	1.60	4.23
100	87.20	9.16	3.61	19.4	1.05	4.26
200	86.80	9.63	3.57	447.2	1.31	4.12
300	88.10	9.33	2.57	11840	0.80	4.35
400	90.40	8.34	1.32	0	0.27	4.79
500	89.10	9.54	1.44	0	0.20	5.55
600	92.20	7.25	0.56	0	0.10	5.79
700	90.80	8.76	0.44	0	0.10	5.83
800	92.30	7.32	0.36	0	0.10	5.73
900	91.82	7.02	1.16	0	0.15	5.80

Table S3. Impact of heating temperature on the average values of sand, silt and clay contents, water drop penetration time (WDPT), soil organic carbon content (SOC), and pH of soils, collected from the surface layer (0–2.5 cm) of soil at research site 2c (silty-clay soil under coniferous forest).

Heating temperature (°C)	Sand (%)	Silt (%)	Clay (%)	WDPT (s)	SOC (%)	pH (–)
20	38.18	29.41	32.41	9.6	7.89	5.21
100	36.40	46.20	17.40	11.4	7.91	5.19
200	33.71	47.20	19.10	11.8	8.15	5.20
300	26.10	56.10	17.90	63.0	6.97	5.01
400	57.70	38.40	3.89	0	5.02	6.27
500	75.80	22.40	1.70	0	3.90	7.32
600	76.70	21.70	1.64	0	3.02	7.97
700	76.90	21.56	1.61	0	2.06	8.45
800	67.70	30.60	1.61	0	1.90	9.07
900	81.60	17.16	1.24	0	1.65	9.22

Table S4. Impact of heating temperature on the average values of sand, silt and clay contents, water drop penetration time (WDPT), soil organic carbon content (SOC), and pH of soils, collected from the surface layer (0–2.5 cm) of soil at research site 2d (silty-clay soil under deciduous forest).

Heating temperature (°C)	Sand (%)	Silt (%)	Clay (%)	WDPT (s)	SOC (%)	pH (–)
20	34.34	33.38	32.29	1	7.20	7.58
100	39.28	42.90	17.80	1	6.98	7.74
200	31.69	52.20	16.10	1	6.98	7.71
300	30.25	53.30	16.60	1	6.33	7.30
400	44.40	46.80	8.75	0	4.35	8.24
500	63.50	35.70	0.69	0	3.44	9.20
600	72.40	26.89	0.60	0	2.31	9.49
700	80.00	19.25	0.76	0	1.33	9.70
800	79.40	20.02	0.64	0	1.11	10.9
900	73.72	25.60	0.68	0	0.90	11.9

Table S5. Impact of heating temperature on the average values of sand, silt and clay contents, water drop penetration time (WDPT), soil organic carbon content (SOC), and pH of soils, collected from the surface layer (0–2.5 cm) of soil at research site 3c (clay soil under coniferous forest).

Heating temperature (°C)	Sand (%)	Silt (%)	Clay (%)	WDPT (s)	SOC (%)	pH (–)
20	26.81	25.28	47.90	1	9.98	7.88
100	24.40	53.70	21.90	1	10.2	7.97
200	16.71	62.90	20.40	18.6	12.0	7.79
300	35.30	48.44	16.30	5.6	9.88	7.27
400	75.40	18.99	5.61	0	8.03	7.95
500	86.00	12.74	1.26	0	6.49	9.08
600	88.50	11.32	0.24	0	5.57	9.38
700	91.40	8.32	0.28	0	3.32	9.94
800	95.20	4.03	0.73	0	3.10	11.4
900	89.56	9.75	0.69	0	3.16	12.4

Table S6. Impact of heating temperature on the average values of sand, silt and clay contents, water drop penetration time (WDPT), soil organic carbon content (SOC), and pH of soils, collected from the surface layer (0–2.5 cm) of soil at research site 3d (clay soil under deciduous forest).

Heating temperature (°C)	Sand (%)	Silt (%)	Clay (%)	WDPT (s)	SOC (%)	pH (–)
20	27.14	25.84	48.62	1	7.83	7.55
100	27.50	52.10	20.40	1	6.84	7.60
200	26.64	53.30	20.10	1	7.48	7.74
300	27.01	53.90	19.00	1	6.99	7.15
400	52.40	35.34	12.20	0	4.75	8.00
500	68.20	28.00	3.73	0	5.03	9.10
600	80.10	19.73	0.12	0	3.78	9.50
700	78.70	20.69	0.57	0	2.86	10.2
800	83.60	15.78	0.64	0	2.36	11.8
900	83.94	14.86	1.20	0	2.11	13.0