

Post-fire changes in soil physicochemical properties following controlled burning in the Greater Poland region

Michał Bajur¹ 

¹ Independent researcher, ul. Plażowa 26, 62-100 Kobylec, Poland
E-mail: bajurmichal@gmail.com

ABSTRACT

This study aimed to evaluate changes in selected physicochemical properties of soil resulting from a forest fire and subsequent suppression activities. The research was conducted in the Majoński Grove in Luboń (Greater Poland Voivodeship, Poland), where controlled burning of forest litter was performed to simulate fire. Soil samples were collected from three depth intervals (0–50 mm, 51–100 mm and 101–150 mm) before and after burning. Laboratory analyses included grain-size distribution, pH, electrical conductivity (EC), calcium carbonate content, cation exchange capacity (CEC), organic carbon content and magnetic susceptibility. The results indicated pronounced alterations in surface soil layers, particularly increases in pH, EC, organic carbon and oxidizable carbon, confirming that fire effects were largely confined to the soil surface. These findings contribute to a better understanding of post-fire soil processes and may support the assessments of forest ecosystem recovery, as well as operational planning for the State Fire Service.

Keywords: Forest soils; post-fire effects; controlled burning; soil physicochemical properties; magnetic susceptibility; cation exchange capacity.

INTRODUCTION

Fire is a natural and global phenomenon that has been shaping terrestrial ecosystems since the emergence of land vegetation. It plays a significant role in regulating vegetation patterns, biogeochemical cycles, and climate-related processes (Bowman et al., 2009). In recent years, however, the frequency and spatial extent of forest fires have increased in many regions, intensifying their environmental impacts.

Statistical data from the State Fire Service indicate an upward trend in the number of forest fires in Poland, including the Greater Poland Voivodeship, particularly between 2017 and 2021. This increase poses a growing threat to forest ecosystems and adjacent areas, highlighting the need for a better understanding of fire-induced environmental changes.

Among the components of forest ecosystems, soil is particularly sensitive to fire disturbance. Elevated temperatures and combustion of organic

material can modify the physicochemical properties of soil, including pH, salinity, organic carbon content, and cation exchange capacity. These changes directly affect post-fire ecosystem regeneration and nutrient cycling.

Previous studies have shown that fire impacts are usually concentrated in surface soil layers, while deeper horizons remain less affected (Certini, 2005). Nevertheless, the magnitude and direction of these changes depend on fire intensity, duration, fuel type, and suppression activities. In particular, controlled burning experiments provide valuable insight into the fire–soil interactions under reproducible conditions.

The aim of this study was to evaluate changes in selected physicochemical properties of forest soil caused by a surface fire simulated by controlled litter burning. The research focused on the vertical variability of soil properties before and after fire exposure, with special attention given to pH, electrical conductivity, organic carbon content, cation exchange capacity, and magnetic susceptibility.

STUDY AREA

The study was conducted in the Majoński Grove, located in the south-eastern part of Luboń, within the Greater Poland Voivodeship (western Poland), in the Warta River valley. The investigated forest complex covers approximately 60 ha and represents a typical lowland forest ecosystem of the region.

The area is dominated by mixed forest stands with a prevalence of birch, accompanied by a well-developed herbaceous understory and forest litter layer. The soils are classified as leached brown soils developed from loose and slightly loamy sands, which are common in central-western Poland and particularly susceptible to thermal disturbance as well as post-fire chemical transformations.

Soil sampling was carried out in May 2022 on a 25 m² experimental plot where controlled burning of forest litter was performed to simulate a surface fire. The burning process lasted approximately 10 minutes. Fire suppression was conducted using a water stream, reflecting typical firefighting practices applied during low-intensity forest fires.

Soil samples were collected from three depth intervals: 0–50 mm, 51–100 mm, and 101–150 mm. Prior to burning, three control samples were taken from each depth. After burning, nine samples were collected from the same depth intervals (three replicates per layer). Mean values obtained from replicate samples were used in subsequent analyses to improve result reliability and reduce the influence of local heterogeneity.

MATERIAL AND METHODS

After collection, the soil samples were air-dried at room temperature to constant mass, homogenized, and sieved through a 2 mm mesh to separate the fine earth fraction. Laboratory analyses were performed using standard soil science procedures. Grain-size distribution was determined using the Casagrande aerometric method, combining sieve and sedimentation techniques. Soil reaction was measured potentiometrically in distilled water (H₂O) and in 1 N KCl. Electrical conductivity (EC) was determined conductometrically in soil extracts.

Calcium carbonate (CaCO₃) content was measured using the Scheibler volumetric method.

Cation exchange capacity (CEC) was determined by the Kappen method. Oxidizable carbon content was analyzed using the modified Tiurin method. Organic matter content was calculated based on oxidizable carbon determined using the modified Tiurin method. Magnetic susceptibility was measured with a Bartington MS2B sensor and expressed as mass-specific magnetic susceptibility.

For organic soil material, pH (H₂O and KCl) and electrical conductivity (EC) were measured using the soil-to-water ratios recommended for organic samples. Soil color was assessed visually using the Munsell Soil Color Charts (Kabała et al., 2017). All analyses were conducted in triplicate for each depth interval. Mean values were used for further interpretation to minimize analytical uncertainty and local variability.

RESULTS

Laboratory analyses demonstrated clear changes in selected physicochemical properties of soil following the controlled surface fire. The magnitude of these changes depended strongly on soil depth and was most pronounced in the surface layer (0–50 mm), while deeper layers exhibited progressively weaker responses (Table 1).

Control samples were collected only from the surface soil layer (0–50 mm); therefore, no control data are available for deeper layers, and depth was treated as a categorical variable due to discrete sampling intervals. A visible change in soil color was observed after burning, from 7.5YR 6/1 in control samples to predominantly 10YR 5/1 in burned samples. This shift was recorded across all analyzed depth intervals. Soil pH remained acidic in all samples; however, differences in pH were observed between control and burned soils across discrete depth intervals.

In the surface layer (0–50 mm), mean pH (H₂O) increased from 5.27 in control samples to 5.49 after burning. In burned soils from deeper layers, the pH values ranged from 5.23 to 5.30, indicating smaller differences compared to the surface layer (Fig. 1). Calcium carbonate (CaCO₃) content was low in all samples and showed only minor variation, ranging from 0.12% to 0.16%, with no distinct differences between depth intervals.

Electrical conductivity (EC) increased markedly in the surface soil after burning, reaching a mean value of 99.65 μS/cm compared to 56.12

Table 1. Mean values of selected physicochemical soil properties in control and burned samples at different depths

Depth (mm)	Treatment	pH (H ₂ O)	CaCO ₃ (%)	Oxidizable carbon (%)	Organic matter (%)	CEC (mmol(+)/100 g)	Magnetic susceptibility (× 10 ⁻⁸ m ³ /kg)
0–50	Control	5.27	0.13	2.92	5.04	9.6	88.3
0–50	Burned	5.49	0.16	5.0	8.61	12.55	118.8
51–100	Burned	5.23	0.12	2.89	4.99	7.1	66.07
101–150	Burned	5.3	0.14	1.77	3.06	6.0	45.3

μS/cm in control samples. In deeper burned layers, the EC values were lower, indicating a reduced response relative to the surface layer.

Oxidizable carbon content differed clearly between depth intervals. In the surface layer, oxidizable carbon increased from 2.92% in control samples to 5.00% after burning. In burned soils from deeper layers, the values decreased to 2.89% at 51–100 mm and to 1.77% at 101–150 mm.

A similar pattern was observed for organic matter content, which increased from 5.04% in surface control soil to 8.61% after burning and declined to 4.99% and 3.06% in the deeper layers (Fig. 2). Cation exchange capacity (CEC) also varied between discrete depth intervals.

In the surface layer, CEC increased from 9.6 mmol(+)/100 g in the control samples to 12.55 mmol(+)/100 g after burning. In burned soils from deeper layers, the CEC values decreased

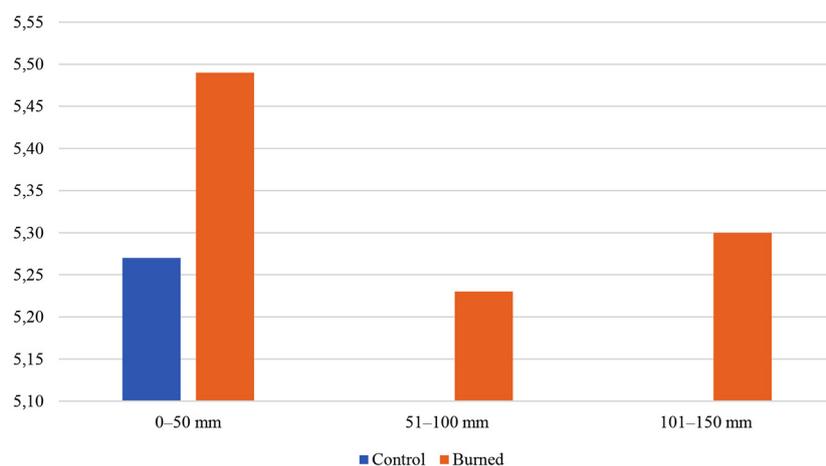


Fig. 1. Mean soil pH (H₂O) in control and burned samples across discrete soil depth intervals

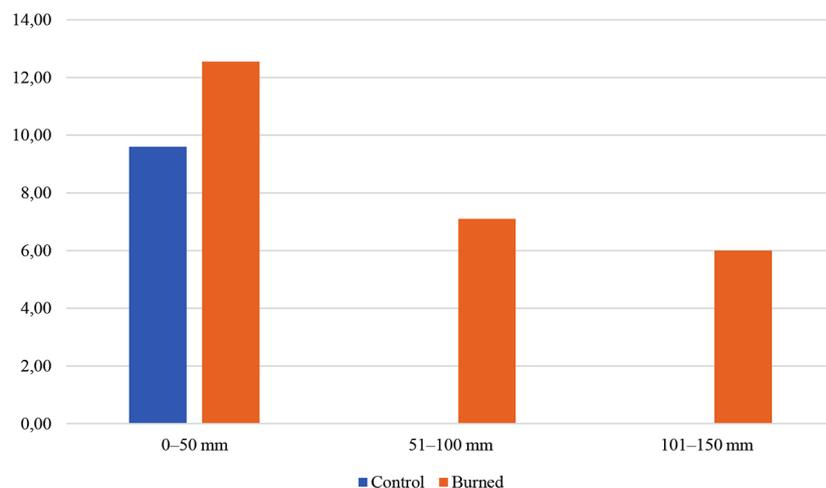


Fig. 2. Cation exchange capacity (CEC) of control and burned soils across discrete soil depth intervals

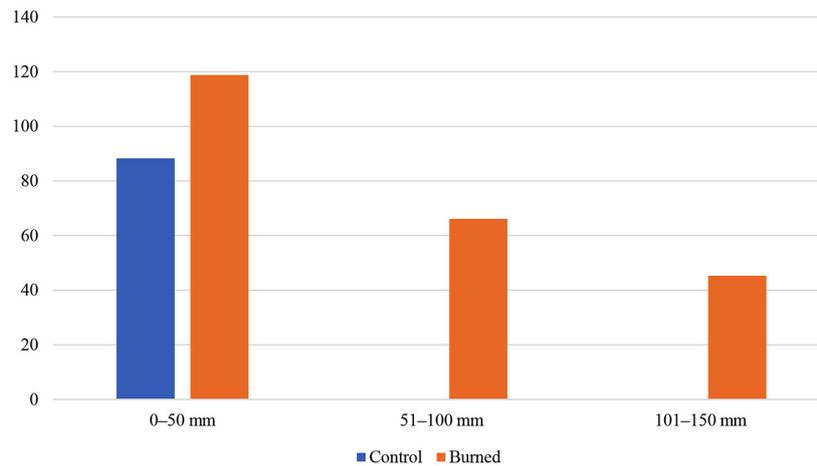


Fig. 3. Magnetic susceptibility (χ) of control and burned soils across discrete soil depth intervals

to 7.1 mmol(+)/100 g at 51–100 mm and to 6.0 mmol(+)/100 g at 101–150 mm (Fig 3). Magnetic susceptibility showed the strongest response to burning.

In the surface layer, values increased from 88.3×10^{-8} m³/kg in control samples to 118.8×10^{-8} m³/kg after burning. In burned soils from deeper layers, magnetic susceptibility decreased to 66.07×10^{-8} m³/kg and 45.3×10^{-8} m³/kg, indicating limited penetration of thermal effects into the soil profile.

Overall, the controlled surface fire caused measurable changes in soil physicochemical properties primarily within the upper soil layer, while deeper horizons remained relatively stable.

DISCUSSION

The results of this study demonstrate that controlled surface fire exerts a pronounced influence on the physicochemical properties of forest soils primarily within the uppermost layer, while deeper horizons remain only marginally affected. This vertical differentiation is a well-recognized characteristic of low-intensity and short-duration fires, in which the heat transfer into the soil profile is rapidly attenuated with depth (Certini, 2005; Neary et al., 1999). In the present study, the burning duration was approximately 10 minutes, which significantly limited the penetration of elevated temperatures and associated physicochemical transformations into deeper soil layers.

The increase in soil pH observed in the 0–50 mm layer after burning reflects a typical post-fire alkalization process. During

combustion, organic acids are volatilized and alkaline ash is deposited on the soil surface, leading to the release of base cations, such as Ca²⁺, Mg²⁺, and K⁺ into the soil solution (Certini, 2005; Úbeda and Pereira, 2019). Similar post-fire increases in pH have been reported for the forest soils subjected to surface fires, particularly when fire severity is low and ash remains largely in situ. The absence of substantial pH changes in deeper layers confirms that the influence of ash inputs and heat-induced reactions was confined mainly to the soil surface.

A comparable depth-dependent pattern was observed for electrical conductivity (EC). Elevated EC values in the surface layer indicate an increased concentration of soluble salts derived from ash and partially combusted organic residues. Previous studies have shown that the post-fire increases in EC are typically short-lived and restricted to surface horizons, as soluble ions are either leached downward or removed during subsequent precipitation events (Certini, 2005; Bodí et al., 2014). In the present case, firefighting suppression using water may have facilitated partial redistribution of ions; however, the limited response in deeper layers suggests that these processes did not substantially alter sub-soil chemistry.

The increase in organic carbon and organic matter content in the surface soil layer following burning may appear counterintuitive, as fire is often associated with organic matter loss. However, similar observations have been documented for low-intensity surface fires, where incomplete combustion results in partial carbonization, rather than complete mineralization of organic material

(Certini, 2005; Santín et al., 2017). Fine charcoal particles and thermally altered organic residues may become incorporated into the mineral soil, leading to an apparent increase in measured organic carbon. These processes can also contribute to changes in soil sorption properties.

This interpretation is supported by the observed increase in cation exchange capacity (CEC) in the surface layer. Fire-altered organic matter and ash-derived mineral phases may provide additional exchange sites, enhancing the ability of soil to retain base cations (Bodí et al., 2014). The lack of significant changes in CEC in deeper soil layers further indicates that the exchange complex below 50 mm remained largely unaffected by the fire event, consistent with the limited thermal penetration associated with short-duration surface burning.

Magnetic susceptibility proved to be a sensitive indicator of fire-induced thermal alteration in the studied soils. The marked increase in susceptibility values in the surface layer after burning can be attributed to the thermal transformation of iron-bearing minerals, resulting in the formation of ferrimagnetic phases, such as magnetite or maghemite (Strzyszczyk et al., 2005; Jordanova et al., 2019). Such transformations occur when soil temperatures exceed critical thresholds during combustion and are commonly reported in fire-affected soils. In contrast, the substantially lower susceptibility values recorded in deeper layers indicate that the temperatures sufficient to induce mineralogical changes were not reached below the surface horizon. This finding is consistent with the experimental and field observations showing that soil temperatures decrease rapidly with depth during short-duration fires (Neary et al., 1999; Szuszkiewicz et al., 2020).

Overall, the clear differentiation between surface and subsurface soil layers highlights the importance of fire duration and intensity in controlling the extent of soil alteration. In the case of controlled surface burning, physicochemical changes were largely confined to the upper 50 mm of soil, leaving deeper horizons structurally and chemically stable. From an ecological perspective, such surface-limited disturbances may temporarily modify nutrient availability, microbial activity, and sorption processes in the topsoil without compromising the overall integrity of the soil profile. Consequently, low-intensity surface fires, such as the one investigated in

this study, are unlikely to cause long-term degradation of soil functions and may be compatible with the natural post-fire recovery processes in forest ecosystems.

CONCLUSIONS

Controlled surface burning caused measurable changes in selected physicochemical properties of forest soil, with effects clearly confined to the upper soil layer. The most pronounced post-fire changes were observed within the 0–50 mm layer and included increases in soil pH, electrical conductivity, oxidizable carbon, organic matter content, cation exchange capacity, and magnetic susceptibility. Subsurface soil layers (51–100 mm and 101–150 mm) exhibited considerably smaller changes in all analyzed parameters, indicating limited vertical propagation of thermal and chemical effects.

Grain-size distribution remained unchanged after burning, confirming that low-intensity surface fires do not significantly affect the physical structure of mineral soils. The increase in magnetic susceptibility in the surface layer highlights its usefulness as a sensitive indicator of thermal impact and fire-induced mineral transformations in forest soils. Overall, the results demonstrate that controlled surface fires primarily modify the chemical properties of topsoil, while deeper horizons remain relatively stable, which is important for the post-fire soil assessment and management in forested areas.

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