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FIRE CHANGES IN SOIL FERTILITY AND MICROBIAL DYNAMICS IN NORTHWESTERN BULGARIA

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Abstract

Some sentences are overly long or repetitive. Consider: Forest fires induce significant environmental changes, with long-term impacts on forest ecosystems and soil properties. These changes affect soil temperature, chemical composition, organic matter content, and microbial communities. This study investigates the alterations in silvicultural properties of Gray Forest soils (Gray Luvisols) in Northwestern Bulgaria following forest fires, considering key variables such as fire type and intensity, time since fire, forest type, and stand density. The results show that forest fires generally reduce soil organic matter and total nitrogen content, alter soil acidity, and affect soil microbial abundance. In particular, low-intensity fires may stimulate microbial activity, whereas high-intensity fires tend to suppress it. These findings provide insights into the mechanisms of post-fire soil transformation and offer a scientific basis for afforestation and land reclamation planning in fire-affected forest areas.

***Key words**: forest fires, soil fertility, silvicultural properties, soil microflora, Gray Luvisols, soil recovery, post-fire management.*

INTRODUCTION

Forest fires, whether natural or anthropogenic in origin, represent a major ecological disturbance with both immediate and long-term consequences for forest ecosystems. One of the most significant effects is the alteration of soil properties, which play a critical role in supporting vegetation recovery and maintaining ecosystem functions.

Soil characteristics are closely tied to vegetation cover and organic matter inputs both of which are drastically altered by fire. The extent and nature of these changes depend on multiple factors, including the type and intensity of the fire, the amount and distribution of combustible material, fuel moisture content, and prevailing weather conditions. These variables introduce considerable variability, making it challenging to generalize the effects of forest fires across different landscapes (Barnes et al., 1998; Kimmins, 1996; DeBano et al., 1998; Bogdanov, 2023a).

Post-fire changes in soils occur on both short- and long-term timescales. Immediately after a fire, the release of energy alters soil temperature regimes and may lead to the combustion of organic matter, volatilization of nutrients, and disruption of soil structure and microbial habitats (Jiménez Esquilín et al., 2008; Neary et al., 1999). Long-term impacts are often associated with increased solar absorption due to surface darkening and reduced organic matter, which can further influence soil temperature and moisture regimes (Molla et al., 2014).

The increase in the concentration of nutrients after a fire is associated with the increase or recovery of the soil microflora. The initial impact of fires usually leads to a decrease in the total amount of microorganisms in the soil, and this is often followed by their increase, which is beneficially affected by the increase in soil temperature (Bogdanov, 2023b).

Microbial communities in soil are particularly sensitive to fire. Initially, fire often results in a decline in microbial abundance and diversity due to elevated temperatures and loss of organic substrates. However, recovery dynamics vary widely. In some cases, microbial populations rebound quickly, facilitated by increased nutrient availability and warmer soil temperatures (Bogdanov, 2023b). The extent of microbial recovery is influenced by both the physical-chemical properties of the soil and the intensity and duration of the fire (Mataix-Solera et al., 2002; Barreiro & Diaz-Ravina, 2021).

In forest management, fires are classified based on the location of fuel consumption (crown, surface, or ground fires) and by their spread and severity. These classifications are important for evaluating the degree of ecological damage and planning appropriate restoration strategies (Bogdanov, 2023a). One of the key post-fire challenges in forestry is the restoration of burned stands, which often cannot regenerate naturally and require targeted afforestation efforts. These efforts depend on a thorough understanding of the soil's silvicultural properties - factors such as organic matter content, nutrient status, and microbial health that determine soil fertility for tree growth (Bogdanov, 2023b).

The present study aims to assess the changes in the silvicultural properties of soils affected by forest fires in Northwestern Bulgaria. Specifically, it analyzes how different factors - fire type and intensity, time elapsed since the fire, forest type, and stand density - affect soil properties such as organic matter, total nitrogen, pH, and microbial abundance. By identifying these relationships, the study contributes to improved understanding of post-fire soil dynamics and supports science-based forest restoration planning.

MATERIALS AND METHODS

Study area and soil classification

The study was conducted in Northwestern Bulgaria, within the territory of the Belogradchik State Forestry. According to Bulgaria's forest-vegetation zoning system (Zahariev et al., 1979), the area is situated in the Lower Forest Vegetation Belt (700-2000 m above sea level) of the Misian Forest Zone.

The soils under investigation are classified as Gray Forest soils (Gray Luvisols), based on the classification system of Penkov et al. (1992). These correspond to the Luvisols soil group in the World Reference Base for Soil Resources (WRB) (IUSS, 2022), with dominant qualifiers being Haplic and Albic (Bogdanov, 2024).

Plot design and sampling procedure

To assess the effects of forest fires, nine paired sample plots (100 m² each) were established - each including a burned area and a corresponding unburned control plot. The plots were selected based on fire history, fire characteristics (type and intensity), forest type (deciduous or coniferous), and stand density (Table 1). Table 1 provides an overview of the plot characteristics, including year of fire occurrence, type and strength of fire, altitude, forest type, and stand density.

Soil samples were collected from the 0-5 cm surface layer, which is known to exhibit the most pronounced post-fire changes (Barnes et al., 1998; Bogdanov, 2023a). For microbiological analysis, all soil samples were collected using sterile tools, placed in sterile bags, and processed within 48 hours to preserve microbial integrity.

Table 1. Characteristics of the sample plots

Sample plots (SP)	Year of the fire	Fire type/strength	Area (1000 m^2)	Altitude (m)	Forest group	Stand density
1	2020	Surface/ Middle	8.0	150	D	0.2
2	2020	Surface/ Middle	4.2	180	D	0.5
3	2020	Surface/ Middle	3.2	200	D	0.5
4	2021	Surface/ Middle	4.4	170	D	0.5
5	2021	Surface/ Middle	1.8	180	C	0.6
6	2022	Crown/ Middle	1.6	180	D	0.5
7	2022	Surface/ Middle	6.0	170	D	0.4
8	2022	Surface/ Strong	2.0	200	D	0.5
9	2022	Surface/ Weak	1.5	200	D	0.4

*D - deciduous; C - coniferous

Fire classification

Within the scope of this study, forest fires were classified based on the visible intensity of their impact on vegetation, following the approach of Bogdanov (2023b). This classification distinguishes between crown fires and surface fires, with further categorization into three levels of severity - weak, medium, and strong.

A strong crown fire involves complete combustion of the tree canopy and stems, corresponding to what is commonly referred to as a "total fire," resulting in the complete destruction of the stand. A medium crown fire also affects the tree crowns but typically results in full stand mortality without complete combustion of all stems. In contrast, a weak crown fire affects the upper canopy more sporadically, causing partial or mosaic mortality within the stand.

Surface fires were characterized by stem scorching at heights ranging from 0.5 to 1.5 meters. A strong surface fire results in significant stem damage and the eventual destruction of the stand. A medium surface fire causes variable mortality within the stand, leading to a mosaic pattern of tree survival. A weak surface fire, while still affecting stem bases within the same height range, does not result in substantial tree mortality.

Laboratory analyses

To analyze the changes in the silvicultural properties of the soil following forest fire events, both primary and supplementary indicators were assessed. The primary indicators included the content of soil organic matter and total nitrogen, which are key determinants of soil fertility. Supplementary indicators - such as soil pH, the carbon-to-nitrogen (C:N) ratio, and the abundance of total soil microflora - were also evaluated, as these parameters are critical to soil biological functioning and are known to undergo significant changes under the influence of fire (Bogdanov, 2023a; Bogdanov, 2023c; Donov, 1976).

Laboratory analyses were conducted using standardized methods. Soil organic matter was determined using the modified Turin method (Filcheva & Tsadilas, 2002). Total nitrogen content was measured using a modified version of the classic Kjeldahl method (ISO 11261:2002). Soil pH was assessed potentiometrically in a water extract. The C:N ratio was calculated based on measured concentrations of carbon and nitrogen, following the method outlined by Bogdanov (2023c). The abundance of total soil microflora was quantified through the method of serial dilutions and inoculation on selective solid nutrient media, followed by incubation (Gousterov et al., 1977). Microbial abundance was expressed in colony-forming units (CFU) per gram of oven-dry soil.

RESULTS AND DISCUSSION

Effects of forest fires on soil organic matter, total Nitrogen, and pH

The analysis of soil samples from burned and corresponding unburned control plots revealed certain changes in the key indicators of soil fertility following forest fires (Table 2).

Table 2. Properties of soils influenced by forest fires

Sample plot (SP)	SOM % M ± SD	Total N % M ± SD	C: N	pH M ± SD
FP 1 Contro l	2.11 ± 0.02 2.35 ± 0.04	0.142 ± 0.003 0.135 ± 0.006	8.6 10.1	5.7 ± 0.007 5.4 ± 0.005
FP 2 Control	2.26 ± 0.05 2.77 ± 0.04	0.121 ± 0.007 0.117 ± 0.007	10.8 13.7	5.9 ± 0.004 5.2 ±0.005
FP 3 Control	1.70 ± 0.04 2.04 ± 0.03	0.173 ± 0.003 0.180 ± 0.005	5.7 6.6	6.1 ± 0.002 5.4 ± 0.002
FP 4 Control	2.17 ± 0.03 2.33 ± 0.05	0.123 ± 0.003 0.135 ± 0.004	10.2 10.0	6.0 ± 0.007 5.2 ± 0.006
FP 5 Control	2.22 ± 0.02 2.48 ± 0.06	0.131 ± 0.005 0.160 ± 0.005	9.8 9.0	6.3 ± 0.004 5.3 ± 0.007
FP 6 Control	2.22 ± 0.04 2.41 ± 0.06	0.110 ± 0.006 0.128 ± 0.003	11.7 10.9	6.2 ± 0.007 5.8 ± 0.007
FP 7 Control	2.21 ± 0.04 2.43 ± 0.04	0.116 ± 0.004 0.120 ± 0.006	11.1 11.7	6.0 ± 0.004 5.5 ± 0.006
FP 8 Control	1.98 ± 0.03 2.61 ± 0.05	0.097 ± 0.002 0.147 ± 0.002	11.8 10.3	6.4 ± 0.005 5.1 ± 0.006
FP 9 Control	2.33 ± 0.05 2.47 ± 0.06	0.132 ± 0.004 0.126 ± 0.005	10.2 11.4	5.4 ± 0.005 5.0 ± 0.007

Note: FP- fire plot, SOM - soil organic matter, M - Mean, SD - Standard Deviation, Amount of soil microflora - 103/g absolutely dry soil

One of the most immediate and pronounced effects observed was the reduction in organic soil matter (SOM). This decline was especially evident in plots affected by moderate to high-intensity fires. The combustion of organic matter during fire events not only reduces humus content but also disrupts soil structure and affects water retention, aeration, and nutrient availability - factors critical to tree growth and regeneration.

Changes in SOM are inherently complex due to the variable composition of organic compounds and the influence of multiple environmental factors, such as topography, microclimate, and vegetation type.

Nevertheless, the consistent decline in SOM across multiple fire-affected plots underscores its vulnerability to fire disturbance and its central role in post-fire soil degradation.

Similarly, total nitrogen content showed a general decrease in the burned plots compared to the control plots. This reduction is attributed to increased soil temperatures during fires, which accelerate volatilization and intensify nitrification processes (Barnes et al., 1998). Furthermore, although microbial populations often recover after fire, the initial microbial decline can lead to immobilization and limited availability of nitrogen in both ammonium and nitrate forms (Bogdanov, 2023a).

The data also indicate an increase in soil pH following fire exposure, suggesting a reduction in acidity. This is commonly observed in post-fire soils and is primarily due to the accumulation of ashes and basic cations such as calcium, magnesium, and potassium. These cations are released during the combustion of organic matter and contribute to an alkaline reaction in the soil solution (Kimmins, 1996). The increase in pH can have both beneficial and detrimental effects depending on the species-specific requirements of the vegetation and microbial communities. High pH levels tend to inhibit the development of micromycetes while favoring the proliferation of non-spore-forming bacteria (Lauber et al., 2009; Ammitzbøll et al., 2022).

These findings clearly demonstrate that forest fires disrupt the balance of key soil properties that are essential for maintaining silvicultural productivity and soil ecological health.

Microbial community responses to fire

The influence of forest fires on soil microbial abundance was assessed by comparing total microbial counts in fire-affected plots and their respective control areas (Figure 1).

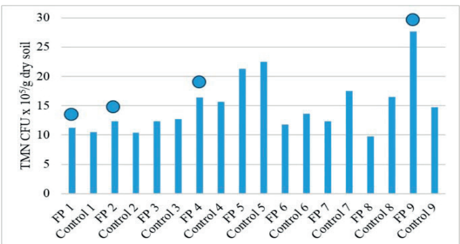

Figure 1. Total microbial number
●Samples with increased TMN compared to controls

The results reveal a heterogeneous response, with no uniform trend across all sites. In some plots - specifically FP1, FP2, FP4, and FP9 - the total microbial number (TMN) was higher in the burned soils than in the control soils. This trend was most pronounced in FP9, where microbial abundance nearly doubled following a low-intensity surface fire. These findings suggest that weak surface fires may not significantly disrupt microbial communities and, under certain conditions, may even stimulate microbial activity due to increased nutrient availability and elevated soil temperatures. In contrast, in the remaining plots, microbial abundance was consistently lower in burned areas compared to controls. The most notable reduction occurred in FP8, which experienced a strong surface fire. Here, microbial counts in the control plot were approximately 40% higher than in the corresponding burned area. This pattern indicates that high-intensity fires exert a stronger suppressive effect on microbial communities, likely due to lethal temperatures and the destruction of habitat and organic substrates. On average, across all other sites (excluding FP8), microbial abundance in control plots was approximately 12.5% higher than in the burned plots. A parallel trend was observed in the population of ammonifying bacteria, which play a vital role in nitrogen cycling (Figure 2). As with total microflora, elevated counts of ammonifying bacteria were recorded in FP1, FP2, and FP9. A marginal increase (approximately 4%) was also observed in FP4. This pattern confirms that ammonifying bacteria constitute a substantial proportion of the total microbial community and respond similarly to fire-induced changes in the soil environment.

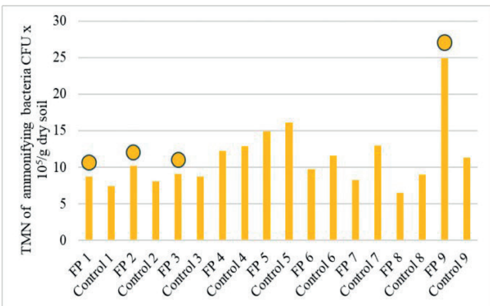

Figure 2. TMN of ammonifying bacteria
●Samples with increased TMN of ammonifying bacteria compared to controls

The variability of microbial responses was further analyzed through the standard distribution of microbial abundance across all sample plots (Figure 3).

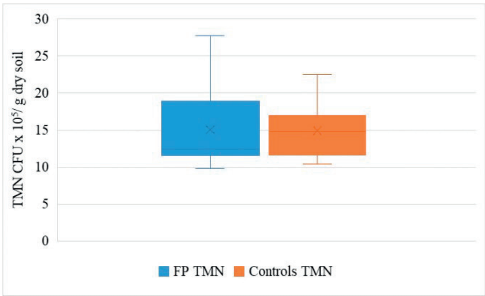

Figure 3. Standard distribution of FPs and Controls

The data show that in the control plots, the mean value closely aligns with the median, indicating a symmetrical distribution of microbial abundance. In contrast, in the burned plots, the mean and median values differ significantly, suggesting a more skewed distribution. In both control and burned areas, the values in the first quartile display a narrow range. However, in the second quartile, the control plots exhibit a wider range (11.5×10^5 to 12.4×10^5 CFU/g of dry soil) compared to the burned plots. This pattern reverses in the third quartile. In the burned plots, 25% of the values fall within a broader range - from 12.4×10^5 to 18.9×10^5 CFU/g - while in the control plots the corresponding range is narrower, from 14.8×10^5 to 17×10^5 CFU/g. A similar trend is observed in the fourth quartile: burned plots exhibit greater variability (18.9×10^5 to 27.8×10^5 CFU/g) than control plots (17×10^5 to 22.5×10^5 CFU/g).

These findings indicate that microbial abundance in burned soils is more variable, reflecting the heterogeneous impact of fire depending on its type and intensity. Such variability underscores the complex influence of fire on soil microbial communities, which play a fundamental role in ecosystem processes in forest environments.

Changes in soil microbial communities resulting from both the direct and indirect effects of forest fires can lead to significant disruptions in ecosystem functions, particularly by slowing the transformation and cycling of nutrients (Mataix-Solera et al., 2009). The impact of fire on soil microbial communities is highly variable and depends on several factors, including fire intensity, duration, and depth of penetration into the soil (Yeager et al., 2005). In some cases, high-intensity fires can lead to near-complete sterilization of the soil, whereas in other instances, fires may have minimal long-term effects on microbial populations (Vázquez et al., 1993).

Zhou et al. (2014) emphasized that the loss of soil microbial life following a fire is not only due to elevated temperatures but also to post-fire conditions that inhibit microbial recovery. In a more recent study, Zhou et al. (2024) further noted that the strength of a fire's impact on microbial communities is influenced by multiple factors, including its intensity, duration, and the depth of soil affected.

The findings of the present study support the idea that, although there is an initial decline in microbial populations after fire, in some cases, microbial abundance may increase beyond control levels in the post-fire environment. This pattern was observed in plots FP1, FP2, FP4, and FP9 (Figure 1). The observed increase in microbial abundance is likely driven by elevated soil temperatures and the enhanced availability of nutrients released during the combustion of organic matter - conditions that can temporarily boost the biogenicity of soils in fire-affected areas (Bogdanov, 2023a; 2023b).

Correlation analysis between microbiological and soil properties

To better understand the relationships between microbial parameters and the physicochemical properties of fire-affected soils, a correlation analysis was conducted. The focus was on examining how total microbial number (TMN) and ammonifying bacteria relate to key soil indicators, including soil organic matter, total nitrogen, and pH. A strong positive correlation was found between the abundance of ammonifying bacteria and the total microbial number in both burned and control plots. However, this relationship was notably stronger in burned areas, where the correlation coefficient reached $r = 0.97$ (Figure 4), compared to $r = 0.87$ in control plots (Figure 5). These results suggest that ammonifying bacteria constitute a substantial proportion of the total microbial community, especially under post-fire conditions. This observation is consistent with previous research indicating that fire-altered environments can accelerate nitrogen cycling by enhancing the conversion of ammonium to nitrate (Duran et al., 2008; Ball et al., 2010).

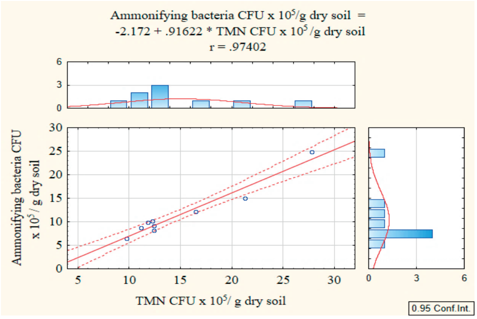

Figure 4. Correlation between TMN and number of ammonifying bacteria in Fire

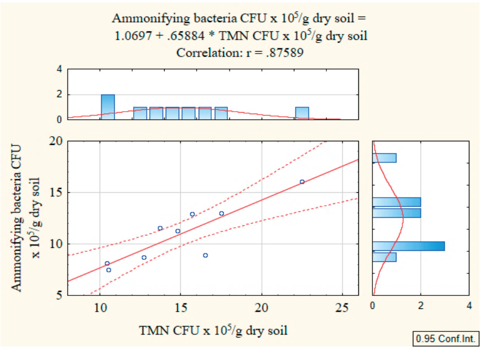

Figure 5. Correlation between TMN and number of ammonifying bacteria in Control Plots

Further analysis explored the relationship between microbial abundance and environmental factors. In unburned control plots, no statistically significant correlations were found between TMN and the soil's organic matter content (r = 0.05), total nitrogen (r = 0.26), or pH (r = –0.09). Similarly, no meaningful correlations were observed between ammonifying bacteria and these soil parameters in the control areas.

In contrast, several noteworthy correlations emerged in burned plots. A moderate positive correlation was identified between TMN and organic matter content (r = 0.48; Figure 6), suggesting that soils with higher residual organic content support a more robust microbial community even after fire. This indicates that partial retention of organic matter can buffer microbial populations against fire-induced decline.

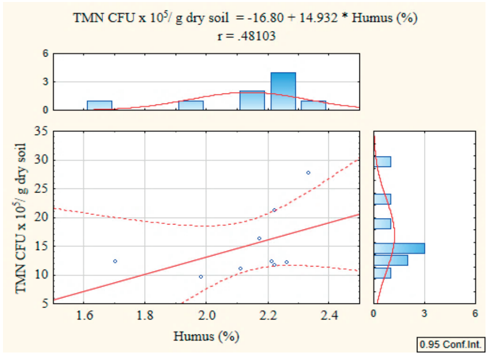

Figure 6. Correlation between total microbial number and humus (%) in fire plots

No significant correlation was found between total nitrogen content and total microbial number (TMN), with a correlation coefficient of r = 0.16, indicating a weak and statistically insignificant relationship. In contrast, the correlation between soil pH and TMN revealed a moderate negative association (r = –0.51, Figure 7), similar to the relationship observed between TMN and soil organic matter.

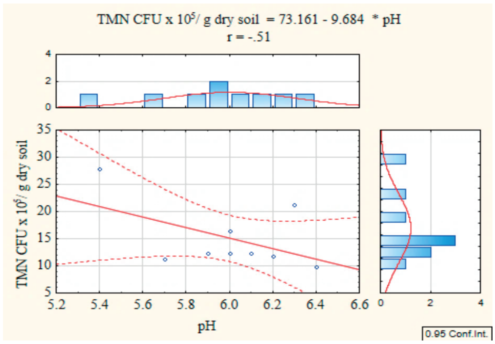

Figure 7. Correlation between total microbial number and pH in fire plots

This inverse correlation suggests that microbial abundance tends to be higher in more acidic soils. This pattern may be attributed to the high sensitivity of soil microbial communities to variations in pH following fire. Even slight deviations from pre-fire acidity levels, when compared to those in control plots, appear to have a positive influence on microbial activity. In such transitional conditions, reduced environmental stress may promote microbial adaptation and facilitate recovery.

These observations highlight the need for more nuanced, multifactorial investigations into the complex interactions between post-fire soil chemistry and microbial dynamics. Notably, previous studies have identified soil pH as a key determinant in structuring the composition and diversity of microbial communities, especially in ecosystems subjected to disturbance events such as wildfires (Lauber et al., 2009).

The strongest correlation observed was between soil pH and the abundance of ammonifying bacteria, with a correlation coefficient of r = –0.63 (Figure 8).

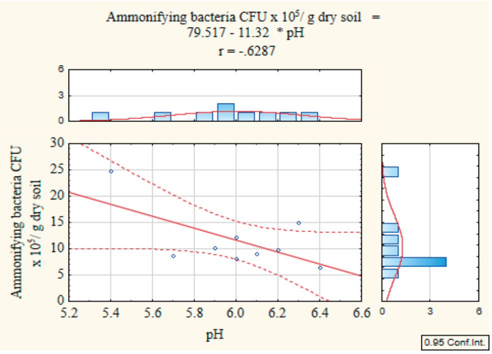

Figure 8. Correlation between number of ammonifying bacteria and pH in fire plots

This significant inverse relationship indicates that the activity of ammonifying bacteria is closely influenced by soil acidity. The findings suggest that microbial communities are particularly responsive to shifts in pH, with greater abundance occurring in soils where acidity levels remain closer to pre-fire conditions.

It is likely that in environments where pH changes are minimal, microbial stress is reduced, allowing for better survival and function of sensitive groups such as ammonifiers. However, to fully understand the thresholds and resilience of microbial communities under more extreme conditions, further research is required, particularly in sites that experience substantial post-fire shifts in soil pH.

Influence of stand density on soil properties after fire

Soil properties are strongly influenced by vegetation cover and the accumulation of organic matter, both of which are significantly altered by fire. The extent of these changes depends largely on the intensity of the fire and the volume of biomass consumed during combustion (Kimmins, 1996). As fire affects vegetation structure and organic inputs, it can lead to substantial modifications in soil chemical and biological characteristics.

In this context, it is particularly important to examine how stand density influences post-fire soil dynamics, as it determines both the amount and spatial distribution of combustible material. In the present study, soils beneath stands of differing densities - 0.2 and 0.5 - were analyzed. Both stands experienced fires of comparable type and intensity, allowing for a focused comparison of density-related effects. The changes in key soil properties, expressed as percentage differences relative to unburned control plots, are illustrated in Figure 9.

Although differences in total nitrogen content remained relatively minor three years after the fire, the stand with higher density exhibited notably higher pH values compared to the unburned control. This increase can be attributed to the combustion of a larger volume of organic matter and the subsequent release of base cations (e.g., Ca^{2+}, Mg^{2+}, K^{+}), which contribute to soil alkalization (Figure 9).

The soil organic matter content in the denser stand was significantly lower, reflecting a higher degree of fire impact due to the increased volume of biomass consumed. This trend was consistent with observed differences in both the C:N ratio and the abundance of total microflora. Following a fire, elevated soil temperatures and enhanced nutrient solubility can stimulate microbial growth in some cases; however, intense fires may lead to the near-complete destruction of microbial communities (Bogdanov, 2023a).

In line with this, the carbon-to-nitrogen (C:N) ratio - an indicator of the rate of organic matter decomposition - was significantly lower in the denser stand. This suggests more rapid mineralization of organic residues, likely driven by post-fire microbial activity and favorable thermal and chemical conditions resulting from a more severe fire impact (Figure 9).

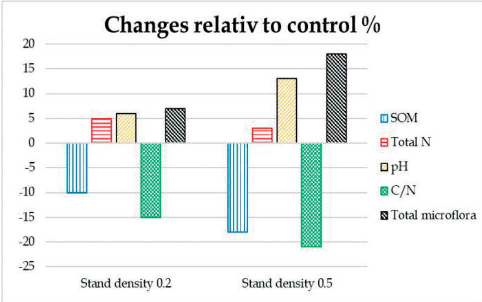

Figure 9. Change in the studied indicators in burned soils compared to control plots depending on the stand density

Influence of forest type on post-fire changes in soil silvicultural properties

To evaluate the influence of forest type on soil response to fire, soil samples were analyzed from both coniferous and deciduous stands affected by moderate-intensity surface fires in 2021, along with samples from their corresponding unburned control plots. The aim was to determine how forest composition affects post-fire changes in silvicultural soil properties.

The results indicate that fire-induced changes were more substantial and persistent in soils under coniferous stands. This finding is consistent with previous studies and can be attributed to the higher combustibility of coniferous litter, which results in more intense and longer-lasting fires compared to those in deciduous forests (Bogdanov, 2023b; Velizarova, 2011). The most significant difference was observed in total nitrogen content, where the largest reduction, relative to the control, occurred in the coniferous stand (Figure 10).

Similar trends were observed for organic soil matter, pH, and the C:N ratio. In all cases, greater deviations from the control were recorded under coniferous stands, indicating more intense alteration of soil chemistry. These changes reflect both the severity of the fire and the nature of the organic material present in coniferous ecosystems, which tends to burn more thoroughly and penetrate deeper into the soil profile. In contrast, the total microbial abundance showed an inverse pattern, though within a narrow margin of 5%. In the deciduous stand, microbial numbers slightly increased post-fire, while in the coniferous stand, they slightly decreased. This discrepancy may be explained by the deeper thermal impact under conifers, which likely caused a greater initial decline in microbial populations. In deciduous forests, the fire's effects appear to have been more superficial, allowing microbial communities to recover more quickly or even benefit from short-term post-fire conditions.

These findings underscore the importance of forest composition as a key factor influencing soil resilience and recovery after fire. From a silvicultural perspective, deciduous stands may offer a degree of natural protection against severe soil degradation, supporting more stable post-fire ecosystem recovery.

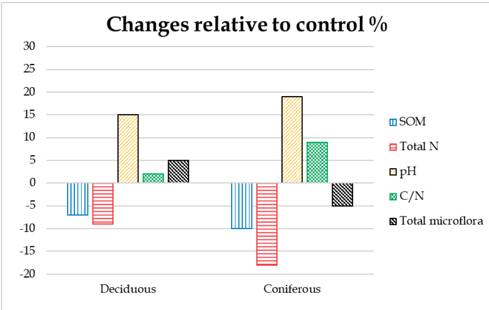

Figure 10. Changes in the studied soil indicators in burned plots compared to control plots, grouped by forest type

Effects of fire type on silvicultural properties of soil

The spatial characteristics of a forest fire - whether it is a surface fire or a crown fire - significantly influence the degree and depth of soil disturbance. These fire types differ in terms of fuel consumption patterns, heat transfer to the soil, and post-fire ecological consequences. In this study, changes in soil properties were analyzed in two forest stands with similar silvicultural characteristics that experienced medium-intensity crown and surface fires in 2022 (SP6 and SP7, respectively), along with their corresponding control plots.

The comparative analysis revealed notable differences in the response of silvicultural soil indicators based on fire type (Figure 11). More pronounced changes were observed in the surface fire-affected plot, particularly in terms of total microflora abundance, total nitrogen content, and the C:N ratio. In this case, microbial populations and nitrogen content decreased more significantly, likely due to more intense heat transfer into the upper soil layers and increased combustion of surface organic matter. The C:N ratio increased in soils affected by crown fires, while it decreased in those affected by surface fires. This suggests that in the case of crown fires, the decomposition of organic matter slowed down, a finding further supported by the observed reduction in total nitrogen content. In contrast, the soil affected by the surface fire exhibited an accelerated rate of organic matter mineralization, as indicated by the lower C:N ratio - even though total nitrogen levels also declined (Figure 11). These opposing trends reflect the distinct thermal and biological impacts associated with each fire type.

This contrasting pattern can be explained by the differing ecological consequences of the two fire types. Moderate-intensity surface fires typically result in mosaic tree mortality, allowing partial canopy retention and less drastic alteration of microclimatic conditions. In contrast, moderate-intensity crown fires often lead to complete stand mortality, causing more abrupt and extensive changes in light, temperature, and moisture regimes. These environmental shifts have a significant influence on the intensity and direction of organic matter transformation in the soil. These findings suggest that the type of forest fire, determined by the spatial distribution of combustible materials, exerts an indirect yet significant impact on the silvicultural properties of soil - primarily through its influence on the rate and dynamics of organic matter decomposition.

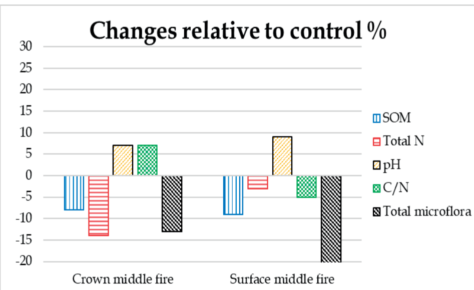

Figure 11. Change of the studied indicators in burnt soils compared to control plots depending on the type of fire

Effects of fire intensity on silvicultural soil properties

The intensity or strength of a forest fire plays a crucial role in determining the extent of its impact on soil properties. To examine this effect, soil samples were analyzed from areas affected by a weak surface fire and a strong surface fire, both occurring in 2022, along with their respective unburned control plots. The results, presented as percentage changes relative to the controls, are summarized in Figure 12.

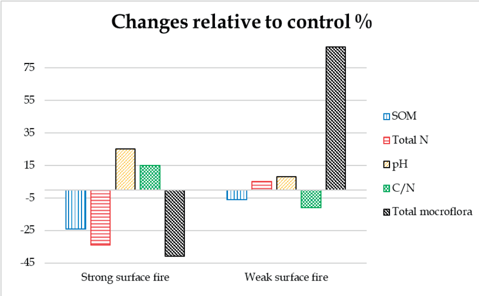

Figure 12. Change of the studied indicators in burnt soils compared to control plots depending on the strength of the fire impact

The analysis revealed that all soil indicators were influenced by fire strength, with the most pronounced changes observed in the strongly burned plots. In areas affected by weak surface fires, the combustion of organic matter was relatively limited, resulting in a slight increase in total nitrogen and minimal changes in pH. In this case, a moderate rise in soil temperature likely stimulated microbial activity, which led to a decrease in the C:N ratio, indicating enhanced decomposition and mineralization of organic material.

Conversely, strong surface fires caused more substantial degradation of silvicultural soil properties. A significant reduction in soil organic matter was observed, accompanied by a decline in total nitrogen content. The more intense combustion released higher quantities of base cations, resulting in elevated soil pH, while simultaneously creating conditions less favorable for microbial recovery. This was reflected in the lower abundance of soil microflora and a higher C:N ratio, suggesting that microbial processes related to organic matter turnover were suppressed.

These findings underscore the fact that fire severity amplifies the disruption of soil fertility, not only by physically consuming organic substrates, but also by altering the chemical and biological environment essential for post-fire recovery. Understanding these variations is critical for predicting the resilience of forest soils and planning appropriate post-fire management strategies.

Temporal changes in silvicultural soil properties following forest fire

Changes in the silvicultural properties of soil following forest fires were examined as a function of time since the disturbance, based on the analysis of soil samples collected from areas affected by fires of similar characteristics in 2020 and 2022.

The results indicate that all studied soil indicators exhibited more pronounced deviations from control values in the more recently burned plots (2022), while the soils affected by the 2020 fire showed changes of reduced magnitude (Figure 13). This trend suggests a gradual recovery of silvicultural soil properties over time.

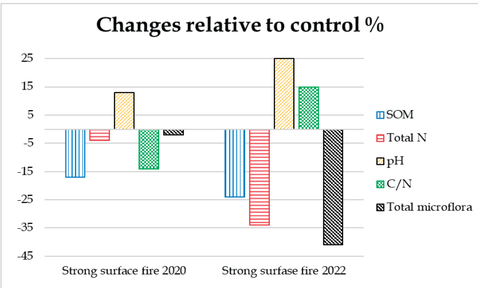

Figure 13. Change of the studied indicators in burnt soils compared to control plots depending on the time after the fire impact

These findings demonstrate that the impact of forest fires on soil silvicultural properties is not necessarily permanent, and that recovery processes can begin within a few years, depending on fire severity and site conditions. However, the rate and completeness of recovery are strongly influenced by factors such as vegetation type, post-fire management, and climatic conditions. This underscores the importance of timing in the implementation of restoration measures, which should consider the post-fire developmental stage of the soil ecosystem to align with periods of optimal nutrient availability and biological activity.

CONCLUSIONS

Forest fires have a pronounced negative impact on the silvicultural properties of soils, primarily through the reduction of soil organic matter and, in most cases, total nitrogen content. Additionally, fires often alter soil pH, creating conditions that may be incompatible with the ecological requirements of dominant tree species.

The response of soil microflora is strongly influenced by fire intensity. While low-intensity fires can stimulate microbial development by increasing soil temperature and releasing readily available nutrients from burned organic matter, high-intensity fires may lead to near-complete microbial destruction and hinder community recovery. In several sampled sites - particularly those affected by weak surface fires - microbial abundance exceeded that of the unburned controls, highlighting the potential for short-term biological enrichment under mild fire conditions. Furthermore, correlations between environmental factors and microbial abundance were observed in burned areas, whereas such relationships were absent in control soils. Notably, microbial suppression was more severe in coniferous stands than in deciduous stands under equivalent fire conditions, likely due to the higher combustibility of coniferous biomass. Stand density was also found to be a critical factor. Higher density forests tend to accumulate more biomass, which, when burned, leads to more severe and longer-lasting impacts on soil properties. Similarly, fires in coniferous forests resulted in more significant and persistent changes than those in deciduous stands, again linked to differences in fuel load and combustibility.

The type of fire - whether surface or crown - was shown to influence soil conditions indirectly, primarily through its effects on the rate and nature of organic matter transformation. In contrast, fire intensity and the time elapsed since the fire had a direct and measurable effect on all assessed soil indicators. These results demonstrate that the changes induced by forest fires are not irreversible; recovery is possible under favorable conditions, especially if supported by appropriate post-fire management.

Restoration efforts in burned areas should be tailored to specific changes in soil composition and fertility, considering the time since the fire and the temporary increase in nutrient availability. Special attention should be given to coniferous plantations in the Lower Forest Vegetation Belt, which are particularly vulnerable to fire. In these areas, afforestation using native deciduous species, along with timely silvicultural interventions, is essential for reducing long-term fire risk and promoting ecological stability.

This study provides a valuable reference for future in-depth investigations on the topic and offers a practical foundation for developing forest restoration and afforestation strategies in fire-affected regions.

REFERENCES

Ammitzbøll, H., Jordan, J., Baker, C., Freeman, J., & Bissett, A. (2022). Contrasting successional responses of soil bacteria and fungi to post-logging burn severity. *Forest Ecology and Management, 508*, 120059. https://doi.org/10.1016/j.foreco.2022.120059

Ball, P., MacKenzie, M., & Holben, W. (2010). Wildfire and charcoal enhance nitrification and ammonium-oxidizing bacterial abundance in dry montane forest soils. *Journal of Environmental Quality, 39*(4), 1243–1253. https://doi.org/10.2134/jeq2009.0082

Barreiro, A., & Díaz-Raviña, M. (2021). Fire impacts on soil microorganisms: Mass, activity, and diversity. *Current Opinion in Environmental Science & Health, 22*, 100264. https://doi.org/10.1016/j.coesh.2021.100264

Barnes, B. V., Zak, D. R., Denton, S. R., Spurr, S. H. (1998). *Fire and the Forest Site*. Forest Ecology. 4th ed. pp. 290-297.

Bogdanov, S. (2023a). *Soil characteristics changes in soils of class Luvisols influenced by forest fires*. Avangard Prima (in Bulgarian).

Bogdanov, S. (2023b). Changes in silvicultural properties of soils influenced by forest fires in Bulgaria. *Ecological Engineering and Environmental Protection, 3–4*(2023), 69–76 (in Bulgarian).

Bogdanov, S. (2023c). *Manual for exercises in forest soil science*. Publishing House at LTU. (in Bulgarian)

Bogdanov, S. (2024). *Forest soil science* (p. 226). LTU Publishing House (in Bulgarian).

Donov, V. (1976). *Assessment of forest soils* (p. 168). Zemizdat (in Bulgarian).

Gousterov, G., Todorov, Z., & Kominkov, K. (1977). *Manual of microbiology* (p. 180). Nauka i Izkustvo (in Bulgarian).

ISO 11261:2002. (2002). *Soil quality - Determination of total nitrogen - Modified Kjeldahl method*. International Organization for Standardization.

IUSS Working Group WRB. (2022). *World reference base for soil resources, 4th edition*. International Union of Soil Sciences (IUSS). https://www3.ls.tum.de/boku/?id=141

Jiménez Esquilín, A. E., Stromberger, M. E., Massman, W. J., Frank, J. M., & Shepperd, W. D. (2008). Microbial community structure and activity in a Colorado Rocky Mountain forest soil scarred by slash pile burning. *Soil Biology and Biochemistry, 40*(9), 2472–2480. https://doi.org/10.1016/j.soilbio.2008.06.005

Kimmins, J. P. (1996). *Forest ecology: A foundation for sustainable management* (2nd ed.). Prentice Hall.

Lauber, C. L., Hamady, M., Knight, R., & Fierer, N. (2009). Pyrosequencing-based assessment of soil pH as a predictor of soil bacterial community structure at the continental scale. *Applied and Environmental Microbiology, 75*(15), 5111–5120. https://doi.org/10.1128/AEM.00335-09

Mataix-Solera, J., Guerrero, C., García-Orenes, F., Bárcenas, G., & Pascual, J. A. (2009). Forest fire effects on soil microbiology. In A. Cerdà & P. R. Robichaud (Eds.), *Fire effects on soils and restoration strategies* (pp. 133–175). Science Publishers.

Molla, I., Ilieva, I., Donov, V., Iliev, N., & Atanassova, V. (2014). Some changes of physical soil properties as a result of forest fire. *Ecologia Balkanica, 6*(1), 71–76.

Neary, D. G., Klopatek, C. C., DeBano, L. F., & Ffolliott, P. F. (1999). Fire effects on belowground sustainability: A review and synthesis. *Forest Ecology and Management, 122*(1–2), 51–71. https://doi.org/10.1016/S0378-1127(99)00032-8

Penkov, M., Yolev, I., Enikova, M., Donov, V., & Blagoeva, R. (1992). *Classification and diagnostics of the soils in Bulgaria*. Zemizdat (in Bulgarian).

Vázquez, F. J., Acea, M. J., & Carballas, T. (1993). Soil microbial populations after wildfire. *FEMS Microbiology Ecology, 13*(2), 93–103. https://doi.org/10.1111/j.1574-6941.1993.tb00040.x

Velizarova, E. (2011). Fire risk in pine plantations in Bulgaria. *Ecological Engineering and Environmental Protection, 2*, 11–17 (in Bulgarian).

Yeager, C. M., Northup, D. E., Grow, C. C., Barns, S. M., & Kuske, C. R. (2005). Changes in nitrogen-fixing and ammonia-oxidizing bacterial communities in soil of a mixed conifer forest after wildfire. *Applied and Environmental Microbiology, 71*(5), 2713–2722. https://doi.org/10.1128/AEM.71.5.2713-2722.2005

Zahariev, B., Donov, V., Petrunov, K., & Masarov, S. (1979). *Forestry-vegetation zoning of the NRB* (p. 197). Zemizdat (in Bulgarian).

Zhou, H., Yang, M., Luo, X., Yang, Z., Wang, L., Liu, S., Zhang, Q., Luo, M., Ou, J., Xiong, S., Qin, Y., & Li, Y. (2024). Short-term impacts of fire and post-fire restoration methods on soil properties and microbial characteristics in Southern China. *Fire, 7*(12), 474. https://doi.org/10.3390/fire7120474