Effects of Simulated Fire Disturbance on Forest Soil Microbial Activity and Nitrogen Mineralization: Postprint

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Abstract

Fire disturbance generates thermal energy that induces chemical oxidation of soil organic matter, alters carbon and nitrogen transformations, and severely impacts soil structure and function, with the extent of impact depending on fire intensity, duration of fire disturbance, and heat penetration. This study investigated the effects of fire disturbance on soil microorganisms and nitrogen mineralization through an experimental design and analysis of variance employing two soil types, three temperatures, and three soil water potentials at a burned site of a Pinus massoniana secondary forest at Gaojian Forest Farm, Zhuzhou City, Hunan Province. The results indicated that inorganic nitrogen concentration was positively correlated with fire intensity and initial soil organic matter content; in the short term following fire disturbance, soil carbon and nitrogen concentrations were elevated, while microbial biomass carbon and potentially mineralizable nitrogen were reduced, and temperature and soil water potential had no significant effect on basal respiration rate; when soil temperature reached 160°C, the concentration of potentially mineralizable nitrogen in unburned soil increased rapidly and unstably, while at 350°C, 90% of non-microbial tissue was destroyed; soil water potential after heating had a significant effect on the nitrogen mineralization process, with higher water potentials resulting in greater losses of potentially mineralizable nitrogen, and a positive correlation existed between water content and nitrate nitrogen in fire-disturbed soils; during the 14-day incubation period, soil fire history, heat treatment, and soil water potential significantly affected microbial activity and carbon and nitrogen mineralization, with the highest microbial biomass carbon content observed in both soils when heated to 380°C at -1.5 MPa water potential, and soil water potential was negatively correlated with soluble sugars; the interaction between water potential and fire disturbance significantly affected microbial activity and nitrogen transformation, with low water potential soils showing higher concentrations of microbial biomass carbon, soluble sugars, and potentially mineralizable nitrogen.

Full Text

Simulating the Effects of Fire Disturbance on Microbial Activity and Nitrogen Mineralization in Forest Soil

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Abstract

Fire disturbance generates thermal energy that induces chemical oxidation of soil organic matter, altering carbon (C) and nitrogen (N) transformations and profoundly affecting soil structure and functions. The extent of oxidation depends on fire intensity, duration, and heat penetration. This study investigated the effects of fire disturbance on soil microbial activity and N mineralization using a burned area of secondary *Pinus massoniana* forest at the Gaojian State Forest Farm in Zhuzhou, Hunan Province. The experiment employed a completely randomized design with two soil types, three heating temperatures (25°C, 160°C, and 380°C), and three soil water potentials (-0.03 MPa, -1.0 MPa, and -1.5 MPa), with three replicates per treatment. Variance analysis revealed that inorganic N concentration and initial soil organic matter content were positively correlated with fire intensity. Shortly after fire disturbance, soil C and N concentrations were elevated, while microbial biomass C and potentially mineralizable nitrogen (PMN) were reduced. Temperature and soil water potential showed no significant effect on basal respiration rates. Compared to unburned soils, fire-disturbed soils exhibited PMN loss. When soil temperature reached 160°C, only a modest increase in PMN concentration occurred in previously unburned soils; however, when temperature exceeded 160°C, PMN content fluctuated before increasing rapidly. At 380°C, 90% of non-microbial tissues were destroyed. Post-heating soil water potential significantly influenced N mineralization, with higher water potentials resulting in greater PMN loss. A positive correlation was observed between water content of fire-disturbed soil and nitrate N. During a 14-day incubation, microbial activity and C and N mineralization were significantly affected by soil fire history, initial heat treatment, and soil water potential. The release of available C and N from fire disturbance supported microbial activity recovery at low water potentials. When soil was heated to 380°C at -1.5 MPa water potential, microbial biomass C reached its highest value in both soils. A negative correlation between soil water potential and soluble sugar was observed for both soils. The concentration of soluble anthrone-reactive carbon (ARC) decreased significantly ($P<0.05$) over time due to microbial consumption of sugars released by fire disturbance. The interaction between water potential and fire disturbance significantly affected microbial activity and N conversion, with low

water potential soils exhibiting high microbial biomass C, soluble sugar, and PMN concentrations.

Keywords: *Pinus massoniana*; secondary forest; fire disturbance; microbe; nitrogen mineralization

Introduction

Fire disturbance exerts complex effects on forest ecosystems by promoting oxidation of soil organic matter and altering its chemical composition. The degree of oxidation depends on fire temperature, duration, and soil heat penetration. Fire directly consumes vegetation, and at extremely high temperatures, causes nitrogen volatilization. Thermally-sensitive microorganisms are killed, and the resulting dead plant and microbial material rapidly oxidizes to inorganic N. Increased soil temperature alters the specific heat and thermal conductivity properties of soil water, making water content a primary factor in assessing fire effects on soil biological and physicochemical properties. The latent heat of vaporization can prevent soil temperature from exceeding 95°C until water completely evaporates. In moist soils, heat conduction occurs more rapidly, and this latent heat effect fails to protect heat-sensitive microorganisms, proving fatal for most high-temperature-resistant microbes.

Numerous studies have demonstrated that prescribed burning can improve forest quality and soil nutrient concentrations in the short term. To avoid fire risks, prescribed burning is typically conducted during relatively moist seasons such as winter and late spring. In contrast, wildfires generally occur during dry seasons when soil moisture and organic layer water are depleted. Recent research has focused on how fire-induced soil heating affects carbon and nitrogen dynamics in forest mineral soils, providing a theoretical basis for soil recovery. This study simulated the effects of low-intensity fire disturbance on soils during both wet and dry seasons to examine how post-fire changes in soil moisture and temperature affect soil microbial activity and how fire history influences post-fire soil ecosystem recovery.

Study Area

The study was conducted at the Gaojian State Forest Farm in You County, Hunan Province, using a secondary *Pinus massoniana* forest. The site features a southern hilly landscape with parent materials primarily consisting of purple sandstone, shale, and Quaternary red clay. Sample plots and profiles were established on a northeast-facing slope (25±5°) at 800 m elevation, with a mean annual temperature of 17.8°C and annual precipitation of 1410 mm .

Soil samples were collected from two locations: a recently burned area (moderate-intensity fire) and an unburned forest stand. Both sites had similar soil types, stand ages, and species composition. The physical and chemical characteristics of the soils are presented in .

Physical and chemical characteristics of soil

Parameter	No fire disturbance	Fire disturbance
Total C (g/kg)	127.2	105.3
Total N (g/kg)	[value missing]	[value missing]
Biomass C (g/g)	[value missing]	[value missing]
Potential mineralizable N (PMN) (g/g)	[value missing]	[value missing]

Methods

Experimental Design

The experiment utilized a 2×3×3 factorial design representing two soil types (unburned and fire-disturbed), three heating temperatures (25°C, 160°C, and 380°C), and three soil water potentials (-0.03 MPa, -1.0 MPa, and -1.5 MPa). Each treatment was replicated three times. Soil samples were collected simultaneously from both unburned and moderately burned plots. Within each stand, 20 m × 20 m plots were established, and soil profiles were randomly selected. Samples from the 0–10 cm depth were collected, sieved through a 2 mm mesh, and stored for analysis. To simulate soil water potentials, subsamples from both soil sets were adjusted to -0.03, -1.0, and -1.5 MPa. Soil samples were placed in metal sealed containers on a preheated muffle furnace for 30 minutes at the target temperatures while monitoring weight changes.

Laboratory Analysis

Soil samples were extracted immediately after heating, including both room-temperature controls and heated treatments. Ammonium N and nitrate N were determined by the salicylic acid nitrification method [16]. Microbial biomass was measured by the ninhydrin reaction method [17-18]. Microbial carbon was calculated as the difference between fumigated and non-fumigated samples multiplied by a conversion factor. Potential mineralizable nitrogen (PMN) was determined through incubation under controlled conditions, with KCl added and samples shaken for 30 minutes. PMN values reflected the difference in ammonium N between incubated and non-incubated samples. Soluble hexose concentration was measured using the anthrone reaction, and microbial respiration was determined by alkaline trap after aerobic incubation [19]. Fresh soil samples were maintained at 0.5 M water-holding capacity in glass bottles and incubated for 3, 7, and 14 days, followed by titration with HCl solution.

Statistical Analysis

All data were analyzed using three-factor ANOVA, which confirmed that no data violated ANOVA assumptions. Statistical Analysis System (SAS Institute) software was used for all analyses [20].

Results

Short-Term Effects

Fire disturbance significantly impacted soil biochemical processes. Microbial biomass C decreased rapidly following fire exposure, with the most severe reductions occurring at higher temperatures. In recently burned soils, carbon and nitrogen concentrations were elevated, while microbial biomass C and potentially mineralizable nitrogen (PMN) were reduced. A significant interaction existed between fire history and heating temperature on microbial biomass C. At 160°C and 380°C, soil biomass C decreased compared to control soils, with greater losses observed at 380°C.

Temperature and soil water potential showed no significant short-term effects on basal respiration rates, as soil respiration is primarily controlled by the combined influence of moisture and temperature [21]. The experimental temperatures resulted in more heat radiating upward than conducting downward, minimizing effects on deeper soil layers and soil moisture content.

Heating caused ammonium N to release from oxidized organic matter, with average concentrations increasing at 160°C. However, heating showed no significant effect on nitrate N concentration, regardless of fire history. The interaction between water potential and fire history significantly influenced microbial activity and N conversion, with low water potential soils exhibiting high microbial biomass C, soluble sugar, and PMN concentrations. These patterns are illustrated in [Figure 1: see original paper], which shows differences in soil microbial biomass C, soluble sugars, basal respiration, PMN, ammonium N, and nitrate N across temperature and moisture levels.

Heating Treatment Effects

At -1.5 MPa water potential, microbial biomass C concentration was lowest after heating, though soluble sugar content remained significantly higher than in control soils. At -0.03 MPa water potential, microbial biomass C reached its highest concentration in both soils. A negative correlation existed between soil water potential and soluble sugar concentration, with greater accumulation occurring in dry soils. The most intense CO evolution occurred at -0.03 MPa water potential.

During the 14-day incubation, PMN decreased in both soils. Unburned soils maintained higher ammonium N concentrations, which decreased over time while nitrate N concentrations increased. High water potential control soils exhibited very low PMN content. The increase in soluble sugars after heating was consistent with previous research showing that drying and rewetting events cause soluble sugar release, which gradually returns to pre-fire levels [16]. These effects across the three water potentials are shown in [Figure 2: see original paper].

The interaction between water potential and fire disturbance significantly affected microbial activity and N conversion. Fire-disturbed soils lost more PMN than unburned soils, attributable to heat-induced volatilization and mineralization of unstable N. Unstable N loss was significantly less under low-intensity fire compared to moderate-intensity fire. Soil water potential after heating significantly influenced the N mineralization process, with higher water potentials resulting in greater PMN loss. A positive correlation existed between water content of fire-disturbed soil and nitrate N. After 14 days of exposure to three temperatures, the differences in microbial biomass, soluble sugars, and basal respiration across three soil water potentials are shown in [Figure 3: see original paper], while [Figure 4: see original paper] illustrates the differences in PMN, ammonium N, and nitrate N.

Discussion

The experimental temperatures primarily affected the surface soil layer (0–3 cm). During fire, heat transfer to the mineral soil layer influences the insulating effect of the porous medium and latent heat of vaporization [24]. The results clearly demonstrate that soil moisture and fire history substantially impact soil biochemical properties.

Shortly after fire disturbance, soil C and N concentrations were elevated while microbial biomass C and PMN were reduced. A significant relationship existed between fire history, heating temperature, and microbial biomass C, with biomass loss increasing with fire temperature. The lower initial microbial biomass C in fire-disturbed soils was associated with previous carbon loss and microbial mortality from prior fire events [19].

When soil temperature reached 160°C, PMN concentration increased rapidly and unstably in unburned soils due to thermal destruction of soil organic matter and microbial tissue. This aligns with findings that inorganic N concentration is positively correlated with fire intensity and initial soil organic matter content [13]. The destruction of non-microbial tissues at 380°C resulted in substantial N loss.

The interaction between water potential and fire disturbance significantly affected microbial activity and N conversion. Low water potential soils exhibited high microbial biomass C, soluble sugar, and PMN concentrations. Under average moisture conditions, the interaction between fire disturbance and heating temperature significantly influenced soil ammonium N. The release of C and N from fire disturbance supported microbial activity recovery in low water potential soils, while newly formed labile N remained protected in low water potential conditions.

Conclusion

This study demonstrates that fire history, soil water potential, and fire disturbance significantly influence soil biochemical characteristics. The experimental temperatures primarily affected the surface layer, with heat radiating upward and conducting minimally downward. Shortly after fire disturbance, elevated soil C and N concentrations coincided with reduced microbial biomass C and PMN. The interaction between water potential and fire disturbance significantly affected microbial activity and N conversion, with low water potential soils showing higher microbial biomass C, soluble sugar, and PMN concentrations. These findings provide important insights into the mechanisms of soil recovery following fire disturbance and highlight the critical role of soil moisture in post-fire nitrogen dynamics.

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Note: Figure translations are in progress. See original paper for figures.