Soil Nitrogen Mineralization Response to Temperature in Communities at Different Successional Stages in Xinglong Mountain, Gansu (Postprint)

Authors: Tang Weichun, Liu Xiao'e, Su Shiping, Tian Xiaojuan, Tang Qingtong, Zhang Jing

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Abstract

Soil nitrogen mineralization is a key process in soil nitrogen cycling, and temperature is one of the most important factors affecting soil nitrogen mineralization. Investigating the effects of temperature variation on soil nitrogen mineralization characteristics in communities at different successional stages is of great significance for elucidating soil nitrogen cycling processes in terrestrial ecosystems. This study took communities at different successional stages in Xinglong Mountain, Gansu Province as research objects, and employed the indoor constant-temperature aerobic incubation method to examine soil nitrogen mineralization characteristics of communities at different successional stages [grassland, shrubland, Betula platyphylla forest, Picea wilsonii-Betula platyphylla forest, and Picea wilsonii forest] at different temperatures (15 °C, 25 °C, and 35 °C). The results showed that: (1) Except for the 0-20 cm soil layer of grassland, the soil nitrogen mineralization rate of communities at other successional stages increased with increasing temperature (15-35 °C), and the cumulative soil nitrogen mineralization amount of communities at different successional stages also increased with increasing temperature; (2) With forward progression of succession, both soil nitrogen mineralization rate and cumulative mineralization amount of communities at different successional stages exhibited a trend of first increasing and then decreasing; the soil nitrogen mineralization rate of Betula platyphylla forest was the highest, being 1.63, 1.61, 1.25, and 1.47 times that of grassland, shrubland, Picea wilsonii-Betula platyphylla forest, and Picea wilsonii forest, respectively; while the cumulative mineralization amount of Picea wilsonii-Betula platyphylla forest was the highest, being 0.68, 0.72, 0.84, and 0.97 times that of grassland, shrubland, Betula platyphylla forest, and Picea wilsonii forest, respectively; (3) With increasing soil depth, both soil nitrogen mineralization rate and cumulative mineralization amount showed a decreasing trend, with the 0-20 cm soil layer being the highest; (4) The temperature sensitivity coefficient Q10 showed significant differences among communities at different successional stages between 15 °C and 25 °C incubations ($P<0.05$), and with forward progression of succession, the temperature sensitivity coefficient Q10 exhibited a trend of first decreasing and then increasing; however, there were no significant differences in the temperature sensitivity coefficient Q10 among communities at different successional stages between 25 °C and 35 °C incubations ($P>0.05$). The research results will provide a theoretical basis for the quality evolution of community soils and the dynamic changes in soil nitrogen supply capacity.

Full Text

Response of Soil Nitrogen Mineralization to Temperature at Different Successional Stages in Xinglong Mountain, Gansu Province, China

TANG Weichun[1], LIU Xiao'e[1], SU Shiping[1], TIAN Xiaojuan[2], TANG Qingtong[1], ZHANG Jing[3]

[1]College of Forestry, Gansu Agricultural University, Lanzhou 730070, Gansu, China
[2]Management and Protection Center of Xinglong Mountain National Nature Reserve, Lanzhou 730100, Gansu, China
[3]College of Science, Gansu Agricultural University, Lanzhou 730070, Gansu, China

Abstract

Soil nitrogen mineralization is a crucial process in the soil nitrogen cycle, and temperature represents one of the most important factors influencing this process. Investigating how temperature variations affect soil nitrogen mineralization characteristics across different successional stages is essential for elucidating soil nitrogen cycling processes in terrestrial ecosystems. This study examined communities at different successional stages in Xinglong Mountain, Gansu Province, using indoor constant-temperature aerobic incubation methods to investigate soil nitrogen mineralization characteristics under varying temperatures (15°C, 25°C, and 35°C) across five successional stages: grassland, shrub forest, *Betula platyphylla* forest, *Picea wilsonii-Betula platyphylla* forest, and *Picea wilsonii* forest. The results demonstrated that: (1) Except for the 0–20 cm soil layer in grassland communities, the soil nitrogen mineralization rate in all other successional stages increased proportionally with temperature, and cumulative nitrogen mineralization across different successional stages showed a similar temperature-dependent increase. (2) With progressive succession, both soil nitrogen mineralization rates and cumulative mineralization amounts exhibited an initial increase followed by a decrease. The *B. platyphylla* forest displayed the highest mineralization rate, which was 1.63, 1.61, 1.51, and 1.47 times greater than that of grassland, shrub forest, *P. wilsonii*-*B. platyphylla* forest, and *P. wilsonii* forest, respectively. The *P. wilsonii*-*B. platyphylla* forest showed the highest cumulative mineralization amount, exceeding those of grassland, shrub forest, *B. platyphylla* forest, and *P. wilsonii* forest by 0.68, 0.72, 0.84, and 0.97 times, respectively. (3) Both soil nitrogen mineralization rate and cumulative mineralization decreased with increasing soil depth, with maximum values observed in the 0–20 cm layer. (4) The temperature sensitivity coefficient (Q_{10}) at 15–25°C differed significantly among successional stages ($P<0.05$), initially decreasing then increasing with progressive succession. However, Q_{10} values among communities at different successional stages showed no significant differences at 25–35°C ($P>0.05$). These findings provide a theoretical foundation for understanding soil quality evolution and the dynamic changes in soil nitrogen supply capacity across successional gradients.

Keywords: soil nitrogen mineralization; temperature; successional stage; Xinglong Mountain; Gansu

Introduction

Most soil nitrogen exists in organic forms, with only minimal inorganic nitrogen content available for direct plant uptake. While small amounts of organic nitrogen such as amide nitrogen can be absorbed directly by plants, the majority must first be mineralized by soil microorganisms into inorganic nitrogen before becoming available for plant assimilation. Soil nitrogen mineralization capacity serves as the primary indicator of soil nitrogen supply potential and represents a core component of the soil nitrogen cycle, fundamentally controlling plant access to available nitrogen and influencing ecosystem productivity. Temperature constitutes one of the most direct environmental factors affecting soil nitrogen mineralization, with variations in temperature leading to differences in microbial communities, litter supply, and ultimately affecting the quantity, composition, and viability of microbial populations, thereby generating distinct nitrogen mineralization patterns across successional stages. Within an appropriate temperature range (15–35°C), elevated temperatures enhance soil microbial activity and enzyme function, thereby promoting nitrogen mineralization, with rates typically doubling for each 10°C increase. Previous research has demonstrated that within the 15–35°C range, both cumulative nitrogen mineralization and mineralization rates increase with temperature in various ecosystems, including tobacco-planting communities, wetland communities, subalpine forest communities, and grassland and forest ecosystems.

Beyond temperature, succession stage significantly influences nitrogen mineralization. As succession progresses, changes in vegetation type alter environmental conditions such as light and heat, modifying both aboveground and belowground processes. Studies in the Loess Plateau gully region have revealed that soil nitrogen mineralization is highly sensitive to plant community composition, directly affecting soil nutrient transformation processes that are crucial for forest succession and regeneration. During community succession, shifts in species composition alter productivity and litter return, modifying soil nutrient conditions, microbial metabolic activity, and accelerating nitrogen cycling. Grassland ecosystems generally exhibit lower cumulative nitrogen mineralization and mineralization rates compared to forest ecosystems, with temperature responses varying according to community type, soil depth, and nitrogen form. Broadleaf forests typically show higher cumulative mineralization and rates than mixed conifer-broadleaf forests, which in turn exceed those of pure coniferous forests, with shrub forests showing the lowest values. These differences arise from variations in dominant species, leading to differences in litter composition, accumulation, and decomposition, ultimately causing qualitative and quantitative differences in soil carbon and nitrogen pools.

The forests of Xinglong Mountain in Gansu Province, located at the westernmost edge of the Loess Plateau where it meets the eastern extension of the Qilian Mountains, represent cryptic forests developed under limited precipitation conditions. Primarily distributed on semi-shady slopes with gradients between 15–35°, these forests constitute a natural ecological barrier for Lanzhou City, providing irreplaceable services in water conservation, soil retention, climate regulation, and air quality improvement. Recent effective protection measures have increased vegetation coverage and significantly improved ecological functions. Previous research on Xinglong Mountain forest communities has focused on soil physicochemical properties, litter dynamics, ecological benefit evaluation, and moss biomass. Building on these studies, vegetation succession-induced changes in species composition alter biotic and abiotic environments, consequently modifying soil nitrogen mineralization characteristics. Therefore, this research investigated soil nitrogen mineralization patterns across different successional stages in Xinglong Mountain using indoor constant-temperature aerobic incubation, aiming to clarify temperature effects on nitrogen mineralization and provide theoretical support for understanding soil quality evolution and dynamic nitrogen supply capacity, thereby informing scientific forest management decisions.

1.1 Study Area Overview

Xinglong Mountain National Nature Reserve is located 45 km southeast of Lanzhou City, Gansu Province, within the geographical coordinates of 35°38 –35°58 N and 103°50 –104°10 E. The region's unique climate has fostered extremely rich flora and fauna resources, establishing it as one of the most valuable gene banks for plants and animals on China's Loess Plateau. The special geographical location of Xinglong Mountain has created unique vegetation types through long-term successional processes, enabling different vegetation types to coexist at similar elevations. The main vegetation types include grassland, shrub forest, *Betula platyphylla* forest, *Picea wilsonii*-*Betula platyphylla* forest, and *Picea wilsonii* forest. The reserve's elevation ranges from 2300 to 3500 m, with water and heat conditions changing along this gradient. Vegetation transitions from deciduous broadleaf forests to conifer-broadleaf mixed forests dominated by broadleaf species, then to subalpine and alpine shrub-meadow communities. Soil leaching intensity increases with elevation, and soil types progressively change from calcareous gray-cinnamon soils and typical gray-cinnamon soils to leached gray-cinnamon soils, subalpine shrub-meadow soils, alpine meadow soils, and alpine shrub-meadow soils. Meadow soils are classified as mountain black soils, while leached gray-cinnamon soils cover the largest area. These diverse soil resources and corresponding geographical features collectively create a unique ecological environment in the western Loess Plateau.

1.2 Experimental Design

This study employed the "space-for-time substitution" methodology, following the approach of Wei et al. Sample collection was conducted in August, with sampling plots selected based on preliminary surveys. Within the same elevation zone, five plots were established across different successional stages (grassland, shrub forest, *B. platyphylla* forest, *P. wilsonii*-*B. platyphylla* forest, and *P. wilsonii* forest) with consistent slope aspect and position [Figure 1: see original paper]. Three replicate plots were established for each successional stage, each measuring 20 m × 20 m, with distances between plots exceeding 20 m. Basic characteristics of the different successional stage communities are presented in .

Within each plot, three soil profiles were excavated following an "S" pattern. Soil samples were collected from depths of 0–20 cm, 20–40 cm, and 40–60 cm at each profile point. Samples from the same plot and soil layer were mixed, and approximately 0.5 kg was taken back to the laboratory. One portion was passed through a 2 mm sieve for inorganic nitrogen determination, while another portion was air-dried, debris was removed, and the samples were prepared for indoor nitrogen mineralization incubation experiments. In the excavated soil profiles, intact soil cores were collected using a cutting ring (diameter 50.46 mm, height 50 mm) from each soil layer for determination of field water-holding capacity using the indoor cutting ring method. Basic physicochemical properties of soils across different successional stages are shown in .

This study utilized the indoor constant-temperature aerobic incubation method. Based on Wei et al.'s research on litter and its physicochemical properties in Xinglong Mountain, which indicated an average annual temperature of 4.1°C and maximum extreme temperatures reaching 33.6°C, and considering that temperatures too low or high can inactivate soil enzymes, this study established three temperature gradients (15°C, 25°C, and 35°C) [Figure 3: see original paper]. For each treatment, 100 g of air-dried soil was weighed into a 300 mL plastic cup. Based on the field water-holding capacity of each successional stage, distilled water was added to adjust soil moisture to 60% of field capacity. After thorough mixing, samples were sealed with plastic wrap, perforated with 3–5 small holes to maintain aeration, and placed in an incubator. Moisture was replenished using the weighing method during the 42-day incubation period. Samples were collected destructively on days 2–3, 7, 14, 21, 28, and 42. Approximately 20 g of fresh soil was taken from each treatment, processed, and analyzed for NH_4^+-N and $NO_3{}^{-}$-N content. $NH_4{}^{+}$-N was determined using the indophenol blue colorimetric method, while $NO_3{}^{-}$-N was measured by ultraviolet spectrophotometry.

Following the formulas from Li et al. for calculating soil nitrogen mineralization amount and rate:

Soil nitrogen mineralization amount (ΔN) was calculated as:

$$\Delta N = N_{i+1} - N_i$$

Soil nitrogen mineralization rate (v) was calculated as:

$$v = \frac{\Delta N}{\Delta t}$$

where N_i represents the initial inorganic nitrogen content ($\mathrm{mg} \cdot \mathrm{kg}^{-1}$), N_{i+1} represents the inorganic nitrogen content at the incubation time ($\mathrm{mg} \cdot \mathrm{kg}^{-1}$), and Δt represents the incubation time interval (days).

The Stanford single-pool model was used to describe the net nitrogen mineralization dynamics:

$$N_{min} = N_0(1 - e^{-kt})$$

where N_{min} represents the mineralizable nitrogen content ($\mathrm{mg} \cdot \mathrm{kg}^{-1}$), N_0 represents the potentially mineralizable nitrogen content ($\mathrm{mg} \cdot \mathrm{kg}^{-1}$), k represents the mineralization constant or rate, and t represents incubation time (days).

To eliminate the confounding relationship between N_0 and k, Heumann and Böttcher demonstrated that N_0 remains constant (for each soil and any combination of moisture and temperature), while k varies with incubation conditions. To obtain the true N_0 value, extreme incubation conditions (35°C temperature and 60% field capacity moisture) were used with nonlinear correlation methods to estimate N_0 values, which were then refined through successive iterations. These refined N_0 values were used to calculate mineralization rates (k) under different incubation conditions.

To assess temperature effects on net nitrogen mineralization, k values for each soil and moisture condition were fitted to the Arrhenius equation:

$$k = ae^{-b/T}$$

The logarithmic transformation yields:

$$\ln k = \ln a - \frac{b}{T}$$

where T represents temperature (K), and a and b are constants.

The temperature sensitivity coefficient Q_{10} was calculated to quantify the temperature response:

$$Q_{10} = \left(\frac{k_{T_2}}{k_{T_1}}\right)^{\frac{10}{T_2 - T_1}}$$

where k_{T_2} and k_{T_1} represent mineralization rates at temperatures T_2 and T_1, respectively.

1.3 Data Processing and Statistical Analysis

Data analysis was performed using Microsoft Excel 2021 and SPSS Statistics 22.0. One-way ANOVA was used to analyze differences in initial inorganic nitrogen content among successional stages. Multi-way ANOVA was employed to test the effects of successional stage, soil depth, incubation temperature, and their interactions on cumulative nitrogen mineralization and mineralization rates. The temperature influence coefficient Q_{10} was used to analyze temperature effects on nitrogen mineralization rates. Figures were prepared using OriginPro 2021 (OriginLab Corporation).

Results

2.1 Initial Soil Inorganic Nitrogen Content Across Successional Stages

Initial inorganic nitrogen content varied significantly among successional stages and soil depths [Figure 4: see original paper]. In the 0–20 cm layer, grassland differed significantly from *P. wilsonii*-*B. platyphylla* forest and *P. wilsonii* forest ($P<0.05$), while shrub forest differed only from *B. platyphylla* forest ($P<0.05$). *P. wilsonii*-*B. platyphylla* forest exhibited the highest initial inorganic nitrogen content at 128.52 $\mathrm{mg \cdot kg^{-1}}$, followed by *P. wilsonii* forest, with grassland showing the lowest values. *P. wilsonii*-*B. platyphylla* forest values were 1.2–1.5 times higher than those of grassland, shrub forest, *B. platyphylla* forest, and *P. wilsonii* forest.

In the 20–40 cm layer, grassland and *P. wilsonii*-*B. platyphylla* forest differed significantly from *P. wilsonii* forest ($P<0.05$), while shrub forest and *B. platyphylla* forest differed only from *P. wilsonii* forest ($P<0.05$). *P. wilsonii*-*B. platyphylla* forest again showed the highest initial inorganic nitrogen content at 124.63 $\mathrm{mg \cdot kg^{-1}}$, with *P. wilsonii* forest ranking second and grassland the lowest. *P. wilsonii*-*B. platyphylla* forest values were 1.3–1.8 times higher than other communities.

In the 40–60 cm layer, grassland differed significantly from *P. wilsonii*-*B. platyphylla* forest and *P. wilsonii* forest ($P<0.05$), while shrub forest and *B. platyphylla* forest differed only from *P. wilsonii*-*B. platyphylla* forest ($P<0.05$). *P. wilsonii*-*B. platyphylla* forest maintained the highest initial inorganic nitrogen content at 92.64 $\mathrm{mg \cdot kg^{-1}}$, followed by *P. wilsonii* forest, with grassland showing the lowest values. *P. wilsonii*-*B. platyphylla* forest values were 0.9–1.2 times higher than other communities.

Compared with the 0–20 cm layer, initial inorganic nitrogen content in the 20–40 cm layer decreased by 3.03%–27.80% across all successional stages, with grassland showing the largest reduction. Compared with the 0–20 cm layer, the 40–60 cm layer showed decreases of 27.92%–42.08%, again with grassland exhibiting the greatest decline. The 20–40 cm and 40–60 cm layers showed reductions of 34.21% and 16.95%, respectively, compared to the 0–20 cm layer. Overall, initial inorganic nitrogen content increased initially then decreased with progressive succession.

2.2 Temperature Effects on Soil Nitrogen Mineralization Rates

Temperature exhibited highly significant effects on soil nitrogen mineralization rates ($P<0.01$). Except for the 0–20 cm layer in grassland, mineralization rates across all successional stages increased with rising temperature (15–35°C), with the timing of peak rates varying according to incubation temperature. Throughout the incubation period, maximum mineralization rates differed significantly among temperature treatments only in shrub forest ($P<0.05$). Across all successional stages, maximum mineralization rates ranged from 6.87 to 25.73 $mg \cdot kg^{-1} \cdot d^{-1}$, with rates at 35°C being 1.2–1.5 times higher than at 25°C, and 1.5–2.7 times higher than at 15°C, demonstrating that elevated temperatures accelerate nitrogen mineralization within a certain range.

Successional stage also showed highly significant effects on mineralization rates ($P<0.01$), with significant differences observed among communities at each temperature ($P<0.05$). With progressive succession, mineralization rates initially increased then decreased, following the pattern: *B. platyphylla* forest > *P. wilsonii*-*B. platyphylla* forest > *P. wilsonii* forest > shrub forest > grassland. Shrub forest differed significantly only from *B. platyphylla* and *P. wilsonii* forests, while all other pairwise comparisons showed significant differences ($P<0.05$). *B. platyphylla* forest exhibited the highest mineralization rate at 16.65 $mg \cdot kg^{-1} \cdot d^{-1}$, which was 1.63, 1.61, 1.51, and 1.47 times higher than grassland, shrub forest, *P. wilsonii*-*B. platyphylla* forest, and *P. wilsonii* forest, respectively.

At 25°C, *B. platyphylla* forest differed significantly only from shrub forest ($P<0.05$), with no significant differences among other communities ($P>0.05$). The mineralization rate in *B. platyphylla* forest reached 20.17 $mg \cdot kg^{-1} \cdot d^{-1}$, 1.61, 1.58, 1.49, and 1.44 times higher than other communities. At 35°C, *B. platyphylla* forest differed significantly from all other communities ($P<0.05$), with no significant differences among the remaining four successional stages ($P>0.05$). The mineralization rate peaked at 25.73 $mg \cdot kg^{-1} \cdot d^{-1}$, 1.59, 1.56, 1.48, and 1.43 times higher than other communities. These results indicate that successional stage significantly influences soil nitrogen mineralization rates.

Soil depth also exerted highly significant effects on mineralization rates ($P<0.01$), with rates decreasing progressively with depth [TABLE:3, TA-

BLE:4]. At each temperature, the 0–20 cm layer showed significantly higher maximum mineralization rates than deeper layers ($P<0.05$). At 35°C, all soil depths differed significantly ($P<0.05$). The highest mineralization rates occurred in the 0–20 cm layer, with *B. platyphylla* forest showing the maximum values. In the 20–40 cm layer, *P. wilsonii*-*B. platyphylla* forest, *B. platyphylla* forest, and *P. wilsonii* forest showed the highest rates. In the 40–60 cm layer, *P. wilsonii*-*B. platyphylla* forest, *B. platyphylla* forest, and *P. wilsonii* forest exhibited the highest rates. These patterns demonstrate that soil depth significantly influences nitrogen mineralization rates.

Multi-way ANOVA revealed that successional stage, temperature, and soil depth each had highly significant effects on mineralization rates ($P<0.01$). Interactions between successional stage and temperature, successional stage and soil depth, and temperature and soil depth all showed highly significant effects ($P<0.01$), as did the three-way interaction among all factors ($P<0.01$) .

2.3 Temperature Effects on Cumulative Soil Nitrogen Mineralization

Temperature showed highly significant effects on cumulative nitrogen mineralization ($P<0.01$). Cumulative mineralization increased with incubation time and temperature across all successional stages. Throughout the incubation period, cumulative mineralization differed significantly among temperature treatments ($P<0.05$), except between grassland and shrub forest and between *P. wilsonii*-*B. platyphylla* and *P. wilsonii* forests. At 15°C, *B. platyphylla* forest exhibited the highest cumulative mineralization at 387.98 $\mathrm{mg \cdot kg^{-1}}$, significantly different from all other communities ($P<0.05$). At 25°C, *B. platyphylla* forest showed the highest cumulative mineralization at 468.24 $\mathrm{mg \cdot kg^{-1}}$, significantly different from grassland, shrub forest, and *P. wilsonii* forest ($P<0.05$) but not from *P. wilsonii*-*B. platyphylla* forest. At 35°C, *B. platyphylla* forest again showed the highest cumulative mineralization at 515.68 $\mathrm{mg \cdot kg^{-1}}$, 1.3–1.8 times higher than other communities. These results demonstrate significant differences in cumulative mineralization among successional stages [Figure 6: see original paper].

With progressive succession, cumulative nitrogen mineralization initially increased then decreased, with *B. platyphylla* and *P. wilsonii*-*B. platyphylla* forests showing the highest values. Soil depth also had highly significant effects ($P<0.01$), with cumulative mineralization decreasing with depth . At each temperature, the 0–20 cm layer showed significantly higher maximum cumulative mineralization than deeper layers ($P<0.05$). The highest cumulative mineralization occurred in the 0–20 cm layer in *B. platyphylla* forest. In the 20–40 cm layer, *B. platyphylla* forest showed the highest values, while in the 40–60 cm layer, *P. wilsonii*-*B. platyphylla* forest exhibited the highest cumulative mineralization.

Multi-way ANOVA indicated that successional stage, temperature, and soil depth each had highly significant effects on cumulative mineralization ($P<0.01$). The interaction between successional stage and temperature had significant effects ($P<0.05$), while interactions between successional stage and soil depth and between temperature and soil depth showed highly significant effects ($P<0.01$). The three-way interaction among all factors was also highly significant ($P<0.01$) .

2.4 Temperature Sensitivity Coefficient (Q_{10}) Across Successional Stages

The temperature sensitivity coefficient Q_{10} decreased with increasing incubation temperature across all successional stages . At 15–25°C, Q_{10} values differed significantly among successional stages ($P<0.05$), showing a pattern of initial decrease followed by increase with progressive succession: grassland > shrub forest > *P. wilsonii-B. platyphylla* forest > *P. wilsonii* forest > *B. platyphylla* forest. At 25–35°C, no significant differences in Q_{10} were observed among successional stages ($P>0.05$), with values ranging from 0.961 to 1.1.

The Q_{10} values at 15–25°C showed much greater variation than those at 25–35°C, indicating that different successional stages respond differently to temperature, with optimal temperature sensitivity ranges. The Q_{10} values did not continue increasing with soil temperature, suggesting an optimal temperature range for microbial activity and enzyme function.

Discussion

This study revealed that initial soil inorganic nitrogen content increased initially then decreased with progressive succession, with *P. wilsonii-B. platyphylla* forest showing the highest values and grassland the lowest [Figure 4: see original paper]. This pattern reflects the simpler vegetation composition in grasslands compared to shrub forests, *B. platyphylla* forests, *P. wilsonii-B. platyphylla* forests, and *P. wilsonii* forests, resulting in lower litter return and soil nutrient content. Wei et al. found that total nitrogen content across successional stages in Xinglong Mountain followed the pattern: *P. wilsonii-B. platyphylla* forest > *P. wilsonii* forest > *B. platyphylla* forest > shrub forest > grassland, with grassland ecosystems having lower total nitrogen than forest ecosystems. Liu et al. demonstrated that initial inorganic nitrogen content is proportional to total nitrogen in karst soils. As vegetation composition diversifies from simple to complex, soil types change accordingly. The *P. wilsonii-B. platyphylla* forest soil contains higher organic matter, total nitrogen, total phosphorus, and potassium than *P. wilsonii* forest soil, consistent with findings from the Niubeiliang Nature Reserve.

Temperature plays a crucial role in soil nitrogen mineralization. This study found that, except for the 0–20 cm layer in grassland, mineralization rates increased with temperature (15–35°C) [Figure 5: see original paper], while cumulative mineralization also increased with temperature. Elevated temperature enhances microbial quantity and enzyme activity, accelerating nitrogen mineralization processes. Soil microbial decomposition constitutes the primary pathway for nitrogen mineralization, and microbial community composition significantly influences internal nitrogen cycling. Higher temperatures accelerate litter decomposition, promoting nutrient mineralization and increasing nutrient availability. Soil enzymes serve as critical catalysts for nitrogen transformation, primarily derived from plant and animal residues, microbial metabolism, and root exudates. Enzyme activity controls nitrogen cycling, and within the optimal temperature range (20–37°C), enzyme activity increases with temperature, accelerating nitrogen mineralization.

The temperature sensitivity coefficient Q_{10} decreased with increasing temperature. At 15–25°C, Q_{10} values differed significantly among successional stages ($P<0.05$), initially decreasing then increasing with succession. At 25–35°C, no significant differences were observed ($P>0.05$). The Q_{10} increase at 15–25°C was much greater than at 25–35°C, indicating that temperature sensitivity does not continuously increase with temperature but has an optimal range. *B. platyphylla* forest showed the lowest Q_{10}, suggesting a slower temperature response, while grassland, shrub forest, *P. wilsonii*-*B. platyphylla* forest, and *P. wilsonii* forest showed Q_{10} values 110.40%, 87.30%, 19.76%, and 64.71% higher, respectively.

Soil depth significantly affected initial inorganic nitrogen content and mineralization characteristics . Initial inorganic nitrogen content, cumulative mineralization, and mineralization rates all decreased with depth. This primarily results from reduced litter input with depth, decreased nutrient content, and weaker surface accumulation effects of total nitrogen, leading to reduced microbial biomass and enzyme activity. Additionally, fine root biomass decreases with depth (152.39 $\mathrm{g \cdot cm^{-2}}$, 119.37 $\mathrm{g \cdot cm^{-2}}$, and 49.30 $\mathrm{g \cdot cm^{-2}}$ in the 0–20 cm, 20–40 cm, and 40–60 cm layers, respectively), reducing soil permeability and effective nitrogen absorption. Wei et al. found that litter effects on soil depth weaken with increasing depth, making microbial decomposition and root activity the primary drivers of nitrogen mineralization.

With progressive succession, both nitrogen mineralization rates and cumulative mineralization showed initial increases followed by decreases, with *B. platyphylla* forest showing the highest mineralization rate and *P. wilsonii*-*B. platyphylla* forest showing the highest cumulative mineralization [FIGURE:5, FIGURE:6]. This pattern reflects how aboveground vegetation indirectly influences nitrogen mineralization through litter quality and quantity. Studies have shown that mineralization rates and cumulative amounts correlate positively with community composition and litter return. Species composition changes alter litter input, modifying soil nutrient conditions and accelerating nitrogen cycling. Another factor is that high temperatures and rainfall can leach nitrogen, particularly in grasslands where simple vegetation structure allows direct rainfall impact on soil, facilitating nitrate leaching. Xinglong Mountain experiences maximum surface temperatures of 33.5°C and average precipitation of 447.2 mm, conditions under which leaching affects initial inorganic nitrogen content, which sets the upper limit for cumulative mineralization under experimental conditions. Hishi et al. demonstrated that nitrate is more susceptible to leaching under high temperature and rainfall conditions, contributing to differences in cumulative mineralization among successional stages.

Multi-way ANOVA revealed that interactions between successional stage, temperature, and soil depth significantly influenced nitrogen mineralization rates and cumulative amounts ($P<0.01$), except for the interaction between successional stage and temperature on mineralization amount. This indicates that nitrogen transformation rates and availability in Xinglong Mountain are strongly correlated with interactions among these factors. Temperature significantly influences community species composition, while plant communities alter environmental conditions that feedback to affect ecological processes, driving species replacement during succession. The feedback relationship between litter quality and soil nitrogen transformation may represent an important mechanism underlying vegetation succession. However, this study controlled temperature and moisture conditions artificially, excluding external factors, plant roots, and litter interference to accurately characterize nitrogen mineralization features across successional stages. Understanding nitrogen mineralization responses to environmental climate change requires further field experiments.

Conclusion

This study investigated soil nitrogen mineralization responses to temperature across different successional stages in Xinglong Mountain using the space-for-time substitution approach and indoor constant-temperature aerobic incubation. The main conclusions are:

1. Temperature had highly significant effects on nitrogen mineralization amount and rate. Except for the 0–20 cm layer in grassland, both mineralization rates and cumulative mineralization increased with temperature (15–35°C) across all successional stages.
2. Successional stage significantly affected nitrogen mineralization amount and rate. With progressive succession, initial inorganic nitrogen content, mineralization rate, and cumulative mineralization initially increased then decreased.
3. Soil depth significantly influenced nitrogen mineralization amount and rate, with both mineralization rates and cumulative mineralization decreasing as soil depth increased across all successional stages.
4. Interactions between successional stage, temperature, and soil depth significantly affected nitrogen mineralization amount and rate, except for the interaction between successional stage and temperature on mineralization amount. While this study controlled environmental conditions to accurately characterize nitrogen mineralization features, understanding responses to actual environmental climate change requires integration with field experiments.

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