Effects of Short-term Warming on Soil Nitrogen-Phosphorus Coupling in Young Chinese Fir Plantations in Mid-Subtropical Regions: Postprint

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Abstract

Global warming has induced a series of ecological problems in terrestrial ecosystems and the entire biosphere, and the continued increase in global average temperature in the future will further exacerbate these issues. Currently, although some studies have examined the effects of warming, nitrogen deposition, and forest regeneration methods on soil nitrogen, phosphorus, and other nutrients in the mid-subtropics, the influence of warming on nitrogen-phosphorus coupling in subtropical forests remains unknown. Using mid-subtropical Chinese fir (Cunninghamia lanceolate) seedlings as the research object, a soil warming experiment was established by burying heating cables (warming magnitude of (5$±$0.5)°C) to investigate the effects of short-term warming on soil water content, microbial biomass nitrogen (MBN), microbial biomass phosphorus (MBP), soil nitrogen and phosphorus nutrients, and the coupling effects of nitrogen (N) and phosphorus (P). The results showed that short-term warming had no significant effect on total nitrogen and total phosphorus; in the first year of warming, it significantly increased the contents of available nitrogen, ammonium nitrogen (NH4+), and available phosphorus, while significantly decreasing MBN content. In the second year of warming, the contents of available phosphorus, NH4+, and MBP in the soil decreased significantly. Although short-term warming had no significant effect on soil total N/P and available N/P ratios, it significantly reduced the ammonium/nitrate+nitrite nitrogen ratio (NH4+/(NO3-+NO2-)). Additionally, warming significantly decreased MBN/MBP, alleviating microbial phosphorus limitation. Correlation analysis indicated that the coupling effect is influenced not only by interactions between N and P, but also by other factors such as soil temperature and water content. The study demonstrated that short-term warming did not significantly affect soil nitrogen-phosphorus coupling in mid-subtropical Chinese fir plantation young forests, but decreased the contents of available nitrogen and available phosphorus after warming. Therefore, in the context of future global warming, these research results provide important theoretical basis for the healthy development and scientific management of mid-subtropical forest ecosystems.

Full Text

Preamble

Influence of Short-Term Warming on the Coupling Mechanism Between Soil Nitrogen and Phosphorus in a Young *Cunninghamia lanceolata* Stand in Mid-Subtropical China

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Abstract

Global warming has caused a series of ecological issues in terrestrial ecosystems and the biosphere as a whole, and these problems will further intensify as global average temperatures continue to rise. While the effects of warming, nitrogen deposition, and forest regeneration on soil nutrients such as nitrogen (N) and phosphorus (P) have been studied, the impacts of warming on soil N-P coupling in subtropical forests remain poorly understood. This study investigated the influence of short-term warming on the coupling mechanism between soil N and P in Chinese fir (*Cunninghamia lanceolata*) seedlings in a mid-subtropical plantation. The experiment employed buried heating cables to raise soil temperature by approximately (5 ± 0.5)°C. We examined the effects of short-term warming on soil water content, microbial biomass N (MBN), microbial biomass P (MBP), soil N and P, and their coupling relationships.

The results showed that short-term warming had no significant effects on total N and total P. In the first year, warming significantly increased effective N, ammonium N, and available P content, while significantly reducing MBN content. In the second year, as temperature increased, the contents of available P, NH_4^+, and MBP decreased significantly. However, the increase in $NH_4^+/(NO_3^- + NO_2^-)$ content significantly reduced the MBN/MBP ratio, alleviating P limitation on microorganisms. The effects of warming on total N/P and available

N/P were not significant. Correlation analysis revealed that the coupling effect was influenced not only by the interaction between N and P but also by soil temperature, water content, and other factors. These results indicate that short-term warming did not significantly affect soil N-P coupling in the subtropical Chinese fir plantation, though it increased available N and P contents by promoting plant growth. Our findings provide an important theoretical basis for the sustainable development and scientific management of subtropical forest ecosystems under future global warming scenarios.

Keywords: warming; soil nitrogen; soil phosphorus; coupling mechanism; mid-subtropical

Introduction

Global climate change encompasses multiple dimensions, including global warming, intensified nitrogen deposition, elevated greenhouse gas concentrations, and increased precipitation variability. Climate warming, as a primary characteristic of global change, is profoundly affecting the structure and function of terrestrial ecosystems and has garnered widespread attention from governments and scientists worldwide [2-3]. According to IPCC (2013) climate model projections, global surface temperatures will increase by 1.8–4.0°C by the end of this century. Temperature is one of the most important abiotic factors influencing nitrogen and phosphorus mineralization. Elevated soil temperature affects the decomposition of organic matter and the quantity and mobility of soil nutrients, thereby influencing ecosystem structure and function [5-6].

Soil nutrients are essential sources of nutrition for plant growth and development [7], with N and P being the most limiting nutrients for ecosystem productivity. These elements play crucial roles in ecosystem carbon and nitrogen cycles and represent key components of ecosystems [8-9]. The N/P ratio is a critical indicator for evaluating soil nutrient supply status and predicting ecosystem health, as it reflects the interaction, promotion, or constraint between these elements. Changes in the N/P ratio profoundly affect soil nutrient content, plant growth, community composition, and ecosystem function [12-13].

Previous research has demonstrated that soil warming can influence microbial activity, enhance soil enzyme activity, and increase available nitrogen content, thereby improving plant primary productivity [14]. Studies in alpine grasslands have shown that warming increases soil available nitrogen, with consequent increases in plant uptake [16-17]. However, warming has also been found to reduce total N, total P, and available nitrogen in temperate grasslands of Inner Mongolia [18-19], while other studies report no significant effects on net mineralization rates or plant productivity [20-21]. Zhang et al. [12] found that warming and drought altered soil biogeochemical decoupling in temperate grasslands, though most research on warming effects has focused on high-latitude grasslands, tundra, and forest ecosystems [20-21]. The response of soil N-P coupling to warming in subtropical forest ecosystems remains poorly documented.

To address this knowledge gap, we conducted a soil warming experiment in a young Chinese fir plantation in mid-subtropical China. Our specific objectives were to: (1) examine the effects of short-term warming on soil temperature, water content, and basic physicochemical properties; (2) investigate how warming influences soil N and P nutrients and their coupling relationships; and (3) assess the impacts of warming on microbial biomass N and P.

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1. Study Area and Experimental Design

The study area is located at the Sanming observation site of the Fujian Normal University Wuyi Evergreen Broadleaf Forest Field Station in Sanming City, Fujian Province, China (26°19 N, 117°36 E). The region has a subtropical monsoon climate with an average annual temperature of 19.1°C, annual precipitation of 1749 mm, and annual evaporation of 1585 mm. Each experimental plot measured 2 m × 2 m and contained Chinese fir seedlings planted between two heating cables buried at 10 cm and 20 cm depths. The warming system was activated after cable installation, with heating cables arranged in parallel in both warmed and control plots. Detailed plot layout information is available in Chen et al. [24].

Based on the IPCC Fifth Assessment Report (2013) projecting atmospheric temperature increases of 0.3–4.8°C by century' s end, and referencing the warming amplitude settings from the Harvard Forest soil warming experiment, we established a warming magnitude of approximately 5°C. The experiment employed a completely randomized block design with warming as the fixed factor, including control (CK) and warming (W) treatments.

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2. Soil Sampling and Analysis

2.1 Soil Sample Collection

Soil samples were collected using an auger at 0–10 cm and 10–20 cm depths in each plot. Five random points were established in each plot, and soils from the same layer were mixed to form a composite sample. Visible roots and animal residues were removed, and a portion was used for moisture content determination. The remaining soil was sieved and divided into two parts: one for nutrient analysis and the other air-dried, ground, and passed through a 0.149 mm sieve for total N and P determination.

2.2 Measurement Methods

Soil temperature and moisture data were collected using a CR3000 data logger (Campbell Scientific, Logan, UT, USA) with hourly scanning. Soil total N content was determined using a carbon-nitrogen elemental analyzer (Elementar Vario EL III, Elementar, Germany). Available N (NH_4^+ and NO_3^- + NO_2^-) was extracted with 2 mol/L KCl and measured using a continuous flow analyzer (Skalar san++, Skalar, Netherlands). Total P was determined by $HClO_4$-H_2SO_4 digestion followed by continuous flow analysis. Available P was extracted using the 0.5 mol/L $NaHCO_3$ method [25] and measured with a continuous flow analyzer. Microbial biomass N and P were determined by chloroform fumigation extraction [25], with MBN calculated as the difference between fumigated and non-fumigated soil organic N multiplied by a conversion coefficient (k = 0.45), and MBP calculated similarly.

2.3 Data Analysis

Soil temperature and water content dynamics were processed using Microsoft Excel 2013 and plotted as line graphs showing daily averages. One-way ANOVA was used to test for significant differences in soil water content and temperature between warming and control treatments ($\alpha = 0.05$). One-way and two-way ANOVA were used to test for significant differences in soil nutrients and their ratios across years. Pearson correlation coefficients were calculated between soil temperature, water content, and soil nutrients and their ratios under both treatments. Statistical significance was set at $P < 0.05$, $P < 0.01$, and $P < 0.001$.

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3. Results

3.1 Effects of Warming on Soil Physicochemical Properties

Short-term warming had no significant effects on total carbon, total nitrogen, or total phosphorus content, though the C/N ratio decreased slightly (Table 1). However, warming significantly reduced soil water content ($P < 0.05$). Soil water content and temperature exhibited similar seasonal variation patterns, peaking during summer months. Compared with the control, warming maintained an average increase of approximately 5°C. In 2014, soil water content decreased from 21.86% to 17.27% and soil temperature increased from 22.49°C to 28.51°C. In 2015, water content decreased from 24.07% to 19.60% and temperature increased from 23.31°C to 26.69°C.

3.2 Effects of Warming on Soil Nutrients

After one year of warming, effective N content increased significantly from 1.42 mg/kg to 1.90 mg/kg, and available P content also increased significantly ($P < 0.05$). NH_4^+ and NO_3^- + NO_2^- contents increased significantly as well. However, MBN content decreased significantly by 26.93%. After two years of warming, both effective N and available P contents decreased, with available P showing a significant decline ($P < 0.05$). The two-year warming treatment caused different responses in total N, total P, MBN, and MBP, though the effects on total N and total P were not significant.

[Figure 1: see original paper]

3.3 Effects of Warming on N/P Ratios

Short-term warming tended to reduce total N/P, $NH_4^+/(NO_3^- + NO_2^-)$, and MBN/MBP ratios, though the effects were not significant in the first year except for MBN/MBP ($P < 0.05$). In the second year, total N/P and MBN/MBP ratios decreased significantly ($P < 0.05$), with MBN/MBP decreasing by 46.58% in 2015 and 48.86% in 2016. As warming duration increased, the trends for $NH_4^+/(NO_3^- + NO_2^-)$ and MBN/MBP ratios diverged, with the former increasing and the latter decreasing.

[Figure 2: see original paper]
[Figure 3: see original paper]

3.4 Correlations Between Soil Temperature, Water Content, and Nutrients

Correlation analysis revealed that soil temperature and water content were significantly correlated with N/P, $NH_4^+/(NO_3^- + NO_2^-)$, and MBN/MBP ratios (correlation coefficients ranging from -0.970 to 0.856). Soil water content was significantly negatively correlated with total N, total P, available N, and MBN, but positively correlated with MBP. Soil temperature showed significant positive correlations with available N, available P, and $NH_4^+/(NO_3^- + NO_2^-)$, but negative correlations with MBN and MBP. These results indicate that temperature and moisture influence microbial activity and nutrient transformation processes in subtropical Chinese fir plantation soils.

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4. Discussion

Nitrogen and phosphorus are essential macronutrients for plant growth, development, and reproduction, and often co-limit ecosystem productivity [26-27]. Our study found that warming had no significant effects on total N and total P, but significantly influenced available nutrients and microbial biomass. After one year of warming, the significant increase in available N and P likely resulted from enhanced mineralization rates, as elevated temperature can increase soil organic nitrogen mineralization and net nitrification rates [29-30]. The increase in $NH_4^+/(NO_3^- + NO_2^-)$ may be attributed to reduced soil water content limiting NO_3^- leaching and creating more aerobic conditions that inhibit denitrification [32-33].

The significant increase in available P after one year of warming may be explained by increased soil acid phosphatase activity, which mineralizes organic P into inorganic forms [34]. However, the decrease in available N and P in the second year suggests rapid uptake by Chinese fir seedlings, which showed increased growth rates under warming [35]. The significant decline in MBN and MBP in the second year indicates that microorganisms may have adapted to warming conditions, with increased microbial activity consuming more nutrients.

The MBN/MBP ratio is a key indicator of microbial nutrient limitation. Our finding that warming significantly reduced MBN/MBP suggests that warming alleviated P limitation on microorganisms. This contrasts with some studies in temperate grasslands [12,14] but aligns with research showing that warming effects vary by climate zone and vegetation type. The coupling between N and P is influenced not only by their direct interactions but also by soil temperature, moisture, and other environmental factors [12]. Soil moisture affects organic matter decomposition rates and redox potential, thereby influencing ion concentrations in soil and solution [38]. In dry and warm climates, these factors can alter biomass accumulation and decomposition, affecting ecosystem services [14].

5. Conclusion

Short-term warming is an important factor affecting soil and microbial N-P cycles in young Chinese fir plantations in mid-subtropical China. Warming significantly increased available N content and enhanced organic N mineralization in the first year, while significantly reducing soil water content. In the second year, available N and P contents decreased significantly, likely due to accelerated plant growth and nutrient uptake. Although warming significantly reduced the MBN/MBP ratio and alleviated microbial P limitation, it did not significantly affect overall soil N-P coupling in this subtropical forest ecosystem. Our results provide important insights for the sustainable management of subtropical forest ecosystems under future warming scenarios, though long-term warming effects on N-P coupling require further investigation.

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