Effects of Simulated Warming and Rainfall Exclusion on the Quantity and Structure of Soil Dissolved Organic Matter in a Mid-Subtropical Chinese Fir Plantation Postprint

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Abstract

Temperature and moisture influence the structure and function of forest ecosystems, while global warming and altered rainfall patterns represent future trends of climate change. In the mid-subtropical region of China, forest coverage is extensive and carbon pools are abundant. Dissolved organic matter (DOM), as a crucial component of forest ecosystems, is significantly affected by climate change in terms of its quantity and composition. This study conducted a simulated warming experiment and 50% rainfall exclusion on soils of Chinese fir (Cunninghamia lanceolata) plantations in the humid subtropical region of China, employing spectroscopic techniques to investigate the effects of warming and rainfall exclusion on the quantity and structure of soil dissolved organic matter (DOM). The experiment consisted of four treatments: control (CK), warming (W), rainfall exclusion (P), and the interaction of warming and rainfall exclusion (WP). The results showed that, compared with the control, soil warming increased soil dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in the 0-10 cm and 10-20 cm soil layers, but decreased their aromaticity index and humification degree. Warming accelerated DOM loss and was detrimental to soil organic matter stabilization. Seasonal variations affected soil environmental conditions, causing rainfall exclusion to exhibit trends of either increasing or decreasing DOM quantity. During the dry season (October 2014 and January 2015), rainfall exclusion reduced soil DOM quantity but increased its aromaticity index and humification degree. Upon entering the rainy season (April 2015), rainfall exclusion tended to increase DOM, but with fewer aromatic compounds in its composition. The interaction of warming and rainfall exclusion promoted DOM production to some extent, and its structure was simpler than that of the control. The effects of temperature and rainfall on DOM are

rather complex. Against the backdrop of global climate change, only through long-term observations and exploration of impacts from other factors can we gain a deep understanding of how climate warming and altered rainfall patterns affect soil carbon and nitrogen.

Full Text

Effects of Experimental Soil Warming and Precipitation Reduction on the Quantity and Structure of Soil Dissolved Organic Matter in *Cunninghamia lanceolata* Plantations in Subtropical China

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Abstract

Temperature and moisture are critical factors influencing the structure and function of forest ecosystems, and global warming coupled with altered precipitation patterns represent major future climate change trends. Dissolved organic matter (DOM) constitutes a crucial component of forest ecosystems, playing a vital role in carbon decomposition/sequestration and nutrient availability for microorganisms and plants. In China' s humid subtropical regions, extensive natural evergreen broad-leaved forests have been converted to *Cunninghamia lanceolata* (Chinese fir) plantations, which cover 6.5% of China' s plantation area and represent a significant forest carbon sink. However, the region' s high temperatures and rapid organic matter decomposition pose substantial risks for carbon loss. This study investigated the effects of simulated soil warming, 50% precipitation reduction, and their interaction on the quantity and composition of soil DOM in a Chinese fir plantation using spectral techniques.

The experiment employed a factorial design with four treatments (three replicates each): (1) control (CK) with natural conditions, (2) warming only (W), (3) precipitation reduction only (P), and (4) combined warming and precipitation reduction (WP). Soil samples were collected from 0–10 cm and 10–20 cm layers in October 2014, January 2015, and April 2015. Soil microbial biomass carbon (MBC) and nitrogen (MBN) were also measured to elucidate relationships between DOM dynamics and temperature/moisture.

Results showed that soil warming increased DOM quantity in both soil layers but decreased its aromaticity index and humification degree, potentially reducing soil organic matter stability. Precipitation reduction exhibited seasonal effects: during the dry season (October 2014 and January 2015), DOM quantity decreased while aromaticity and humification increased; during the rainy season (April 2015), DOM quantity increased as microbial growth and aromatic compound content decreased. The combined warming and precipitation reduction treatment increased DOM quantity due to accelerated soil organic matter decomposition, while the DOM structure became simpler compared to control. These findings demonstrate that temperature and moisture effects on DOM quantity and structure are complex and seasonally dependent. Long-term observations are needed to fully understand how climate warming and altered precipitation will affect carbon and nitrogen cycling in these forest ecosystems.

Keywords: soil warming; precipitation reduction; *Cunninghamia lanceolata* plantation; soil dissolved organic matter

Introduction

Soil organic matter (SOM) represents the largest carbon pool in forest ecosystems [1], while dissolved organic matter (DOM) constitutes a small but highly active fraction. Defined as water-soluble natural organic compounds that pass through a 0.45 m filter, DOM includes both monomeric compounds and supramolecular systems [2-4] and plays a crucial role in ecosystem carbon and nitrogen cycling [5-6].

Since the Industrial Revolution, extensive fossil fuel combustion has increased atmospheric CO concentrations, causing climate change characterized by global warming. Climate change reports indicate that global average surface temperature increased by approximately 0.85°C between 1880 and 2012, with altered precipitation patterns that will likely increase rainfall at high latitudes and some mid-latitude regions while decreasing it in subtropical zones [7-9]. These changes will profoundly affect forest ecosystem structure and function [10-11].

DOM is central to questions of soil carbon sequestration and nutrient availability for microorganisms and plants [12]. Previous studies show positive correlations between DOM quantity and temperature, attributed to enhanced microbial activity at higher temperatures [13]. In Arctic soils, experimental warming increased plant growth and DOM production [14]. However, in water-limited systems, reduced precipitation can decrease DOM quantity while increasing its aromaticity and humification [15-17]. Drought conditions may reduce DOM concentrations, but subsequent rainfall can increase them through altered redox conditions and phenol decomposition [18-19].

China' s humid subtropical zone contains the world' s largest remaining area of evergreen broad-leaved forests, but extensive conversion to Chinese fir plantations has occurred. These plantations occupy 6.5% of China' s plantation area and are crucial for timber production [20]. The region' s high temperatures and rapid organic matter decomposition create significant carbon loss risks, making DOM dynamics particularly important for carbon cycling [21]. Despite numerous warming experiments in high-latitude regions, few studies have examined combined warming and precipitation changes in subtropical forests. This study establishes a multi-factor climate manipulation platform in a young Chinese fir plantation to investigate how warming and precipitation reduction affect DOM quantity and composition, providing scientific basis for predicting future forest ecosystem responses to climate change.

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1. Study Site and Experimental Design

The study site is located at the Sanming Forest Ecosystem and Global Change Research Station in Fujian Province (26°19 N, 117°36 E), characterized by a mid-subtropical monsoon climate with a mean annual temperature of 19.1°C and mean annual precipitation of 1749 mm, concentrated in the spring and summer. The soil is red soil developed from biotite granite [22]. The experimental site is a young Chinese fir plantation with an average tree height of 25.7 ± 2.52 cm and mean basal diameter of 3.35 ± 0.48 cm.

The experiment utilized a randomized block design with 2 m × 2 m plots. Each plot was surrounded by PVC boards (200 cm × 70 cm) inserted into the soil to isolate plots and prevent interference. To eliminate soil heterogeneity, soil was excavated from a mature Chinese fir forest in layers (0–10, 10–20, and 20–70 cm), sieved to remove coarse roots and debris, mixed uniformly by layer, and repacked into the plots at original bulk density.

Four treatments were established with three replicates each: - **CK:** Control with natural temperature and precipitation - **W:** Warming with heating cables maintaining soil temperature 5°C above ambient - **P:** 50% precipitation reduction using transparent shelters - **WP:** Combined warming and precipitation reduction

Heating cables were installed uniformly across plots in April 2014, with an outer perimeter loop to ensure even heating. Warming plots consistently maintained temperatures 5°C higher than control plots. Precipitation shelters were constructed to intercept 50% of natural rainfall [22].

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2. Sample Collection and Analysis

Soil samples were collected in October 2014, January 2015, and April 2015. At each sampling time, five soil cores were taken from each plot and separated into 0–10 cm and 10–20 cm layers. Samples from the same plot and layer were composited, sieved (2 mm) to remove roots and debris, and divided for analysis. Soil basic physicochemical properties, MBC, and MBN were measured on fresh subsamples, with the remainder used for DOM extraction.

DOM was extracted using a water extraction method [23]: 10 g fresh soil was mixed with 25 mL deionized water (soil:water ratio 1:2.5), shaken for 30 minutes, centrifuged at 4000 rpm for 10 minutes, and filtered through 0.45 m membranes. Dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) concentrations were determined using a TOC analyzer (TOC-VCPH, Shimadzu, Kyoto, Japan) and continuous flow analyzer (Skalar, Breda, Netherlands), respectively.

MBC and MBN were measured using the chloroform fumigation-extraction method [24]. Organic carbon in extracts was analyzed with a total organic carbon analyzer (Thermo Orion), and organic nitrogen with a continuous flow analyzer (Skalar). MBC and MBN were calculated as: - MBC = ΔC / 0.45 - MBN = ΔN / 0.54 where ΔC and ΔN are differences between fumigated and non-fumigated extracts, and 0.45 and 0.54 are conversion factors.

UV-Vis absorbance was measured using a UV-Vis spectrophotometer (UV-2450, Shimadzu) with 1 cm cuvettes. Absorbance at 254 nm (UV) was used to calculate the aromaticity index (AI) as: $\mathbf{AI = (UV\ \ / DOC) \times 100}$

Fluorescence spectra were obtained with a Hitachi F-7000 fluorometer (Tokyo, Japan). Excitation wavelength was set at 254 nm, emission scanned from 250–500 nm, with slit widths of 5 nm and scan speed of 1200 nm/min. Samples were acidified with dilute HCl before measurement to enhance sensitivity [25].

Two humification indices were calculated: - **HIXem:** Ratio of peak area at 435–480 nm to 300–345 nm in emission spectra - **HIXsyn:** Ratio of fluorescence intensity at 460 nm to 345 nm in synchronous scan spectra (Δ = 18 nm)

These indices indicate the degree of aromatic condensation and polymerization, with higher values representing more complex, humified DOM [26-28].

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3. Results

3.1 Effects on Soil Physicochemical Properties Soil water content (SWC) showed significant treatment effects (Table 2). In October 2014 (first sampling), W and WP treatments significantly reduced SWC in the 0–10 cm layer compared to CK, while P showed no significant difference. In the 10–20 cm layer, W, P, and WP all reduced SWC, but differences were not significant. Soil organic carbon (SOC) and total nitrogen (STN) showed no significant differences among treatments at any sampling time.

In January 2015 (second sampling), W and WP significantly decreased SWC in both layers. In April 2015 (third sampling), W and WP reduced SWC in the 0–10 cm layer, while all treatments reduced SWC in the 10–20 cm layer, though not significantly. SOC, STN, and C/N ratios remained unaffected by treatments.

Temporal patterns revealed that SWC was lowest during the dry season (October 2014, January 2015) and increased during the rainy season (April 2015).

However, plant water uptake during the growing season moderated this increase. Three-way ANOVA showed that warming (W) and precipitation reduction (P) significantly affected SWC, with warming having stronger effects on the surface layer and precipitation reduction affecting both layers (Table 2).

3.2 Effects on DOM Quantity Warming significantly increased DOC and DON concentrations in both soil layers across all sampling times (Figure 2). In the 0–10 cm layer, W, P, and WP treatments increased DOC and DON over time, with the highest values in April 2015. In the 10–20 cm layer, DOC and DON showed similar trends, though temporal variation was greater.

Precipitation reduction effects were season-dependent. During the dry season (October 2014, January 2015), P treatment decreased DOM quantity, while during the rainy season (April 2015), it increased DOM as microbial activity and aromatic compound content decreased. The WP treatment consistently increased DOM quantity due to accelerated SOM decomposition, with the effect being additive or synergistic depending on season.

Three-way ANOVA indicated that warming significantly affected DOC and DON in both layers, while precipitation reduction had significant effects only in the 10–20 cm layer (Table 2). The interaction effect (W × P) was significant for DOC in the 0–10 cm layer.

3.3 Effects on Microbial Biomass Microbial responses varied temporally (Figure 3). In January 2015, MBC and MBN increased over time in both layers under CK, W, and P treatments. Warming decreased MBC in the 10–20 cm layer, while WP increased MBC in the 0–10 cm layer. In April 2015, MBC and MBN generally decreased compared to January, except for increases under P and WP treatments.

Warming significantly reduced MBN in the 10–20 cm layer, while precipitation reduction increased MBN in the 0–10 cm layer. The interaction effect was significant for MBC in the 0–10 cm layer (Table 2). Temporal dynamics suggested microbial communities were still adapting to treatments, as the experiment was in its early phase.

3.4 Effects on UV Spectral Characteristics The aromaticity index (AI) showed complex responses (Figure 4). In the 0–10 cm layer, AI under CK and W treatments decreased from October to January then increased in April. P and WP treatments showed decreasing AI over time. In the 10–20 cm layer, AI under CK and P increased then decreased, while W and WP showed decreasing trends.

Warming significantly reduced AI in both layers, indicating lower aromatic compound content. Precipitation reduction decreased AI in the surface layer but increased it in the subsurface layer. The interaction effect was significant for AI in the 0–10 cm layer (Table 2).

3.5 Effects on Fluorescence Spectral Characteristics Humification indices (HIXem and HIXsyn) revealed treatment effects on DOM complexity (Figure 5). In the 0–10 cm layer, HIXem and HIXsyn under all treatments increased from October to January then decreased in April. In the 10–20 cm layer, similar patterns occurred, though absolute values were lower.

Warming significantly decreased both humification indices in the 0–10 cm layer, indicating simpler DOM structure. Precipitation reduction increased HIXem in the surface layer but decreased HIXsyn in both layers. The interaction effect was significant for HIXsyn in the 0–10 cm layer (Table 2).

4. Discussion

Soil moisture is a critical factor regulating ecosystem processes. Warming increases temperature and accelerates evaporation, while precipitation reduction directly limits water input. Our results show warming primarily affected surface soil moisture, whereas precipitation reduction influenced both layers, particularly the subsurface (Table 2). This occurs because surface water evaporates more readily, while deeper soil moisture is more buffered but dependent on water percolation.

Soil pH is closely linked to moisture. High moisture dilutes electrolytes, increasing cation mobility and pH [29-31]. The positive correlation between SWC and pH observed here supports this mechanism. DOM quantity and quality are mediated by microbial activity, which depends on both temperature and moisture [32-33]. MBC and MBN are sensitive indicators of soil fertility and responded strongly to treatments, though temporal variation suggested microbial communities were still acclimating.

Warming increased DOC and DON concentrations (Figure 2) but decreased aromaticity and humification (Figures 4, 5), indicating production of more labile DOM. This likely resulted from: (1) accelerated SOM decomposition, (2) increased root exudation due to higher plant productivity [14, 41], and (3) reduced microbial assimilation due to moisture limitation. The negative correlation between DOC and AI (Table 3) confirms that high DOM concentrations were associated with less aromatic, more decomposable compounds.

Precipitation reduction effects were seasonally dependent. During the dry season, reduced moisture limited microbial activity and plant growth, decreasing DOM quantity but increasing its aromaticity as only recalcitrant compounds persisted. During the rainy season, increased moisture stimulated microbial activity, but the legacy of drought may have caused soil structure collapse, releasing previously protected DOM [48]. The resulting DOM was less aromatic and more abundant.

The combined WP treatment showed complex interactions. While warming alone produced labile DOM, and precipitation reduction alone produced more aromatic DOM during drought, their combination resulted in increased DOM quantity with intermediate aromaticity. This suggests that warming' s effect on decomposition dominated, while precipitation reduction' s effect on DOM quality was modulated by seasonal moisture availability.

The lower HIX values under warming indicate reduced polymerization and condensation, meaning DOM contained fewer humic substances and more simple compounds [34, 36]. This has important implications for carbon stabilization, as less humified DOM is more vulnerable to mineralization and leaching [35, 37]. The positive correlation between HIX and MBC (Table 3) suggests that microbial processing contributes to DOM humification.

5. Conclusion

Temperature and moisture are fundamental ecological factors controlling forest ecosystem functions. This study demonstrates that: 1. **Warming** increases DOM quantity but reduces its aromaticity and humification, producing more labile carbon that is vulnerable to loss. 2. **Precipitation reduction** has season-dependent effects: during drought it decreases DOM quantity while increasing aromaticity; during rainy periods it can increase DOM quantity. 3. **Combined warming and precipitation reduction** increases DOM quantity and simplifies its structure, with effects that are not simply additive but interact with seasonal conditions. 4. **Soil moisture** is the key factor mediating these responses, affecting both microbial activity and DOM transport.

The short experimental duration (one year) means microbial communities and plant-soil feedbacks may not have reached equilibrium. Long-term observations are essential to fully understand how climate change will affect carbon and nitrogen cycling in subtropical forest ecosystems. Future research should continue monitoring DOM dynamics, microbial community composition, and plant productivity to improve predictions of forest carbon storage under changing climate regimes.

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