Effects of Short-term Warming and Reduced Rainfall on the Quantity and Spectroscopic Characteristics of Soil DOM in Chinese Fir Plantations: Postprint

Authors: Li Huan, Yang Yusheng, Si Youtao, Liu Zhu

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Abstract

This study selected soils from mid-subtropical Chinese fir (Cunninghamia lanceolata) plantations in China for a short-term warming and 50% rainfall reduction experiment, utilizing spectroscopic techniques to investigate the effects of warming and precipitation reduction on the quantity and structure of soil dissolved organic matter (DOM). The experiment consisted of four treatments: control (CT), warming (W, soil temperature increased by 5°C), precipitation reduction (P, natural rainfall reduced by 50%), and the interactive effect of warming and precipitation reduction (WP). The results showed: 1) Warming increased the quantity of soil dissolved organic carbon (DOC), decreased the aromaticity index and humification index of DOM, and simplified its structure to make it more easily decomposable; soil DOM in the 0–10 cm layer contained more alkanes and fewer esters; DOM in the 10–20 cm layer contained more carbohydrates. 2) Precipitation reduction decreased soil moisture and reduced the quantity of soil DOC. In the 0–10 cm soil layer, the aromaticity index and humification degree of DOM decreased, with DOM containing abundant alkanes; whereas in the 10–20 cm soil layer, the aromaticity index and humification index of DOM increased, with fewer carbohydrates. The precipitation reduction treatment increased the quantity of soil dissolved organic nitrogen (DON). 3) The interactive effect of warming and precipitation reduction increased the quantities of DOC and DON, and decreased the aromaticity and humification degrees of DOM; it resulted in DOM in the 0–10 cm layer containing more carbohydrates, while DOM in the 10–20 cm layer contained fewer carbohydrates. 4) For the 0–10 cm soil layer, warming exerted the strongest effect on the quantity and structure of soil DOM; as soil depth increased to 10–20 cm, the effect of precipitation reduction became progressively more pronounced, and its influence on DOM structure also reached a significant level. Temperature and precipitation play important roles

in the changes of DOM quantity and chemical structure; these research findings can provide a scientific basis for elucidating the dynamic turnover of soil DOM under global climate change and for predicting future trends in forest soil carbon and nitrogen changes.

Full Text

Effects of Short-Term Global Warming and Precipitation Reduction on the Quantity and Spectral Characteristics of Soil DOM in *Cunninghamia lanceolata* Plantation

LI Huan, YANG Yusheng, SI Youtao, LIU Zhu
(College of Geographical Sciences, Fujian Normal University / Key Laboratory for Subtropical Mountain Ecology (Ministry of Science and Technology and Fujian Province Funded), Fuzhou 350007, China)

Abstract: As a small but reactive soil organic matter (SOM) pool, dissolved organic matter (DOM) is considered a sensitive indicator of SOM dynamics and an important component of terrestrial biogeochemical cycles. The quality and quantity of DOM are crucial to the cycling of carbon, nitrogen, and other nutrients in forest soils because these attributes are closely related to carbon accumulation and nutrient availability to microorganisms and plants. Global warming has been widely recognized and has induced drastic changes in global precipitation patterns. Because temperature and precipitation are the two most important environmental drivers regulating forest SOM cycling, it is critical to understand how soil DOM responds to such climatic changes. In this study, we conducted a short-term experiment in a *Cunninghamia lanceolata* plantation in subtropical China that simulated soil warming and precipitation decline to address the effects of these two factors on DOM quantity and composition. The experimental design was a randomized complete block factorial design with warming and precipitation as fixed factors. Four treatments (each replicated three times) were established: no warming with natural precipitation (CT), warming with natural precipitation (W), no warming with reduced precipitation (P), and warming with reduced precipitation (WP). We found that: (1) The W treatment increased the quantity of labile soil dissolved organic carbon (DOC) but decreased the aromaticity and humification degree of DOM. The 0–10 cm soil layer contained more alkanes and fewer esters, while the 10-20 cm layer had more carbohydrates. (2) The P treatment resulted in lower soil water content, which limited DOC production. In the 0–10 cm layer, soil DOM was apparently less humified and less condensed, with abundant alkanes present. However, in the 10-20 cm layer, aromaticity and humification degree were enhanced while carbohydrate quantity decreased. Additionally, precipitation decline increased soil dissolved organic nitrogen (DON) quantity. (3) The combination of warming and declining precipitation increased DOC and DON concentrations and reduced both aromaticity and humification degree. The 0-10 cm layer contained relatively more carbohydrates than the 10–20 cm layer.

(4) In the 0–10 cm layer, warming was the dominant factor significantly influencing DOM quantity and quality. With increasing soil depth to 10–20 cm, precipitation decline became the second significant factor influencing soil DOM structure. Our results provide deeper insight into the dynamic changes of soil DOM under global warming and declining precipitation, which will help more accurately predict soil carbon and nitrogen cycles in response to future climate change.

Keywords: *Cunninghamia lanceolata* plantation; soil warming; precipitation reduction; soil dissolved organic matter; aromaticity index; humification degree; spectral characteristics

Dissolved organic matter (DOM) is defined as organic matter that can dissolve in water, acids, or alkaline solutions, typically characterized as a continuum of organic molecules passing through a 0.45 m filter [1]. It includes dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and dissolved organic phosphorus (DOP) [1-2]. DOM represents an extremely active chemical component in terrestrial ecosystems that can sensitively reflect changes in soil organic matter [3]. It is also the most important energy and nutrient source for soil microorganisms and constitutes a vital component of terrestrial biogeochemical cycles [2], while playing a crucial role in transporting nutrients from forest ecosystems to aquatic environments [4].

Since the Industrial Revolution, extensive fossil fuel extraction and use have caused dramatic increases in atmospheric "greenhouse gases," altering Earth' s original atmospheric composition and biogeochemical cycles and producing climate change characterized primarily by global warming [5]. According to the latest IPCC climate change report from 2013, global average surface temperature increased by approximately 0.85°C between 1880 and 2012 [6]. Climate warming also leads to frequent droughts in terrestrial ecosystems and altered precipitation patterns, with zonal average precipitation likely increasing at high latitudes and some mid-latitude regions while decreasing in subtropical zones [7]. Such changes in terrestrial precipitation patterns have now been widely observed at both global and regional scales [8]. Temperature and moisture are key factors affecting ecosystem processes, and global warming combined with altered precipitation patterns will inevitably affect forest ecosystem structure and function [9-10], first manifesting as changes in forest soil DOM quantity and quality. Therefore, studying soil DOM responses to temperature and moisture is theoretically important for understanding future forest ecosystem carbon and nitrogen cycles.

Current research on temperature and precipitation as single-factor controls has been reported but remains incomplete and controversial. Some studies indicate that DOC quantity increases under warmer climates [11], while MacDonald et al. [12] found no temperature effect on soil DOC, possibly because DOC decomposition and production rates were equivalent. McDowell et al. [13] showed that DON concentration increases with temperature, with higher DON content in summer than winter, yet opposite results have also been reported: despite higher summer temperatures, DON concentration was actually lower due to increased mineralization rates [14]. Soil temperature and moisture are the main factors affecting microbial decomposition of litter and soil organic matter, which in turn influences soil DOM; however, Guggenberger et al. [15] found no effect of moisture on soil DOC concentration and composition. These findings demonstrate that the combined effects of temperature and moisture on soil DOM are extremely complex.

Therefore, establishing multi-climate-factor experimental platforms in typical forest ecosystems under field conditions to simulate future global climate change and explore temperature and moisture effects on soil DOM is of great significance. However, existing field warming platforms are concentrated primarily in mid- to high-latitude regions, with few reports on ecosystem-level field warming experiments incorporating multiple climate change factors in China' s subtropical regions [16]. China' s humid subtropical zone represents an "oasis" at similar latitudes globally, and due to commercial forest base construction, large areas of evergreen broadleaf forests in this region have been converted to *Cunninghamia lanceolata* plantations, which account for 6.5% of the world's plantation area [17]. To better understand how *C. lanceolata* plantations will respond to future climate change, we established a warming and precipitation reduction multi-factor experimental platform in a young *C. lanceolata* stand, using soil DOM as our research object. Combining UV-Vis spectroscopy, fluorescence spectroscopy (FS), and Fourier-transform infrared spectroscopy (FTIR) techniques, we examined how DOM quantity and chemical structure respond to warming and precipitation changes to deepen our understanding of global climate change impacts on forest ecosystem carbon and nitrogen cycles.

1.1 Study Site Overview

The experimental site is located at the Sanming Chen Da State Forest Farm observation point (26°19 N, 117°36 E) of the Sanming Forest Ecosystem and Global Change Research Station. The site has an average elevation of 300 m, a mid-subtropical monsoon climate, mean annual precipitation of 1,749 mm, mean annual temperature of 19.1°C, and relative humidity of 81%. The soil is red soil developed from biotite granite [18].

1.2 Experimental Design

In 2013, several 2 m × 2 m experimental plots were established. Each plot was isolated from adjacent plots by four welded PVC boards (200 cm × 70 cm) to prevent interference. Soils developed from biotite granite were excavated by horizon (0-10 cm, 10-20 cm, 20-70 cm), transported back to the laboratory, and sieved to remove coarse roots, stones, and other debris. The soils were then mixed by horizon and repacked into the plots, with bulk density adjusted using compaction methods to approximate original field conditions and minimize heterogeneity among plots.

Four treatments were established, each with three replicates: control (CT), warming (W), precipitation reduction (P), and warming × precipitation reduction (WP). In October 2013, heating cables were installed parallel in all plots at 10 cm depth with 20 cm spacing, with an additional cable looped around each plot perimeter to ensure uniform warming. Warming began five months after cable installation (March 2014), with warmed soils maintained 5°C above control soils (only W and WP plots were heated). Precipitation reduction was achieved in P and WP plots by installing transparent U-shaped tubes (0.05 m × 5 m) at 1.5 m height with 5 cm spacing, intercepting 50% of natural rainfall [16]. Four young *C. lanceolata* trees were planted in each plot, positioned between cable lines [Figure 1: see original paper].

1.3 Sample Collection

Sampling was conducted in October 2014. Five soil sampling points were arranged in an S-shaped pattern in each plot, with samples collected by horizon (0–10 cm, 10–20 cm). Samples were transported to the laboratory, where debris, gravel, and plant roots were removed. The five subsamples from the same horizon in each plot were combined into one composite sample, passed through a 2 mm sieve, and divided for determination of basic soil physicochemical properties and DOM extraction.

1.4.1 Determination of Basic Soil Physicochemical Properties

Soil pH was measured using a CHN868 pH meter (Thermo Orion) at a 2.5:1 water-to-soil ratio. Total soil organic carbon and total nitrogen were determined using a VarioMAX C/N analyzer (Elementar, Munchen, Germany). Basic soil properties for the four treatments are shown in Table 1 .

1.4.2 Determination of Soil DOM

Soil DOM was extracted using water extraction [19]. DOC content in the filtrate was measured using a TOC-VCPH analyzer (Shimadzu, Kyoto, Japan), and DON content was determined using a San++ continuous flow analyzer (Skalar, Breda, Netherlands). UV-Vis absorbance was measured using a UV-2450 spectrophotometer (Shimadzu, Kyoto, Japan). The aromaticity degree of DOM was analyzed by measuring absorbance at 254 nm (Special Ultraviolet-Visible Absorption, SUVA). SUVA, also called the aromaticity index (AI), was calculated as AI = (UV254/DOC) × 100 (where UV254 is UV absorbance at 254 nm) [20].

Fluorescence spectra were measured using a Hitachi F7000 instrument (Hitachi, Tokyo, Japan) with excitation and emission slit widths of 5 nm and scanning speed of 1,200 nm · min^{1}. Excitation wavelength was 254 nm with emission range of 300–480 nm; synchronous scan range was 250–500 nm. To improve sensitivity, sample pH was adjusted to 2 with dilute HCl before measurement [20]. The humification index (HIX) in synchronous mode was calculated as the ratio of fluorescence intensity at 460 nm to that at 345 nm: HIX = I460/I345 (I460: fluorescence intensity at 460 nm; I345: fluorescence intensity at 345 nm) [20]. HIX represents DOM polymerization degree [21].

For FTIR analysis, 4 mg of freeze-dried sample was ground with 400 mg dried KBr (spectroscopic grade) and pressed into pellets at 10 t • cm ^{2} pressure. Spectra were obtained using a Cary 660 FTIR spectrometer with scanning range of 4,000–400 cm ^{1}.

1.5 Data Processing and Analysis

Data were analyzed using SPSS 19.0 software. One-way ANOVA and independent samples t-tests were used to compare differences in DOM quantity and spectral characteristics among treatments within the same soil layer and between soil layers under the same treatment. Two-way ANOVA was used to analyze the effects of warming (W) and precipitation reduction (P) factors on DOM quantity and spectral characteristics within the same soil layer ($P < 0.05$). Figures and tables were prepared using Microsoft Excel and Origin.

2.1 Changes in Soil Properties Under Warming, Precipitation Reduction, and Their Interaction

As shown in Table 1 , compared with CT, soil water content in both layers showed a decreasing trend after W, P, and WP treatments. Soil pH decreased under all three treatments, with pH in W and WP plots significantly lower than in non-warmed soils. Under the same treatment, pH in the 10–20 cm layer was higher than in the 0–10 cm layer. In both layers, SOC, STN, and C/N ratios showed decreasing trends under W, P, and WP treatments compared with CT.

2.2 Effects of Warming, Precipitation Reduction, and Their Interaction on Soil DOM Quantity

As shown in Figure 2 [Figure 2: see original paper], in the 0–10 cm layer, W and WP treatments increased soil DOC content by 7% and 19% respectively compared with CT, while P treatment decreased DOC content. In the 10–20 cm layer, DOC content showed similar trends across treatments as in the 0–10 cm layer, but differences were not significant. For any given treatment, DOC content was higher in the 0–10 cm layer than in the 10–20 cm layer. For both layers, soil DON content under W, P, and WP treatments was higher than under CT, with greater DON content in the upper layer than the lower layer.

2.3 Effects of Warming, Precipitation Reduction, and Their Interaction on UV Spectral Characteristics of Soil DOM

Table 2 shows the UV spectral characteristics of soil DOM under the four treatments. In the 0-10 cm layer, compared with CT, the AI values of W, P, and WP treatments decreased by 53%, 27%, and 60% respectively. Two-way ANOVA showed that the W effect was significant (Table 3). In the 10-20 cm layer, AI values under W and WP treatments decreased by 45% and 15% respectively, while AI under P treatment increased by 78%. Two-way ANOVA showed that both W and P effects were significant (Table 3). Overall, AI values under CT and W treatments decreased with soil depth, while AI values under P and WP treatments increased with depth, though not significantly.

2.4 Effects of Warming, Precipitation Reduction, and Their Interaction on Fluorescence Spectral Characteristics of Soil DOM

Figure 3 [Figure 3: see original paper] shows fluorescence emission spectra of soil DOM under the four treatments. In both 0-10 cm and 10-20 cm layers, the emission wavelength corresponding to the fluorescence peak shifted to shorter wavelengths after W, P, and WP treatments, with the order of peak wavelengths being WP < W < P < CT, indicating that CT soil DOM had more complex structures while W, P, and WP structures were relatively simple.

As shown in Table 2 , in the 0-10 cm layer, HIX values under W, P, and WP treatments were lower than CT, with W and WP significantly reducing HIX by 50% and 46% respectively, indicating that CT soil DOM had the highest humification degree. Two-way ANOVA showed that the W effect was significant (Table 3). In the 10-20 cm layer, HIX values under W and WP showed no significant change compared with CT, while P treatment significantly increased HIX. Two-way ANOVA showed that the P effect on HIX was significant (Table 3).

2.5 Effects of Warming, Precipitation Reduction, and Their Interaction on FTIR Characteristics of Soil DOM

Figure 4 [Figure 4: see original paper] shows FTIR spectra of soil DOM under different treatments. The absorption peak near 3,696 cm ^{1} corresponds to N-H stretching vibrations. The strong, broad absorption in the 3,600-3,200 cm ^{1} range represents hydrogen-bonded hydroxyl stretching vibrations, primarily from carbohydrates (cellulose, starch, sugars) as well as alcohols and phenols in DOM samples. The peak near 2,960 cm ^{1} corresponds to asymmetric -CH stretching, while the peak near 2,852 cm ^{1} represents symmetric -CH stretching. The peak near 1,680 cm ^{1} corresponds to C=O stretching. The absorption near 1,610 cm ^{1} represents asymmetric stretching of organic carboxylate R-CO and C=O stretching in lignin connected to benzene rings. The 1,383 cm ^{1} peak corresponds to alkane C-H bending vibrations. Peaks near 1,149 cm ^{1} and 1,120 cm ^{1} represent carbohydrate C-O stretching. The 1,033 cm ^{1} peak may indicate esters. Absorption at 900-650 cm ^{1} corresponds to aromatic C-H out-of-plane bending [22-23].

In the 0-10 cm layer, the W treatment showed higher relative absorption intensity at 1,383 cm ^{1} but weaker absorption at 1,033 cm ^{1} compared with CT, indicating that warming promoted DOM decomposition and produced abundant alkanes. The P treatment showed the strongest absorption at 1,383 cm ^{1}, with higher relative proportions than the other three treatments, demonstrating that precipitation reduction also affected DOM decomposition, corresponding to decreased aromaticity and humification indices and fewer aromatic compounds in soil DOM compared with CT. The WP treatment showed significantly higher relative absorption intensity in the carbohydrate region than the P treatment but weaker alkyl absorption than P treatment, similar to CT, indicating that the combined warming and precipitation reduction treatment reduced DOM condensation and aromatic content, producing more carbohydrates after decomposition. Notably, WP showed the most pronounced N-H absorption, corresponding to higher DON content than other treatments.

For the 10-20 cm layer, the W treatment showed stronger absorption at 1,149 cm ^{1} and 1,120 cm ^{1}, indicating more carbohydrates, because warming promoted organic matter decomposition and reduced DOM aromaticity and humification degree. The P treatment showed a sharp alkyl absorption peak (1,383 cm ^{1}), indicating that precipitation reduction produced more alkyl compounds after organic matter decomposition. FTIR absorption was similar between WP and CT treatments. Overall, P and WP treatments contained fewer carbohydrates.

DOM is an active component of soil organic matter [3]. This study examined young *C. lanceolata* plantation soil DOM to explore the effects of soil warming and precipitation reduction. In the 0-10 cm layer, warming increased DOC quantity and simplified DOM structure. The aromaticity degree and molecular weight of soil DOM samples are positively correlated with UV absorbance SUVA [24-25], while DOM humification degree HIX can describe DOM molecular structure and aromatic compound content [26-27]. The W treatment had the lowest SOC content but highest DOC content, likely because warming alone reduced SOC activation energy and accelerated SOC decomposition [28]. Marilley et al. [29] found that warming can increase microbial biomass carbon (MBC) content, and priming effects can promote SOC decomposition by activating microbial activity to release more extracellular enzymes [30]. FTIR showed that W had greater absorption proportion at 1,383 cm ^{1} but smaller at 1,033 cm ^{1} compared with CT. The 1,383 cm ^{1} absorption originates from alkyl structures, products of mineralization, providing evidence that warming accelerated DOM mineralization. Compared with CT, W showed enhanced relative proportions in the carbohydrate absorption region, consistent with W having the lowest AI and HIX values.

The P treatment alone resulted in the lowest soil DOC quantity and more complex structure than W and WP treatments. Due to reduced moisture, SOC transformation to DOC decreased, and readily decomposable DOC had already been mineralized. Consequently, P showed the largest alkyl absorption peak at 1,383 cm ^{1}, and its DOC structure was more complex than in warmed plots. SOC under P treatment was lower than CT, possibly due to increased autotrophic respiration from larger soil pores and reduced carbon input from throughfall and root exudates. Prolonged drought limits plant growth by reducing water availability [31], thereby decreasing DOC sources. The WP treatment showed the highest DOC quantity and SOC content similar to CT. WP represents the 叠加 of W and P factors: soil warming activation facilitates SOC-to-DOC transformation, while reduced soil moisture greatly decreases microbial activity and DOC decomposition rate, resulting in the highest DOC quantity. WP also showed the lowest AI, and its FTIR spectrum was most similar to CT, indicating that microbial decomposition activity was significantly lower under WP than under W or P treatments. Two-way ANOVA showed that for 0–10 cm soil, only the W factor significantly affected DOC quantity and structure.

For the 10–20 cm layer, DOC and DON quantities showed similar trends to the upper layer, but DOC structure differed slightly. In this layer, the P treatment produced the lowest DOC quantity and most complex structure (significantly different from other treatments), likely because moisture reduction effects were more pronounced at 10–20 cm depth than in the 0–10 cm surface layer. Reduced moisture was unfavorable for SOC activation to DOC and for plant growth, decreasing root exudate production and resulting in low carbohydrate content in soil DOC and less microbially available carbon. In FTIR, the P treatment showed stronger 1,383 cm ^{1} absorption than CT in this layer—these alkyl structures are not readily utilized by microorganisms and represent decomposition products. Meanwhile, P treatment weakened absorption at 1,033 cm ^{1}, unlike in the 0–10 cm layer where no weakening occurred, consistent with AI and HIX values. Due to these P treatment effects, WP soil DOC structure was also more complex than W treatment. Two-way ANOVA showed that both P and W treatments significantly affected AI and HIX of 10–20 cm soil DOC. However, although P treatment soil DOC was least available to microorganisms, SOC under P treatment was relatively low, only higher than W treatment, indicating that SOC under P treatment had also undergone rapid mineralization, leaving only recalcitrant materials by the sampling time.

The P factor had greater influence on DON quantity than the W factor, with P and WP treatments showing the highest DON content. Nitrogen is a required nutrient element for microbial organic matter decomposition. DON accumulation suggests slow microbial mineralization rates, likely due to low-quality carbon substrates. In this experiment, SOC and STN in both layers were lower under P and WP treatments than CT, indicating that microbial decomposition requires both carbon and nitrogen sources, and low quality of either element affects SOC mineralization rates.

This study used spectroscopic techniques to demonstrate that soil warming can activate SOC to DOC, promote SOC mineralization through priming effects, and transform soils from carbon sinks to carbon sources, reducing DOM aromaticity and humification degree. Precipitation reduction accelerates SOC mineralization in the short term, decreasing SOC content and simplifying DOM structure. However, in later stages, precipitation reduction inhibits microbial activity by reducing substrate availability, making soil DOC structure more complex with increased aromaticity and humification, while enriching DON. The warming × precipitation reduction treatment produced the highest DOM quantity as a result of combined effects, reducing both aromaticity and humification indices. For 0–10 cm soil, warming was the dominant factor; with increasing depth to 10–20 cm, moisture reduction effects became more apparent, and precipitation reduction emerged as a significant factor affecting DOM structure, being the only factor significantly influencing DON quantity.

Temperature and precipitation are important drivers of DOM quantity and structural changes. However, field conditions are complex, and other mechanisms also affect DOM dynamics. Only through long-term observation and consideration of other influencing factors can we better understand climate change impacts on soil carbon and nitrogen cycles.

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