

Effects of Increased Precipitation on Soil Respiration in *Pinus yunnanensis* Plantations in Arid Valley Regions: Postprint

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Date: 2017-03-22T00:00:00+00:00

Abstract

From May 2013 to June 2014, a precipitation addition experiment was conducted in a *Pinus yunnanensis* plantation in a dry valley region, with four treatment levels: control (CK, 0 mm m² a⁻¹), 10% precipitation increase (A1, 80 mm m² a⁻¹), 20% precipitation increase (A2, 160 mm m² a⁻¹), and 30% precipitation increase (A3, 240 mm m² a⁻¹). Soil respiration rates were measured monthly using the LI-8100 open-path soil carbon flux measurement system. The results demonstrated that soil respiration rates across all four treatments exhibited distinct seasonal patterns, peaking in July and reaching their minimum in February. Compared with CK, the annual average soil respiration rate in A1 showed no significant difference ($P > 0.05$), whereas A2 significantly increased by 12.88% ($P < 0.05$), and A3 significantly decreased by 17.71% ($P < 0.05$). All three precipitation addition treatments enhanced the temperature sensitivity of soil respiration and attenuated the relationship between soil respiration and soil moisture. Relative to soil temperature, soil moisture exerted a comparatively minor influence on soil respiration. Precipitation addition increased soil microbial carbon and nitrogen contents during the wet season; however, during the dry season, it had no effect on microbial carbon content but significantly reduced microbial nitrogen content. These findings indicate that the effects of increased precipitation on soil respiration in *Pinus yunnanensis* plantations in dry valley regions are not uniform; moderate precipitation addition promotes soil respiration, while excessive precipitation addition suppresses it.

Full Text

Effects of Precipitation Increase on Soil Respiration of a *Pinus yunnanensis* Plantation in a Dry River Valley Area

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Abstract

This study examined the effects of altered precipitation patterns induced by global climate change on soil respiration (Rs) in a *Pinus yunnanensis* plantation in the dry river valley area of Shimian, Ya' an, Sichuan Province. Based on the average annual precipitation, four treatments were established: CK (natural state, 0 mm/m²), A1 (precipitation increased by 10%, 80 mm/m²), A2 (precipitation increased by 20%, 160 mm/m²), and A3 (precipitation increased by 30%, 240 mm/m²). Soil respiration rate was measured monthly using a LI-8100 open-path soil carbon flux measurement system from June 2013 to May 2014. Results indicated that soil respiration rate in the *Pinus yunnanensis* plantation exhibited obvious seasonal variation, with maximum rates in July and minimum rates in February. Precipitation increase treatments significantly affected Rs differently: A2 significantly increased Rs by 12.88% ($p < 0.05$), A3 significantly decreased Rs by 17.71% ($p < 0.05$), while A1 showed no significant effect. The Q10 value calculated from soil temperature increased under precipitation addition treatments. Compared with soil temperature, soil moisture had less effect on soil respiration. Increasing precipitation enhanced soil microbial biomass carbon (MBC) in the wet season but had no effect in the dry season; however, it significantly reduced microbial biomass nitrogen (MBN). All precipitation addition treatments increased the temperature sensitivity of soil respiration and weakened the relationship between soil respiration and soil moisture. These findings demonstrate that the effects of precipitation increase on soil respiration in *Pinus yunnanensis* plantations in dry river valley areas are not uniform: moderate water addition promotes soil respiration, while excessive addition inhibits it.

Keywords: increasing rainfall; soil respiration; *Pinus yunnanensis* plantation

Introduction

Soil respiration is a critical component of terrestrial ecosystem carbon cycling and plays a vital role in maintaining global carbon balance [1-2]. As a key process in terrestrial ecosystem carbon cycles, soil respiration is closely related to global climate change. Atmospheric circulation and hydrological cycles affected

by global climate change have already altered the spatial and temporal distribution patterns of precipitation [3], making soil respiration more uncertain and ultimately impacting the global carbon cycle [4-5]. Soil respiration is a complex biological process influenced by multiple factors, including biotic factors, abiotic factors, and human activities [6-8]. Soil moisture is one of the main factors affecting soil respiration, as precipitation is the primary source of soil water and regulates underground biochemical processes, particularly in arid and semi-arid regions [9].

Previous research on precipitation effects on soil respiration has made substantial progress [1, 10-11], but results remain uncertain [12-14]. Most studies have focused on precipitation events and short-term precipitation [1], with relatively few long-term observations and dynamic studies. Research areas have concentrated on grassland and desert ecosystems in arid and semi-arid regions [11, 15], with forest ecosystems receiving less attention. Wang et al. [16] studied soil respiration responses to precipitation in subtropical pine forests in China. Shimian County in Ya' an City, Sichuan Province, is located in a dry river valley area with distinct wet and dry seasons. Historical precipitation records [17] indicate that precipitation in this region shows an increasing trend, with particularly significant increases in early-year precipitation. *Pinus yunnanensis* is the main plantation tree species in this region, yet few studies have reported on soil respiration in *Pinus yunnanensis* plantations. This research, focusing on *Pinus yunnanensis* plantations in dry river valley areas and investigating the effects of precipitation increase on understory soil respiration, aims to provide fundamental data for understanding the response and adaptation of forest soil carbon cycling processes to precipitation changes in this region.

1. Study Site Overview

The study area is located in Shimian County, Ya' an City, Sichuan Province (29°14'030 N, 102°21'882 E), at an elevation of 1145 m. This region belongs to a mid-latitude subtropical humid climate zone characterized by distinct wet and dry seasons, with abundant rainfall concentrated in the wet season (June-September). The area has a vertical climate pattern with no severe cold in winter and no extreme heat in summer, with multi-year average precipitation of 801.3 mm and annual average temperature of 16.9°C. The study site is a typical dry river valley area.

The experimental plot is situated on the sunny mid-slope of Jigong Mountain in Shimian County, with flat terrain and minimal human disturbance. The *Pinus yunnanensis* plantation is a single-layer mature forest with an average tree height of 10.6 m and average diameter at breast height of 14.8 cm. The shrub layer is dominated by *Bauhinia faberi* var. *microphylla* and *Sophora viciifolia*, while the herbaceous layer consists mainly of *Arisaema shimienense* and *Festuca modesta*. The soil is primarily yellow-brown with a thickness greater than 30 cm. The

0-15 cm soil layer has a bulk density of (1.24 ± 0.16) g/cm³, total carbon content of (24.86 ± 3.18) g/kg, and total nitrogen content of (1.34 ± 0.35) g/kg.

2. Experimental Design

A randomized block design was established in the *Pinus yunnanensis* plantation under consistent site conditions. Four replicate blocks were set up in the horizontal direction (perpendicular to the slope), with four 4 m × 4 m plots in each block. Buffer zones were established around each plot, and plastic sheets were inserted to a depth of 15 cm to prevent surface runoff and deep soil water exchange between plots.

Four precipitation treatments were established based on multi-year average precipitation: CK (control, 0 mm/m²), A1 (precipitation increased by 10%, 80 mm/m²), A2 (precipitation increased by 20%, 160 mm/m²), and A3 (precipitation increased by 30%, 240 mm/m²). Annual water addition for each plot was calculated as: annual water addition = percentage increase × unit area average annual precipitation (801.3 mm).

To maintain consistency with natural precipitation, annual water addition was divided into dry and wet seasons according to monthly precipitation distribution. The dry season treatment period ran from November to May of the following year, accounting for approximately 18% of annual precipitation, with water added on the 5th, 15th, and 25th of each month. The wet season treatment ran from June to October, accounting for approximately 82% of annual precipitation, with the same addition schedule. Water was calculated using the conversion coefficient of 1 L/mm and applied evenly and slowly to each plot using a watering can. Details of water addition amounts are shown in .

3. Materials and Methods

3.1 Soil Respiration Measurement Three PVC soil respiration collars were randomly placed in each plot and remained in place throughout the experiment, with the upper edge extending approximately 2 cm above ground. Soil respiration was measured monthly from June 2013 to May 2014 using a LI-8100 open-path soil carbon flux measurement system (LI-COR Inc., Lincoln, Nebraska, USA). On rain-free days between the 1st and 4th of each month (before water addition), three measurement cycles were conducted between 9:00-12:00, and the average of these measurements was used as the monthly soil respiration rate.

3.2 Soil Temperature and Moisture Measurement Soil temperature and moisture dynamics were measured using temperature-humidity data loggers (Apresys UTH-179, Apresys, USA) buried at 10 cm depth in the center of each

plot. Data were downloaded monthly, after which instruments were recharged, reset, and reburied. Loggers were programmed to record data continuously at 2-hour intervals throughout the day.

3.3 Soil Microbial Biomass Carbon and Nitrogen Soil samples (0-15 cm) were collected using a five-point sampling method in each plot during both wet and dry seasons. Samples were immediately placed in insulated coolers with ice packs and transported to the laboratory, where they were sieved (2 mm mesh) to remove roots and stones before analysis. Microbial biomass carbon (MBC) and nitrogen (MBN) were determined using the chloroform fumigation-extraction method [18] and analyzed with a total organic carbon-nitrogen analyzer (Shimadzu model TOC-VcPH+TNM-1, Kyoto, Japan).

4. Data Processing

Data were organized and charts prepared using Microsoft Office Excel 2003. Soil temperature, soil respiration rate, and soil microbial biomass carbon and nitrogen were analyzed using repeated measures ANOVA in SPSS 19.0 (SPSS Inc., USA). Annual average soil respiration rates and cumulative soil respiration were analyzed using one-way ANOVA, with multiple comparisons performed using the least significant difference (LSD) method. Linear and nonlinear models were used to fit relationships between soil respiration rate and soil temperature/moisture. Correlation analysis was conducted between wet/dry season soil respiration rates and soil microbial biomass carbon/nitrogen.

The temperature sensitivity coefficient (Q10) of soil respiration was calculated as $Q_{10} = e^{\frac{10}{b}}$, where b is the temperature response constant from the single-factor exponential curve model $R_s = e^{b(T-10)}$. To minimize temperature effects, measured soil respiration rates were standardized to 10°C using the Q10 function. The standardization formula was: $R_{s_{10}} = R_s / e^{b(T-10)}$, where R_s is the measured soil respiration rate at soil temperature T , and b is the fitting parameter from the exponential equation between soil respiration rate and soil temperature [15,19].

Soil microbial biomass carbon and nitrogen were calculated as: $MBC = [(C_f - C_{nf}) / K_C]$ and $MBN = [(N_f - N_{nf}) / K_N]$, where C_f and N_f are total carbon and nitrogen in fumigated samples, C_{nf} and N_{nf} are total carbon and nitrogen in non-fumigated samples, and K_C and K_N are conversion coefficients for microbial biomass carbon and nitrogen, respectively [18].

5. Results

5.1 Effects of Precipitation Increase on Soil Temperature and Moisture Soil temperature in the *Pinus yunnanensis* plantation showed distinct

seasonal dynamics, peaking in summer and reaching minimum values in winter. Annual mean temperatures were 15.9°C (CK), 15.6°C (A1), 15.4°C (A2), and 15.5°C (A3), with no significant differences among treatments ($p>0.05$). Soil moisture exhibited clear wet/dry season characteristics, with high moisture during the wet season (June-September). Throughout the year, soil moisture in all precipitation addition treatments remained higher than CK, with significant differences ($p<0.05$). Annual mean moisture values were 45.21% (CK), 46.00% (A1), 46.42% (A2), and 46.82% (A3), though no significant differences existed among treatment levels ($p>0.05$). Seasonal variations in soil temperature and moisture across treatments are shown in [Figure 1: see original paper].

5.2 Effects of Precipitation Increase on Soil Respiration Rate Soil respiration rate in the *Pinus yunnanensis* plantation showed significant monthly dynamics, following the same trend as soil temperature variation. The annual mean soil respiration rate was (2.36 ± 1.20) mol m² s⁻¹ for CK, with annual carbon emissions of (981.89 ± 45.02) g C m². After precipitation addition, annual mean soil respiration rates were (2.58 ± 1.40) mol m² s⁻¹ for A1, (2.91 ± 1.90) mol m² s⁻¹ for A2, and (2.12 ± 1.28) mol m² s⁻¹ for A3, with corresponding annual carbon emissions of (898.91 ± 38.40) g C m², (1109.02 ± 60.27) g C m², and (807.47 ± 40.83) g C m², respectively.

Repeated measures ANOVA indicated no significant difference in annual mean soil respiration rate between A1 and CK ($p>0.05$). However, A2 significantly promoted soil respiration by 12.88% ($p<0.05$), while A3 significantly inhibited soil respiration by 17.71% ($p<0.05$). Monthly dynamics of soil respiration rates across treatments are presented in [Figure 2: see original paper], and annual average rates and cumulative respiration are shown in [Figure 3: see original paper].

5.3 Relationships Between Soil Respiration Rate and Soil Temperature/Moisture Soil respiration rates under all treatments showed significant positive exponential relationships with soil temperature ($p<0.05$). Q10 values were 1.95 (CK), 2.01 (A1), 2.59 (A2), and 2.77 (A3), representing increases of 3.08%, 32.00%, and 42.00% for A1, A2, and A3, respectively. Precipitation addition thus enhanced the temperature sensitivity of soil respiration. Regression equation parameters for the soil respiration-temperature relationship are provided in .

Both linear and exponential models were used to fit relationships between soil respiration rate and soil moisture. Linear equations explained 18.60%-60.40% of monthly variation in soil respiration rates, while exponential equations explained 19.40%-65.40%. The R² values for both models under precipitation addition treatments were significantly lower than CK, indicating that precipitation addition weakened the relationship between soil respiration and soil moisture.

To minimize temperature effects, measured soil respiration rates were standardized to 10°C using the Q10 function. Linear and exponential models were then

fitted to relationships between these standardized rates and soil moisture. Neither model achieved significance: linear equations explained only 1.80%-6.50% of variation in standardized soil respiration rates, and exponential equations explained just 2.50%-9.80%. The R^2 values for precipitation addition treatments were again lower than CK, and both were substantially lower than the variation explained by soil temperature, confirming that soil moisture had relatively minor effects compared to temperature. Relationships between soil respiration rates (both measured and standardized to 10°C) and soil moisture are shown in [Figure 5: see original paper], with model parameters in .

5.4 Effects of Precipitation Increase on Soil Microbial Biomass Carbon and Nitrogen After the wet season, soil microbial biomass carbon (MBC) content increased significantly under all precipitation addition treatments ($p < 0.05$), with increases of 38.84% (A1), 258.22% (A2), and 115.91% (A3) compared to CK. However, no significant differences in MBC existed among treatments ($p > 0.05$). Microbial biomass nitrogen (MBN) content also increased significantly under all precipitation addition treatments ($p < 0.05$).

After the dry season, MBN content decreased significantly under all precipitation addition treatments ($p < 0.05$), with reductions of 37.00% (A1), 38.84% (A2), and 37.00% (A3). No significant differences in MBN were found among treatments ($p > 0.05$). Soil microbial biomass carbon and nitrogen contents across treatments after dry and wet seasons are illustrated in [Figure 6: see original paper].

Correlation analysis revealed strong relationships between wet-season soil respiration rates and microbial biomass carbon and nitrogen, with correlation coefficients of 0.912 ($p < 0.01$) and 0.763 ($p < 0.05$), respectively. Correlation coefficients for the dry season were 0.752 ($p < 0.05$) and 0.857 ($p < 0.01$), respectively. These relationships are summarized in .

6. Discussion

Soil respiration shows positive correlations with seasonal precipitation variation [7]. This study demonstrated that soil respiration in *Pinus yunnanensis* plantations has distinct seasonal dynamics, peaking in July when soil temperature and moisture are high and plants enter their growth period, with enhanced root growth and soil microbial activity. Minimum respiration occurred in February when temperature and moisture were lowest and root growth and microbial activity were weakest, consistent with most research findings [15,20].

In arid, semi-arid, and seasonally dry regions, precipitation-induced soil moisture fluctuations can increase uncertainty in soil respiration [21]. Holt et al. [22] found that precipitation increase enhanced soil respiration by 33% in tropical semi-arid forests of northern Queensland, Australia, while studies in cloud

forests of Taiwan and Colombia showed precipitation increase significantly inhibited soil respiration [14]. The present study revealed different responses to varying precipitation amounts: A2 promoted soil respiration, while A3 inhibited it. This occurs because moderate precipitation increase enhances soil moisture, stimulating soil respiration by improving water availability and biological activity. However, as precipitation continues to increase, higher water content blocks soil pores, limiting oxygen contact with microorganisms and plant roots and inhibiting respiration [5]. Some studies indicate that precipitation has no significant effect on total soil respiration when soil moisture is already high [23], while others show strong stimulation of soil respiration following precipitation events, particularly in dry soils, with effects lasting 2-6 days (the Birch effect) [12]. However, this stimulation does not occur in all precipitation events and may be inhibited in already moist soils [13]. In this study, soil respiration was measured on rain-free days between the 1st-4th of each month (before water addition), so potential Birch effects require further investigation.

Soil microbial respiration constitutes an important component of total soil respiration [2], and soil microorganisms are highly sensitive to moisture changes [14]. This study showed that precipitation addition promoted MBC in the wet season but had no effect in the dry season, while significantly reducing MBN. Rosacker and Kieft [24] also found that soil microbial numbers increase with the onset of wet seasons and decrease as dry seasons approach. Most studies indicate significant positive correlations between microbial biomass and soil respiration [1,18]. This research demonstrated strong correlations between wet-season soil respiration rates and both MBC and MBN, likely because increased precipitation enhances the availability and mobility of soluble organic matter, thereby increasing microbial numbers and activity [2] and ultimately elevating soil respiration. During dry seasons, reduced temperature and moisture place soil microbes in dormant or inhibited states; excessive water may also leach soluble organic matter, suppressing microbial activity and reducing respiration [1].

Soil temperature is a crucial factor affecting soil respiration, with which it has significant correlations [25]. This study found significant positive exponential relationships between soil respiration rates and soil temperature across all treatments, consistent with other research [26]. The Q10 value represents temperature sensitivity of soil respiration. This study found that precipitation addition increased Q10 values, consistent with Smith [27], likely because altered soil moisture conditions changed microbial activity and ultimately enhanced temperature sensitivity [28].

Soil moisture also importantly influences soil respiration, though its relationship is difficult to quantify [1] and is generally weaker than temperature effects under normal conditions [26]. Various equations can represent this relationship [29-31]. This study found that both linear and exponential models explained less variation in soil respiration rates and 10°C-standardized rates than temperature-based models. Precipitation addition weakened the soil respiration-moisture

relationship, consistent with Zhang et al. [15], confirming that moisture effects were relatively minor compared to temperature.

In conclusion, precipitation increase effects on soil respiration in dry river valley *Pinus yunnanensis* plantations are not uniform: moderate addition promotes respiration, while excessive addition inhibits it. However, due to the complexity of soil respiration mechanisms, this study only explored responses from the precipitation perspective. Comprehensive evaluation of precipitation change effects on forest soil respiration requires further research.

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