

Article

Effects of Prescribed Burning on Soil CO₂ Emissions from *Pinus yunnanensis* Forestland in Central Yunnan, China

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Abstract: The effects of low-intensity and high-frequency prescribed burning on the soil CO₂ emissions from *Pinus yunnanensis* forestland should be explored to achieve sustainable operation and management under fire disturbance. A Li-6400XT portable photosynthesis meter (equipped with a Li-6400-09 soil respiration chamber) and a TRIME[®]-PICO 64/32 soil temperature and moisture meter were used to measure the soil CO₂ flux, soil temperature, and soil moisture at fixed observation sites in two treatments (i.e., unburned (UB) and after prescribed burning (AB)) in a *Pinus yunnanensis* forest of Zhaobi Mountain, Xinning County, Yunnan, China from March 2019 to February 2021. We also determined the relationships between the soil CO₂ flux and soil hydrothermal factors. The results showed that (1) the soil CO₂ flux in both UB and AB plots exhibited a significant unimodal trend of seasonal variations. In 2020, the highest soil CO₂ fluxes occurred in September; they were 7.08 μmol CO₂·m⁻²·s⁻¹ in the morning and 7.63 μmol CO₂·m⁻²·s⁻¹ in the afternoon in the AB treatment, which was significantly lower than those in the UB treatment ($p < 0.05$). The AB and the UB treatment showed no significant differences in annual soil carbon flux ($p > 0.05$). (2) The relationship between the soil CO₂ flux and moisture in the AB and UB plots was best fitted by a quadratic function, with a degree of fitting between 0.435 and 0.753. The soil CO₂ flux and soil moisture showed an inverted U-shaped correlation in the UB plot ($p < 0.05$) but a positive correlation in the AB plot ($p < 0.05$). Soil moisture was the key factor affecting the soil CO₂ flux ($p < 0.05$), while soil temperature showed no significant effect on soil CO₂ flux in this area ($p > 0.05$). Therefore, the application of low-intensity prescribed burning for fire hazard reduction in this region achieved the objective without causing a persistent and drastic increase in the soil CO₂ emissions. The results could provide important theoretical support for scientific implementation of prescribed burning, as well as scientific evaluation of ecological and environmental effects after prescribed burning.

Keywords: prescribed burning; *Pinus yunnanensis*; soil CO₂ flux; soil temperature; soil moisture



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1. Introduction

The flux of carbon from soils to the atmosphere occurs in the form of CO₂, and is primarily the result of soil respiration [1]. Increase in the storage of carbon in soils could help offset further anthropogenic emissions of CO₂, whereas a release from soils could significantly exacerbate the increased atmospheric CO₂ and reinforce the greenhouse-warming effect [2]. Soil respiration, as the second-largest flux of terrestrial ecosystems, not only strongly affects the global carbon balance but also plays an important role in regulating global climate change [3]. Soil respiration releases approximately 80–98 Pg C·a⁻¹ of CO₂ [4], which is 10 times higher than the emissions from global fossil fuels [5]. Small variations in soil respiration would significantly affect the amount of atmospheric CO₂ and thus the global carbon balance [6]. Therefore, variations in soil respiration play a critical role in regulating the regional and global carbon cycles [7–9]. The changes in soil respiration and its

influencing factors must be determined for prediction of global climate change. Most studies have focused on undisturbed ecosystems, such as forests [10], grasslands [11], wetlands [12], deserts [13], and tundra [14], while ignoring the changes in the carbon cycle in these ecosystems in response to factors such as fire control [15], litter removal [16], clear-cutting [17], and nitrogen addition [18]. In particular, the carbon cycle of an ecosystem under disturbance is more complex and has practical significance, which needs much more attention.

Soil respiration dynamics in undisturbed ecosystems is generally determined by soil temperature and moisture. Soil temperature is considered to be the main controlling factor of soil respiration because it significantly affects microbial decomposition, root respiration, and diffusion of enzymes and substrates [19]. Generally, the rate of CO₂ emission increases with the increasing soil temperature [20]. However, soil temperature is not necessarily proportional to soil respiration rate, and some studies have shown that soil respiration rate decreases when the temperature exceeds 40 °C [21]. The results of Davidson et al. showed that soil temperature decreased significantly after autumn, but soil respiration rate increased rather than decreased [22]. Other studies have shown that CO₂ emissions in the ecosystem are greatly affected by light radiation, while the correlation with temperature is weak [23]. Thus, there is much uncertainty about the relationship between soil respiration and temperature. Soil moisture is another abiotic environmental factor affecting soil respiration. The study of a semi-evergreen forest in Panama showed that soil respiration decreased significantly with the increase in soil moisture [24]. In contrast, other studies observed an increase in soil respiration with increased soil water content [25]. Furthermore, soil moisture may replace temperature as the main control factor of soil respiration in arid or semi-arid areas [26,27].

As one of the major disturbance factors of forest ecosystems, fire disturbance affects soil respiration through changing the physical (temperature and moisture), chemical, and biological properties in the soil [28]. The inconsistent results about the effects of forest fires on soil respiration are related to the intensity [29,30], postfire observation time [31–33], forest type [34,35], restoration process of the aboveground vegetation in the burned area [33], and climatic conditions [36,37]. As an important means of afforestation and forest fire prevention, prescribed burning eliminates excessive combustibles through the beneficial nature of low-intensity burning in a controlled, purposeful, planned, and step-by-step manner [38]. In contrast, prescribed burning is characterized by lower intensity and higher frequency, and its impact on the soil ecosystem is long-term and periodic [39]. Relevant studies in China and other countries have been based on the effect of forest fires (high intensity) or one-time burning of the cutover land (low frequency) on the soil carbon cycle in forests [40–43]. Since different fire behaviors can impact the soil respiration to different degrees and through different processes, there is an urgent need to identify the long-term effects of low-intensity and high-frequency burning disturbances on forest soil respiration. The results would provide theoretical and empirical support for evaluating the effects of prescribed burning on the forest carbon cycle and developing effective scientific forest fire management strategies.

Central Yunnan is one of the areas in Yunnan Province where forest fires often occur frequently and severely. It is a key area for the implementation of prescribed burning, with a long history of prescribed burning that can be traced back to the 1980s [44]. *Pinus yunnanensis*, as one of the major tree species in the Yunnan–Guizhou Plateau, comprises a large proportion of the forests in this area [45,46]. Given that prescribed burning has been continuously implemented for many years for preventing forest fires in the Central Yunnan Plateau, we conducted a prescribed burning experiment to explore the impact on the dynamics of soil CO₂ flux in the 30 year-old nearly mature *Pinus yunnanensis* forests from the end of January to mid-February for nearly 20 years. This study aimed to: (1) explore the temporal variations of soil CO₂ emissions in *Pinus yunnanensis* forests in response to prescribed burning, and (2) identify the primary driving factors of soil CO₂ emissions after prescribed burning. The results could provide important theoretical support

for scientific implementation of prescribed burning, as well as for scientific evaluation of ecological and environmental effects after prescribed burning.

2. Materials and Methods

2.1. Overview of the Study Area

The study area was located at the eastern pediment of the middle-segment Ailao Mountain in Zhaobi Mountain, southern Xinping County, Yuxi City, Central Yunnan Plateau (102°0'7"–102°0'8" E, 24°2'38"–24°2'41" N, Figure 1). The terrain is dominated by mountains, and the elevation is 1990–2050 m. The study area has a subtropical plateau monsoon climate, and the soil taxonomy belongs to red soil. The mean annual precipitation and temperature are 869 mm and 18.1 °C, respectively. The total annual sunshine duration is 2838.7 h, and the length of the frost-free period is 316 days. Prescribed burning of the *Pinus yunnanensis* forest in Xinping County has been carried out yearly from the end of January to mid-February for nearly 20 years. The occurrence of haze events in Kunming City since 13 February 2019 has raised environmentalists' opposition to the prescribed burning of the *Pinus yunnanensis* forest in central Yunnan. Consequently, the Department of Ecology and Environment of Yunnan Province notified the Yuxi Municipal Government to stop prescribed burning-related activities.

A 30 year-old *Pinus yunnanensis* natural secondary forest was selected as the study subject. The sample plots were subjected to two treatments: unburned (UB) and after prescribed burning (AB). The UB plot and the AB plot were located at the upper and lower sides of a fire escape, respectively. The *Pinus yunnanensis* forest in the AB plot had a stand canopy density of approximately 0.55, a mean diameter at breast height (DBH) of 16.14 cm, a mean tree height of 13.00 m, and a mean scorch height of 1.48 m, indicating that the prescribed burning had a low intensity [47]. After the prescribed burning, there were no understory shrubs or herbs, and the burning residues accumulated to 50.00 g·m⁻². The *Pinus yunnanensis* forest in the UB plot had a total canopy density of approximately 0.95, a mean DBH of 16.93 cm, a mean tree height of 12.24 m, and an accumulative litter density of 244.00 g·m⁻². The shrubs mainly included *Schima superba* and *Rhododendron decorum*, and the herbs mainly included *Chalcites xanthorrhynchus*, *Cyrtomium fortunei*, *Ranunculus japonicus*, and *Imperata cylindrica* [48].

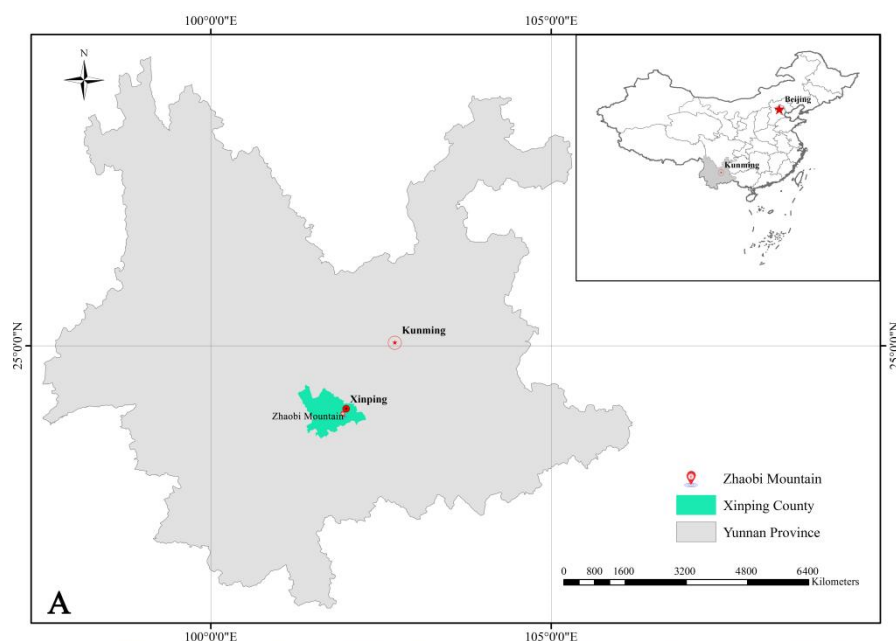


Figure 1. Cont.



Figure 1. Sampled plots in the Zhaobi Mountain, Southern Xinping County, Yuxi City, Central Yunnan Plateau (A); unburned (B); and after prescribed burning (C).

2.2. Determination of Forestland Soil CO₂ Flux, Soil Temperature, and Soil Moisture

Six fixed plots of 20 m × 20 m (three plots for UB treatment and three plots for AB treatment) were set up in the *Pinus yunnanensis* forest. In each plot, three measurement sites were arranged on the upper slope, the mid-slope, and the lower slope, each. The prescribed burning was conducted on 12–13 February 2019, and continuous observations were made from March 2019 to February 2021. At the end of each quarter, the soil CO₂ flux, soil temperature, and soil moisture were measured twice at each measurement site, once in the morning from 9:00 to 12:00 and once in the afternoon from 14:00 to 17:00. The measurement was repeated three times at each measurement site. The measurement could be carried out 1–3 days earlier or later if necessitated by rainfall. The soil CO₂ flux was measured using a Li-6400XT portable photosynthesis meter (equipped with a Li-6400-09 soil respiration chamber). A polyethylene ring (an inner diameter of 10 cm, a height of 5 cm, buried 3 cm underground, and 2 cm above the ground) was embedded in each measurement site 24 h before the measurement to minimize the effect of soil disturbance. The soil temperature (°C) and soil moisture (volumetric moisture, %) at 10 cm depth were simultaneously measured using a TRIME®-PICO 64/32 soil temperature and moisture meter.

2.3. Calculation and Data Analysis

The annual soil carbon flux ($\text{g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$) was estimated by the following equation: $F_C = 12 \times 86,400 \times 10^{-6} \times \sum(R_i D_i)$, where F_C is the annual carbon flux ($\text{g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$), 12 is the molecular weight of C, 86,400 is the conversion coefficient between d and s, R_i is the average soil respiration rate ($\mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) in quarter i , and D_i is the number of days in quarter i . The correlation between soil temperature and soil CO₂ flux is usually described by an exponential equation or the Arrhenius equation [49]. Therefore, the correlation between soil CO₂ flux and soil temperature was fitted using the exponential model [50]: $R_s = ae^{\beta T}$ (where R_s is the soil CO₂ flux; T is the soil temperature; a is the soil CO₂ flux when the soil temperature is 0 °C; and β is the temperature sensitivity coefficient). Q_{10} is an index that reflects the sensitivity of soil CO₂ flux to temperature variations based on the fold of the increase in the soil CO₂ flux for every 10 °C increased in temperature [49]. The value of the commonly used model for Q_{10} is $Q_{10} = e^{10\beta}$ (where β is the temperature response coefficient in the soil CO₂ flux and soil temperature index model $R_s = ae^{\beta T}$). Recent studies on the respective and combined influences of soil moisture and temperature on soil CO₂ flux still have inconsistencies. Therefore, we analyzed the soil moisture ($W/\%$) and soil CO₂ flux (R_s) by three regression models [45] (linear: $R_s = a + bW$; quadratic: $R_s = a + bW + cW^2$; and exponential: $R_s = ae^{bW}$) and analyzed the combined effects of soil temperature and moisture on soil CO₂ flux using the two-factor models [45] ($R_s = a + bTW$, $R_s = a + bT + cW$, and $R_s = ae^{bTW^c}$).

All statistical nonlinear regression and significant difference analyses were performed using SPSS 17.0. All data normality and equal variance were tested. Analysis of variance (ANOVA) was used to test the differences in R_s , T , and W among the different treatments or time. Regression analysis was applied to describe the relationships between R_s and T and W . The significance level of all statistical tests was 0.05, and OriginPro 8.0 was used for plotting.

3. Results

3.1. Seasonal Dynamics of Soil CO₂ Flux

Based on the long-term continuous observation of soil CO₂ flux in the *Pinus yunnanensis* forest (Figure 2), the soil CO₂ flux in UB and AB plots after 2 years consecutive treatments exhibited an overall unimodal trend in seasonal dynamics ($p < 0.05$). Starting in June 2019, the soil CO₂ flux in the UB plot increased, peaking in September 2019 ($9.26 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the morning and $8.76 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the afternoon). The soil CO₂ flux in the AB plot showed a similar trend. The maximum in soil CO₂ flux in the AB plot also reached $9.26 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the morning and only reached $6.57 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the afternoon, which was lower than that of the UB plot ($p < 0.05$). After September, the soil respiration rate continued to decrease, reaching the lowest values in March of the following year ($p < 0.05$). The lowest soil respiration rates of the UB plot were $1.73 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the morning and $1.60 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the afternoon, while the lowest soil respiration rates of the AB plot were $1.94 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the morning and $1.66 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the afternoon. The dynamics of soil CO₂ flux in the following year was similar to those in the previous year, but there were significant interannual fluctuations. In 2020, the highest soil CO₂ flux was again in September ($p < 0.05$). The highest soil CO₂ fluxes in the UB plot were $8.80 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the morning and $8.95 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the afternoon, while those in the AB plot were $7.08 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the morning and $7.63 \mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the afternoon, which was lower than those of the UB plot ($p < 0.05$).

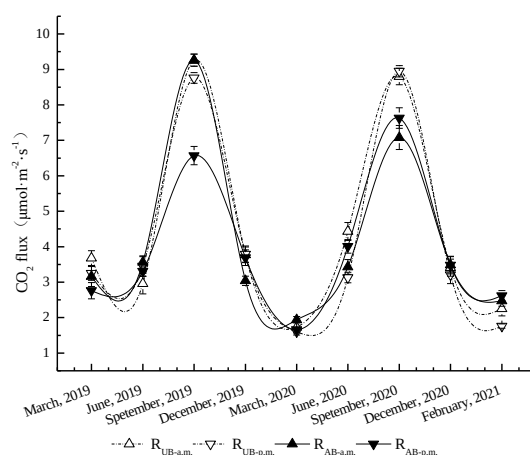


Figure 2. Seasonal variations in soil CO₂ flux in the *Pinus yunnanensis* forest after prescribed burning. $R_{UB-a.m.}$, $R_{UB-p.m.}$, $R_{AB-a.m.}$, and $R_{AB-p.m.}$ represent the soil respiration dynamics under unburned treatments in a.m. and in p.m. and burned treatments in a.m. and in p.m., respectively. The error bars represent the standard error ($n = 9$).

The annual soil carbon flux was calculated by adding the mean soil respiration rate in each quarter (Figure 3). During the observation period, the annual soil respiration in the UB plot were $1797.15 \pm 169.49 \text{ g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ in 2019 and $1589.75 \pm 169.49 \text{ g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ in 2020, indicating that the interannual difference was not significant. The annual soil respiration fluxes in the AB plot were $1659.59 \pm 169.49 \text{ g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ in 2019 and $1547.60 \pm 169.49 \text{ g C} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ in 2020. There were no significant differences in the annual or interannual soil respiration fluxes between the UB and AB plots in a given year the UB or AB plot ($p > 0.05$).

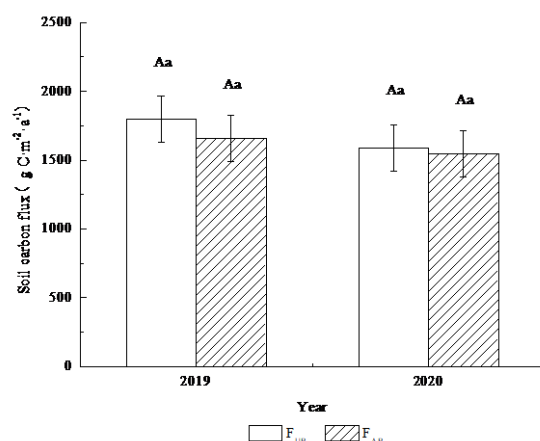


Figure 3. Annual variations in soil carbon emissions from the *Pinus yunnanensis* forest after prescribed burning. F_{UB} and F_{AB} represent the annual carbon flux of unburned and burned treatments, respectively. The error bars represent the standard error ($n = 9$). The different lowercase and uppercase letters are significant at the 95% level in a given year and in the interannual level, respectively.

3.2. Seasonal Dynamics of Soil Temperature and Moisture

For this study, the soil temperature in the UB and AB plots showed significantly seasonal variations with the maximum occurring in summer and the minimum in winter (Figure 4). Soil temperature in the UB plot peaked in June (24.38 °C in the morning and 32.04 °C in the afternoon). The soil temperature in the AB plot showed a similar trend. The maximum soil temperature in the AB plot reached 25.68 °C in the morning but reached 35.57 °C in the afternoon, which was higher than that in the UB plot ($p < 0.05$). The soil temperature continued to decrease after June, with the lowest values in December. In January of the following year, the soil temperature began to rise. The soil temperature in the UB plot reached the highest value in June, while it reached the highest values 3 months earlier in the AB plot. The maximum soil temperatures in the AB plot were 30.79 °C in the morning and 31.15 °C in the afternoon, which was higher than those in the UB plot ($p < 0.05$).

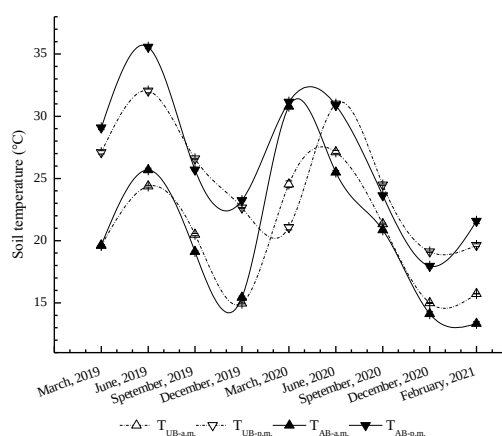


Figure 4. Seasonal variations in soil temperature in the *Pinus yunnanensis* forest after prescribed burning. $T_{UB-a.m.}$, $T_{UB-p.m.}$, $T_{AB-a.m.}$, and $T_{AB-p.m.}$ represent the soil temperature dynamics under unburned treatments in a.m. and in p.m. and burned treatments in a.m. and in p.m., respectively. The error bars represent the standard error ($n = 9$).

The soil moisture in the UB and AB plots exhibited seasonal dynamics of being higher in the rainy season than in the dry season (Figure 5). Starting in March 2019, the soil moisture decreased, then increased in the rainy season (June). The soil moisture in the

UB plot reached the maximum in September (13.09% in the morning and 10.37% in the afternoon). The AB plot showed a similar trend. The maximum soil moisture in the AB plot reached 16.20% in the monitoring and 17.22% in the afternoon, which was significantly higher than those in the UB plot ($p < 0.05$). After September, the soil moisture continued to decrease until March of the following year. The overall trend of soil moisture in 2020 was similar to that in 2019. The mean soil moisture in the UB plot in September 2020 was 19.84%, which was significantly higher than that (13.09%) in the UB plot in September 2019 ($p < 0.05$). The mean soil moisture in the AB plot in September 2020 was 23.10%, which was higher than that (16.71%) in the AB plot in September 2019 ($p < 0.05$).

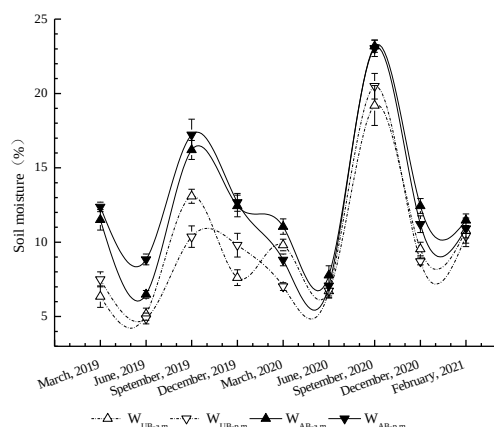


Figure 5. Seasonal variations in soil moisture in the *Pinus yunnanensis* forest after prescribed burning. $W_{UB-a.m.}$, $W_{UB-p.m.}$, $W_{AB-a.m.}$, and $W_{AB-p.m.}$ represent the soil moisture dynamics under unburned treatments in a.m. and in p.m. and burned treatments in a.m. and in p.m., respectively. The error bars represent the standard error ($n = 9$).

3.3. Linking the Soil CO₂ Flux with Soil Hydrothermal Factors

3.3.1. Relationship between Soil CO₂ Flux and Soil Temperature

There was no significant correlation between the soil CO₂ flux and soil temperature in the UB and AB plots (Table 1; $p > 0.05$). According to the exponential regression equation, the soil respiration rate in the AB plot decreased by 0.741 times for every 10 °C increase in the soil temperature. In addition, the soil respiration rate had a greater decrease with the increasing soil temperature in the AB plot than in the UB plot in the morning, indicating that the sensitivity of the soil CO₂ flux to soil temperature was low in the AB plot.

Table 1. Model parameters of the correlation between CO₂ flux (R_s) and soil temperature (T).

Treatment		$R_s = ae^{bT}$	R^2	p	Q_{10}
UB	a.m.	$R_s = 5.340e^{-0.013T}$	0.009	0.659	0.878
	p.m.	$R_s = 2.129e^{0.023T}$	0.029	0.425	1.259
AB	a.m.	$R_s = 7.275e^{-0.030T}$	0.055	0.140	0.741
	p.m.	$R_s = 8.404e^{-0.030T}$	0.064	0.123	0.741

3.3.2. Relationship between Soil CO₂ Flux and Soil Moisture

The three regression models showed significant correlations between the soil CO₂ flux and soil moisture (Table 2; $p < 0.05$). The linear model showed a positive effect of soil moisture on the soil CO₂ flux in the UB and AB plots, with a fitness between 0.459 and 0.727. There was a positive correlation between the soil CO₂ flux and soil moisture in the UB and AB plots based on an exponential model, with a goodness of fit between 0.424 and 0.567. The quadratic function model showed an inverted U-shaped curve between the CO₂ flux and soil moisture in the UB plot, with goodness of fit between 0.435 and 0.753. The

soil CO₂ flux was positively correlated with soil moisture when the soil moisture in the UB plot was lower than 44.00% and 30.19% in the morning and afternoon, respectively, while soil CO₂ flux was negatively correlated with soil moisture otherwise. The trend in the prescribed burning plot was different: when the soil moisture in the morning and afternoon was higher than 0% and 2.69%, respectively, the soil CO₂ flux was positively correlated with the soil moisture.

Table 2. Model parameters of the correlation between CO₂ flux (R_s) and soil moisture (W).

Treatments		$R_s = a + bW$				$R_s = a + bW + cW^2$					$R_s = ae^{bW}$			
		a	b	R ²	p	a	b	c	R ²	p	a	b	R ²	p
UB	a.m.	0.415	0.448	0.579	0.000	−0.446	0.616	−0.007	0.564	0.000	1.802	0.084	0.424	0.000
	p.m.	0.402	0.436	0.583	0.000	−1.420	0.785	−0.013	0.580	0.000	1.667	0.088	0.495	0.000
AB	a.m.	0.192	0.331	0.459	0.000	0.764	0.240	0.003	0.435	0.001	1.605	0.069	0.440	0.000
	p.m.	−0.109	0.336	0.727	0.000	2.508	−0.070	0.013	0.753	0.000	1.452	0.074	0.567	0.000

3.3.3. Association of Soil CO₂ Flux with Soil Temperature and Soil Moisture

The three two-factor models indicated significant correlations of soil CO₂ flux with the composite roles of soil temperature and soil moisture (Table 3; $p < 0.05$). The exponential model well-explained the composite effects of soil temperature and soil moisture on the soil CO₂ flux, with a goodness of fit between 0.437 and 0.721. The observational data of the UB plot showed that the soil CO₂ flux was negatively correlated with soil temperature but positively correlated with soil moisture in the morning, while soil CO₂ flux was positively correlated with both soil temperature and soil moisture. The observational data in the AB plot showed a similar trend, and the soil CO₂ flux was more sensitive to the variations in soil temperature and moisture after the prescribed burning.

Table 3. Model parameters of the correlation between CO₂ flux (R_s) and the composite relationship between soil temperature (T) and moisture (W).

Treatments		$R_s = a + bTW$				$R_s = a + bT + cW$					$R_s = ae^{bTW^c}$			
		a	b	R ²	p	a	b	c	R ²	p	a	b	c	p
UB	a.m.	0.980	0.019	0.499	0.000	0.139	0.013	0.449	0.559	0.000	0.625	−0.002	0.917	0.560
	p.m.	−0.032	0.019	0.682	0.000	−4.853	0.190	0.480	0.659	0.000	0.128	0.054	0.987	0.673
AB	a.m.	1.158	0.012	0.270	0.000	0.541	−0.014	0.326	0.434	0.000	0.424	−0.007	0.977	0.437
	p.m.	−0.411	0.014	0.615	0.000	−1.172	0.032	0.351	0.721	0.000	0.203	0.007	1.113	0.721

4. Discussion

4.1. Responses of Soil CO₂ Flux, Soil Temperature, and Soil Moisture to Prescribed Burning of Forest

Seasonal variations in soil CO₂ flux are mainly driven by temperature, moisture, photosynthate production, and/or their combined effects [49]. Forest fires can result in decreased forest canopy density and increased solar radiation on the surface, thereby changing the soil respiration rate [51]. This study showed that the soil respiration rates in the UB and AB plots had obvious seasonal variations, exhibiting a unimodal curve. Yunnan has a plateau monsoon climate with a distinct wet–dry cycle. The wet season lasts from May to October, and the dry season from November to April of the next year, so soil respiration is sensitive to the variations in soil temperature and moisture. According to our observations over two consecutive years, the soil CO₂ fluxes in the UB and AB plots were both higher in the rainy season than in the dry season. In contrast, the annual soil respiration was not different after the prescribed burning, which is similar to the findings of Concilio et al. [52]. This may be owed to this *Pinus yunnanensis* forest having been subjected to low-intensity and high-frequency burning. Although low-intensity burning can damage the shrubs and grass, it may have not much of an influence on the plant roots and their

respiration. Furthermore, the bark of *Pinus yunnanensis* has fire resistance, avoiding the damage of long-term periodic burning.

In this study, the soil temperature showed obvious seasonal dynamics which exerted a crucial impact on the soil respiration dynamics. The observed CO₂ flux was significantly higher in the AB plot than in the UB plot, perhaps because the prescribed burning destroyed the shrubs, herbs, and surface litter in the forestland which induced an increase in solar radiation that heated up the soils of the AB plot [53]. On the global scale, the soil CO₂ flux is the largest in summer when plant growth is also the most active [54,55]. In general, factors that are conducive to plant growth may be also favor soil metabolic activities. During the active growth season, plants distribute many substrates to roots and microorganisms that promote soil respiration [49].

Soil moisture is one of the main limiting factors for the soil CO₂ flux, so the pattern of the variation in soil CO₂ fluxes is highly consistent with that of soil moisture [56]. In this study, the soil moisture in the UB and AB plots began to decrease in March, increased significantly after entering the rainy season (June), and reached its maximum in September. After September, the soil moisture continued to decrease until March of the following year. This variation pattern of soil moisture was relatively consistent with the that of the soil CO₂ flux. Therefore, we could preliminarily speculate that water deficit during the 6 month-long dry season might limit the biological activities; the seasonal dynamics of soil CO₂ flux in the dry season are largely determined by the availability of soil water. Furthermore, the results from regression models further identified the associations of the dynamic pattern of soil CO₂ fluxes with soil temperature and moisture.

4.2. Relationships between Soil CO₂ Flux and Hydrothermal Factors under Prescribed Burning

Soil temperature and moisture are the main factors affecting soil respiration in forests. The soil temperature and moisture can explain most of the seasonal variations in soil respiration. The results from the exponential regression indicated that soil temperature had no significant effect on soil CO₂ flux in this study, which agrees with the findings of Raich et al. [23]. The sensitivity of the respiration process to temperature (Q_{10}) is an important indicator that expounds the effect of soil temperature on soil respiration variations. The sensitivity of soil CO₂ flux to soil temperature was lower in the AB plot than in the UB plot. Studies in the past 5 years have shown that the measured Q_{10} values in *Pinus yunnanensis* forestlands are usually 2.12–3.86 [57,58]. The Q_{10} values of the AB plot did not fall in this range, indicating that the soil temperature in the study area was not the main factor affecting the forest soil CO₂ flux. This may be related to the long-term periodic burning.

Soil moisture is another important factor affecting soil respiration. The study area has a distinct wet–dry cycle and thus has a wide variation in soil moisture. Under long-term drought conditions, some of the soil carbon is not released due to the suppressive effects of the drought. The rainy season following a long dry season brings lots of rainfall, which promotes the release of drought-suppressed carbon under the stimulation of microorganisms [57]. Therefore, soil moisture may be the main factor affecting the soil respiration, which agrees with the findings of Rey et al. [59]. Among all the regression models, the quadratic function had the highest fitness that could explain up to 75.3% of the soil respiration variations. The two-factor models showed a combined effect of soil temperature and soil moisture, which was superior to the models of the correlation between soil CO₂ flux and soil temperature but inferior to the models of the correlation between soil CO₂ flux and soil moisture. This again confirmed that soil moisture rather than soil temperature was the main factor affecting soil CO₂ flux in this region. There is still a lack of consistency about the respective and combined influences of soil moisture and water on the soil respiration [60]. The study of a *Larix gmelinii* forest in northeast China found that CO₂ flux was mainly affected by soil temperature [4]. In the study of a *Pinus tabulaeformis* forest in the loess hilly region of China, soil respiration was mainly controlled by soil moisture when it was low; however, soil respiration could be determined by soil temperature when it was higher than 13% [61]. For this study, soil moisture was the main factor affecting soil

respiration rate in the *Pinus yunnanensis* forest during the drought period in southwest China [49]. The complex relationship between the soil CO₂ flux and soil moisture has many underlying mechanisms and variations at different regional and temporal scales. Because seasonal and altitudinal variations in moisture are often accompanied by variations in soil temperature, root structure, and microbial activity, the relationship between soil CO₂ flux and moisture is often confounded by other environmental factors. In order to understand how soil moisture affects soil CO₂ flux, it is necessary to conduct a single-factor experiment that controls soil moisture alone, leaving constant other environmental factors such as soil temperature and biological conditions. This will be explored in our future experiments that will be conducted under laboratory conditions.

5. Conclusions

(1) Continuous 2 year observation found that the soil CO₂ fluxes in the UB and AB plots of the *Pinus yunnanensis* forestland both exhibited a significant unimodal trend in seasonal variation. Furthermore, the soil CO₂ flux was higher in the rainy season than in the dry season. In 2020, the highest soil CO₂ fluxes occurred in September, with 7.08 $\mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the morning and 7.63 $\mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in the afternoon in the AB plot, which was lower than those in the UB plot ($p < 0.05$). There were no significant differences in annual soil carbon fluxes between the AB and UB plots.

(2) The relationships between soil CO₂ flux and soil moisture in the UB and AB plots were best fitted by a quadratic function (the fitness between 0.435 and 0.753). The soil CO₂ flux and soil moisture showed an inverted U-shaped correlation in the UB plot, while a positive correlation was observed in the AB plot ($p < 0.05$). Soil moisture was the more important factor that regulates the variations in soil CO₂ flux compared with soil temperature in this region.

Therefore, the application of low-intensity periodic prescribed burning for fire hazard reduction in this region achieved the objective without causing a persistent and drastic increase in the soil CO₂ emissions.

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