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Seasonal Dynamics of Soil Respiration and Its Autotrophic and Heterotrophic Components in Subtropical Camphor Forests

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Abstract: On a global scale, soil respiration (R_s), representing the CO_2 flux between the soil surface and the atmosphere, ranks as the second-largest terrestrial carbon (C) flux. Understanding the dynamics between R_s and its autotrophic (R_a) and heterotrophic (R_h) components is necessary for accurately evaluating and predicting global C balance and net ecosystem production under environmental change. In this study, we conducted a two-year root exclusion experiment in subtropical China's Camphor (*Cinnamomum camphora* (L.) Presl.) forests to assess seasonal changes in R_a and R_h and their relative contributions to R_s. Additionally, we examined the influence of environmental factors on the dynamics of R_a, R_h, and R_s. Our results showed that seasonal mean R_s values were 2.88 μmol m^{-2} s^{-1}, with mean R_a and R_h of 1.21 and 1.67 μmol m^{-2} s^{-1}, respectively, in the studied forests. On an annual basis, the annual values of mean R_s in the studied forests were 405 ± 219 g C m^{-2} $year^{-1}$, with R_h and R_a accounting for 240 ± 120 and 164 ± 102 g C m^{-2} $year^{-1}$, respectively. The seasonal mean ratio of R_h to R_s (R_h/R_s) was 58%, varying from 45 to 81%. Seasonal changes in R_s and R_h were strongly correlated with soil temperature but not soil water content. Both R_h and R_s increased exponentially with the average soil temperature measured in the topsoil layer (about 5 cm), with Q_{10} values of 2.02 and 1.73 for R_h and R_s, respectively. Our results suggest that the composition and activity of soil microbes and fauna play a primary role in releasing carbon flux from soil to the atmosphere in the studied forest ecosystems.

Keywords: camphor forest; root respiration; microbial respiration; carbon cycling; soil CO_2 efflux

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1. Introduction

Soil CO_2 efflux (FCO_2), often referred to as soil respiration (R_s), is the second-largest carbon (C) flux between terrestrial ecosystems and the atmosphere. On a global scale, land plants absorb approximately 120 Pg (10^{15} g) of C per year through the photosynthetic process. Concurrently, the R_s process releases around 68–98 Pg of C back into the atmosphere annually [1–3]. Therefore, R_s is a critical component of the global C cycle, significantly affecting global climate [4,5]. In terrestrial ecosystems, R_s is the result of soil autotrophic respiration (R_a, mainly from roots and associated rhizosphere respiration) and soil heterotrophic respiration (R_h, from microbes and soil fauna respiration) [6,7]. R_a is primarily influenced by root growth and productivity, photosynthesis capacity, C substrate availability, soil organic matter, and nutrient contents [4,7,8]. Since different C sources, biological processes, and metabolic pathways are involved in R_s components, the feedback of the R_a and R_h components to environmental changes varies. Hence, partitioning R_s into R_a and R_h components is important. It can provide insight into the C cycle and sequestration in terrestrial ecosystems under natural and anthropogenic disturbances [4,8].

Numerous studies have focused on partitioning R_s, yet significant uncertainty and variability persist in estimates within forest ecosystems [9,10]. For example, we summarized and evaluated the advantages and disadvantages of three commonly used methods for partitioning R_s into R_a and R_h components in plant communities [11]. The ratio of R_h to R_s varied from 10 to 90% in terrestrial ecosystems, depending on vegetation types and seasonal variations [12]. On average, R_a contributed 45.8% in forest ecosystems and 60.4% in non-forest ecosystems to R_s [13]. Based on soil FCO_2 data from 54 forest sites, we summarized that R_a and R_h were approximately evenly partitioned, ranging between 50 and 60% [4]. Recent studies found that in longleaf pine forests, R_h dominated R_s, with an annual ratio of R_h to R_s ranging from 66 to 96% [14,15]. In addition, the R_a, R_h, and R_s processes are largely regulated by environmental factors, primarily soil temperature (T_{soil}) and soil water content (W_{soil}) [16]. R_s exhibits a distinct seasonal pattern, primarily controlled by T_{soil} [17], and the annual pattern of precipitation indirectly influences the interannual variation of R_s by affecting W_{soil} in subtropical forests [18]. Thus, significant variations in the proportions of R_a and R_h components to R_s highlight the need for further research to better understand the mechanisms that regulate R_a, R_h, and R_s dynamics in forest ecosystems.

Among the methods used to partition R_a and R_h, studies have used trenching method as a root exclusion method to separate R_a and R_h from R_s [19,20]. Previous studies showed that the trenching technique is easy to use in field conditions, adaptable to various circumstances, yields reasonable values, and produces comparable partitioning results with other methods [9,20]. Nevertheless, the trenching method used to separate the contribution of R_a and R_h components to total R_s has limitations [21]. The literature extensively discusses major shortcomings associated with this method, including (1) the potential influence of newly deceased fine and coarse roots [22]; (2) disturbance effects caused by the act of trenching [23]; (3) alterations in soil water regimes resulting from the artifacts of the trenching treatment [24]. Significantly, recent research has highlighted that trenching artifacts may lead to increased soil water content due to reduced water uptake and elevate the relative proportion of R_h to R_s due to inputs from newly severed dead roots [25].

Subtropical evergreen broad-leaved forests in Southern China are globally significant biomes that play a crucial role in C cycling and sequestration at regional, national, and global scales [26,27]. The total net ecosystem productivity (NEP) in East Asian subtropical forests has been 0.72 ± 0.08 Pg C year^{-1}, accounting for 8% of the global forest NEP [28]. Camphor (*Cinnamomum camphora* (L.) Presl.) forests are a significant part of evergreen broad-leaved forests in this region. This species contains volatile chemical compounds in all plant parts, which have allelopathic effects on certain plant species and natural habitats [29]. In Camphor forests, numerous studies have examined the characteristics of the R_s process, but little is known about how it contributes to R_a and R_h components in these forest ecosystems. The purpose of the current study was to examine the contribution patterns of R_a and R_h components of R_s in a Camphor forest ecosystem. We hypothesized that (a) R_h would contribute more to R_s than R_a based on the findings from our previous experiments and other studies in subtropical forests; (b) the relative proportions of R_h and R_a to R_s would change following seasonal variations in the study region's weather conditions. The specific objectives of this project were: (1) to quantify the seasonal and annual fluxes of R_s, R_a, and R_h; (2) to explore the respective contributions of R_a and R_h components to R_s; (3) to examine the relationships between T_{soil} and W_{soil} and R_s and its components.

2. Materials and Methods

2.1. Study Site

The experimental site is located in Tianjiling National Park in Changsha, Hunan province, China, at coordinates 113°02′–01′ E and 28°06′–07′ N. This region features a low mountain and hill terrain, with elevations ranging from 46 to 114 m above sea level and slopes varying from 5° to 20°. The site experiences a typical monsoon subtropical climate, characterized by a mean annual temperature of 17.2 °C, with the lowest monthly mean air temperature in January at 4.7 °C and the highest in July at 29.4 °C. The mean annual rainfall is 1422 mm, falling primarily between April and August. Annual relative humidity averages above 80%.

The dominant tree species in the experimental area included Camphor (*Cinnamomum camphora* (L.) Presl.), Chinese sweet gum (*Liquidambar acalycina*), Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), Masson pine (*Pinus massoniana* Lamb.), and slash pine (*Pinus elliottii*). The soil beneath these forests has been classified as a typical clay-loam red soil developed from slate parent rock, corresponding to Alliti-Udic Ferrosols as per the World Reference Base for Soil Resources (CRG-CST 2001). The soil has an acidic pH, with an average of 5.0 in the surface layer (0–10 cm) and a soil organic C content of 19.77 ± 0.68 mg g^{-1} at a depth of 10 cm.

For this study, the selected Camphor forests were established as pure forests in 1990, commencing with an initial tree density of 1600 trees per hectare. The mean diameter at breast height (DBH) was 14.9 cm, and the mean tree height was 12.6 m. These Camphor forests were in a young stage of growth and development. The understory plant species at the study site consisted of *Sassafeas tsumu* Hemsl.; *Clerodendron cyrtophyllum Turcz*; *Cinnamomum camphora*; *Symplocos caudata* Wall. ex A. DC.; *Lophantherum gracile Brengn.*; *Nephrolepis auriculata* Trimen; *Miscanthus floridulus* Warb; and *Phytolacca acinosa* Roxb.

2.2. Experiment Design

Soil FCO_2 measurements in the 20-year-old Camphor forests began in August 2010 and were routinely conducted for two years. The experiment was conducted following a completely random design (CRD). Three 20 × 20 m sites were established within the study area's Camphor forests. Each site was divided into six square plots, each with a side length of 2 m (area 4 m^2). Among these plots, three plots were randomly selected for trenched treatments, and the remaining three were designated as un-trenched treatments. This arrangement resulted in three pairs of trenched and un-trenched plots within each forest site.

The sites and plots were chosen based on their relatively homogeneous topography within the Camphor forests. To minimize the potential influence of tree proximity on soil FCO_2 rate measurements, the selected plots were positioned near the center of the tree lines within the forests. These plots represented factors within the experiment, with trenched plots devoid of living roots and un-trenched plots serving as the control, representing intact areas with living roots. The trenched plot was a cubic block with a narrow ditch, approximately 0.2 m wide, excavated to a depth of 0.8 m along the four sides of the square. This depth extended below the rooting zone, where minimal root presence was observed [29]. The excavated trenches excluded live tree roots. To create a barrier, we placed several 2 mm thick polyethylene plastic sheets around the trenches, extending them to the trench's depth. Afterward, we backfilled the trenches with excavated soil, carefully removing herbaceous vegetation from the trenched plots by hand throughout the study to minimize soil disturbance.

Each trenched plot was equipped with a PVC respiration collar measuring 10.5 cm in diameter and 4.5 cm in height, inserted at approximately 2 cm into the soil. These collars were installed at least one week before the first measurement of R_s and remained in place throughout the experiment. To mitigate both root decay and soil disturbance effects resulting from trenching and the use of flux chambers, the trenched plots were established two months before the experiment, and the PVC collars were inserted into the soil at least one week before the initial R_s measurement, where they remained for the entire study duration. The un-trenched plot was located 35 m away from the trenched plot and remained undisturbed, with no excavation or removal of herbaceous vegetation. In each un-trenched plot, a PVC respiration collar was installed for soil FCO_2 measurements.

2.3. Field Measurements

Soil FCO_2 rates were measured in the field biweekly from August 2010 to August 2012 using a portable infrared gas analyzer (LI-COR 8100, LI-COR Inc., Lincoln, NE, USA) equipped with a chamber. During measurements, the respiration collar was sealed with a soil chamber connected to the infrared gas analyzer. All measurements were conducted between 10:00 a.m. and 2:00 p.m. to avoid diurnal fluctuations. For data analysis, we used the mean value of the two measurements per plot.

Soil FCO_2 rates were expressed as μmol CO_2 m^{-2} s^{-1}. Measurements from trenched plots represented R_h due to root exclusion, while measurements from un-trenched plots reflected the total R_s, including both R_a and R_h. As a result, R_a can be estimated by subtracting R_h from R_s [29,30].

During each soil FCO_2 measurement, T_{soil} was monitored using a soil thermocouple probe (LI-COR 8100-09 TC, LI-COR Inc., Lincoln, NE, USA) inserted into the soil at a depth of 5 cm below the surface. We also measured W_{soil} (volumetric soil water content, %) in the topsoil layer (0–5 cm) using an ECH2O EC-5 soil moisture sensor (METER Environment, formerly Decagon Devices, Inc., Pullman, WA, USA) [8]. Both T_{soil} and W_{soil} measurements were obtained outside the PVC collars.

2.4. Data Analysis

We assessed the differences in soil FCO_2 between trenched and un-trenched plots using analysis of variance (ANOVA). To meet the normality and homoscedasticity assumptions of ANOVA, the original R_s and R_h data were log-transformed. A repeated two-way ANOVA was applied to assess the effects of treatments and monitoring time on soil FCO_2 rates, T_{soil}, and W_{soil}. The ratios R_a/R_s and R_h/R_s were used to represent the respective contributions of the R_a and R_h components. All statistical analyses were performed with a significance level set at $p < 0.05$ using SAS statistical software (Version 8, SAS Institute Inc., Cary, NC, USA, 1999–2001). Nonlinear regression analysis was employed to model the relationship between R_s and T_{soil} and W_{soil}. To assess the temperature sensitivity of R_s, we calculated the Q_{10} index, defined as the difference in respiration rates over a 10 °C interval, using the following equation:

$$Q_{10} = e^{10b} \quad (1)$$

where, b is the constant fitted into Equation (1).

3. Results

During the two-year study period, soil respiration (R_s) rates were significantly lower in the trenched plots than in the control plots of the Camphor forests ($p < 0.05$). R_s rates ranged from 0.61 to 3.55 μmol m^{-2} s^{-1} in trenched plots and from 0.73 to 5.85 μmol m^{-2} s^{-1} in un-trenched plots (Figure 1). On average, soil FCO_2 rates were reduced by approximately 60% in trenched plots (1.67 ± 0.13 μmol m^{-2} s^{-1}, Mean ± SD) compared to un-trenched plots (2.88 ± 0.09 μmol m^{-2} s^{-1}) (Table 1).

Throughout the two-year study, there was significant seasonal variability in soil FCO_2 rates. The mean monthly contributions of each R_s component varied, with R_a/R_s contributing between 25.5 and 51.4% to R_s (Table 2).

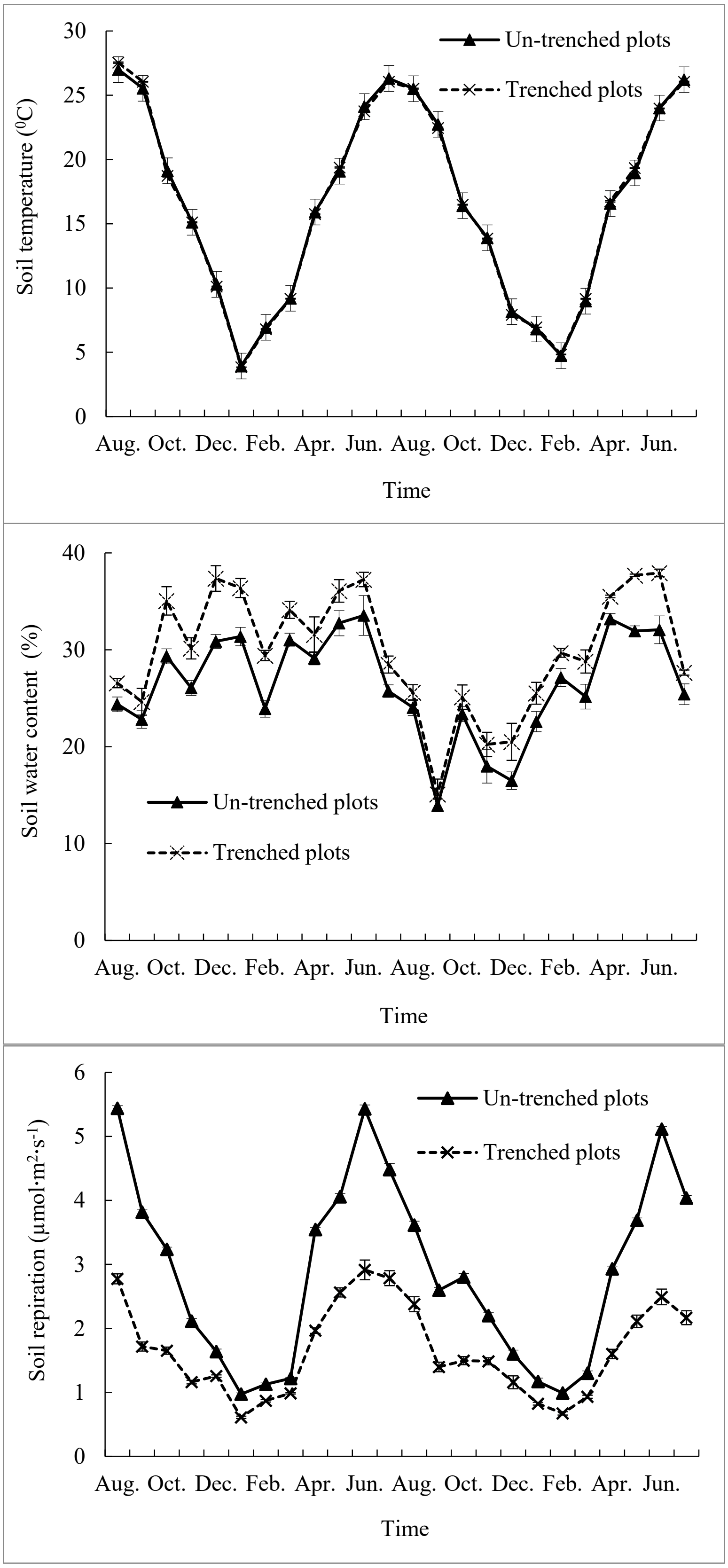

Figure 1. Seasonal changes in soil temperature at 5 cm soil depth, topsoil soil water content at the 5 cm layer, and soil respiration rate in trenched and un-trenched plots in the Camphor forest during the study period. Error bar indicates standard error ± s.e.

Table 1. Annual mean soil CO_2 efflux (FCO_2) rates, soil temperature (T_{soil}), and soil water content (W_{soil}) from trenched and un-trenched plots in Camphor forests during the study period.

Time (Year)	**Treatment**	**Soil FCO_2 Rate (µmol m^{-2} s^{-1})**	**T_{soil} (°C)**	**W_{soil} (%)**
2010–2011	Trenched	1.77 ± 0.12 a	16.86 ± 0.07 a	32.26 ± 2.12 a
	Un-trenched	3.09 ± 0.09 b	16.88 ± 0.09 a	28.41 ± 1.86 b
2011–2012	Trenched	1.56 ± 0.15 a	16.11 ± 0.06 a	27.45 ± 1.75 a
	Un-trenched	2.67 ± 0.10 b	16.09 ± 0.19 a	24.45 ± 1.95 b
Average	Trenched	1.67 ± 0.13 a	16.49 ± 0.06 a	29.85 ± 1.94 a
	Un-trenched	2.88 ± 0.09 b	16.49 ± 0.14 a	26.43 ± 1.90 b

Note: Values are presented as mean ± standard deviation. Distinct letters within the same column and year indicate significant differences ($p < 0.05$).

Table 2. Average monthly patterns of R_a, R_h, and R_s (µmol m^{-2} s^{-1}), and a relative proportion of R_a component to R_s (%) in studied forests over the 2-year study period.

Month	**R_a**	**R_h**	**R_s**	**R_a/R_s**
January	0.354	0.718	1.071	33.0
February	0.287	0.771	1.058	27.1
March	0.300	0.959	1.259	23.8
April	1.453	1.785	3.237	44.9
May	1.537	2.337	3.874	39.7
June	2.568	2.704	5.272	48.7
July	1.783	2.477	4.260	41.9
August	1.950	2.577	4.527	43.1
September	1.650	1.558	3.207	51.4
October	1.445	1.574	3.019	47.9
November	0.832	1.324	2.155	38.6
December	0.413	1.207	1.620	25.5

Note: R_a, autotrophic respiration; R_h, heterotrophic respiration; R_s, total soil respiration.

The monthly relative proportion of R_a to R_s was consistently below 50% for all months throughout the year, except in September (Table 2). In addition, the ratio of R_a/R_s reached its maximum in summer and autumn, and its minimum in winter. On average, the ratio of R_a/R_s was lower than that of R_h/R_s for all four seasons, with a difference of about 10% in summer and autumn, 40% in winter, and 30% in spring at the study site (Table 2). While T_{soil} exhibited significant variation throughout the study, there were no notable differences in T_{soil} between trenched and un-trenched plots ($p > 0.05$). However, trenching had statistically significant effects on W_{soil} ($p < 0.005$). In general, the soil was generally dry during the autumn and winter seasons and wetter in the spring and summer.

The maximum and minimum T_{soil} values were 26.1 and 26.3 °C in July 2011, and 3.9 and 3.9 °C in January 2011 for trenched and un-trenched plots, respectively (Figure 1). The mean values of W_{soil} were consistently higher in trenched plots than in un-trenched plots, with an average value of 29.9 and 26.4% in trenched and un-trenched plots, respectively (Figure 1). The peak value of W_{soil} occurred in June 2010 at 37.9 and 33.6%, whereas the minimum value was recorded in September 2011 at 15.1 and 13.9% for trenched and un-trenched plots (Figure 1). Soil FCO_2 rate was significantly correlated with T_{soil} ($p < 0.0001$) (Figure 2), but not with W_{soil} ($p > 0.05$) (Figure 3). Instantaneous soil FCO_2 rates were exponentially related to T_{soil}, and the corresponding Q_{10} was 1.73 for trenched plots and 2.02 for un-trenched plots.

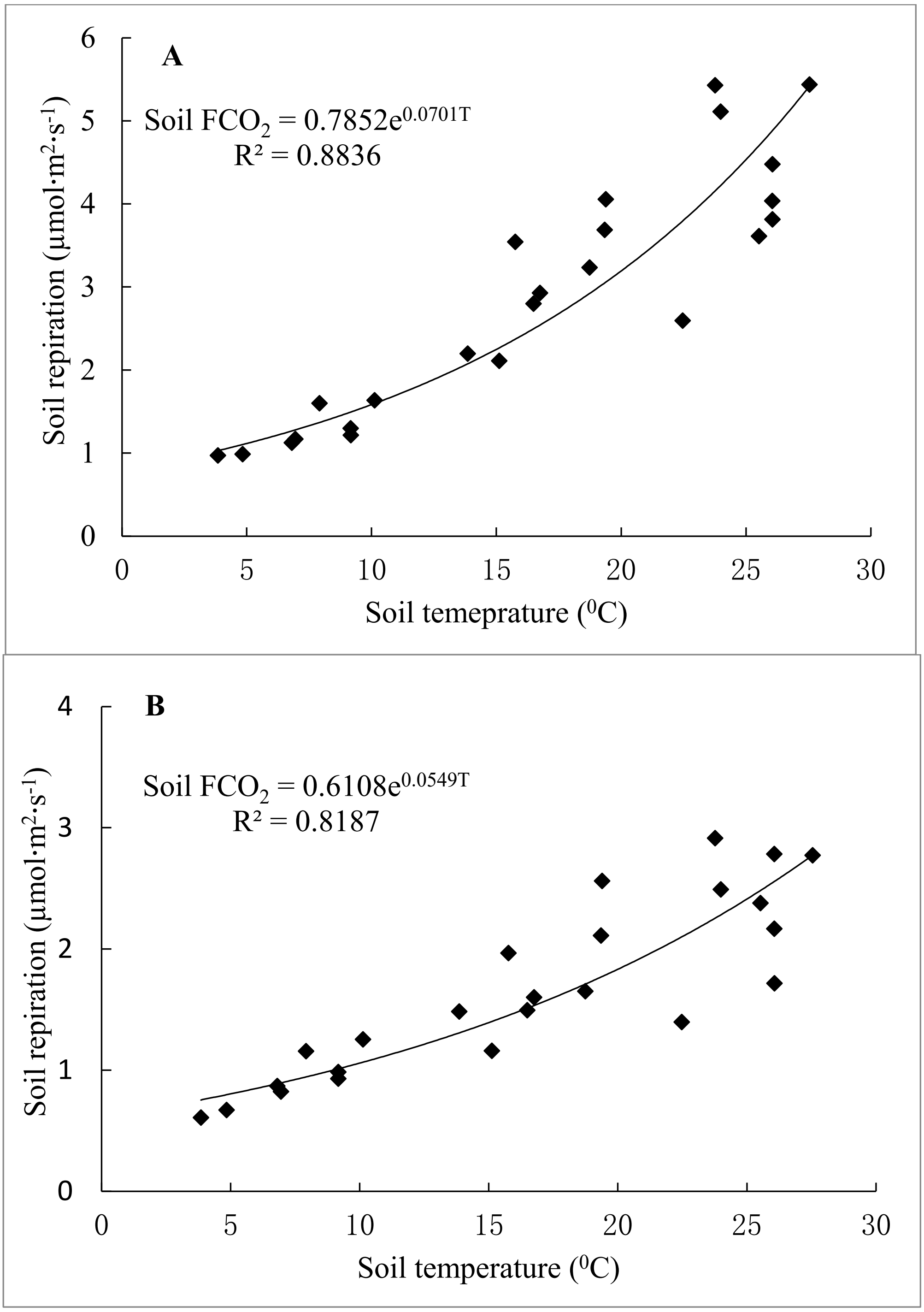

Figure 2. The relationships between soil respiration rates and soil temperature (T_{soil}) in un-trenched plots (**A**) and trenched plots (**B**) in the Camphor forest over the study period.

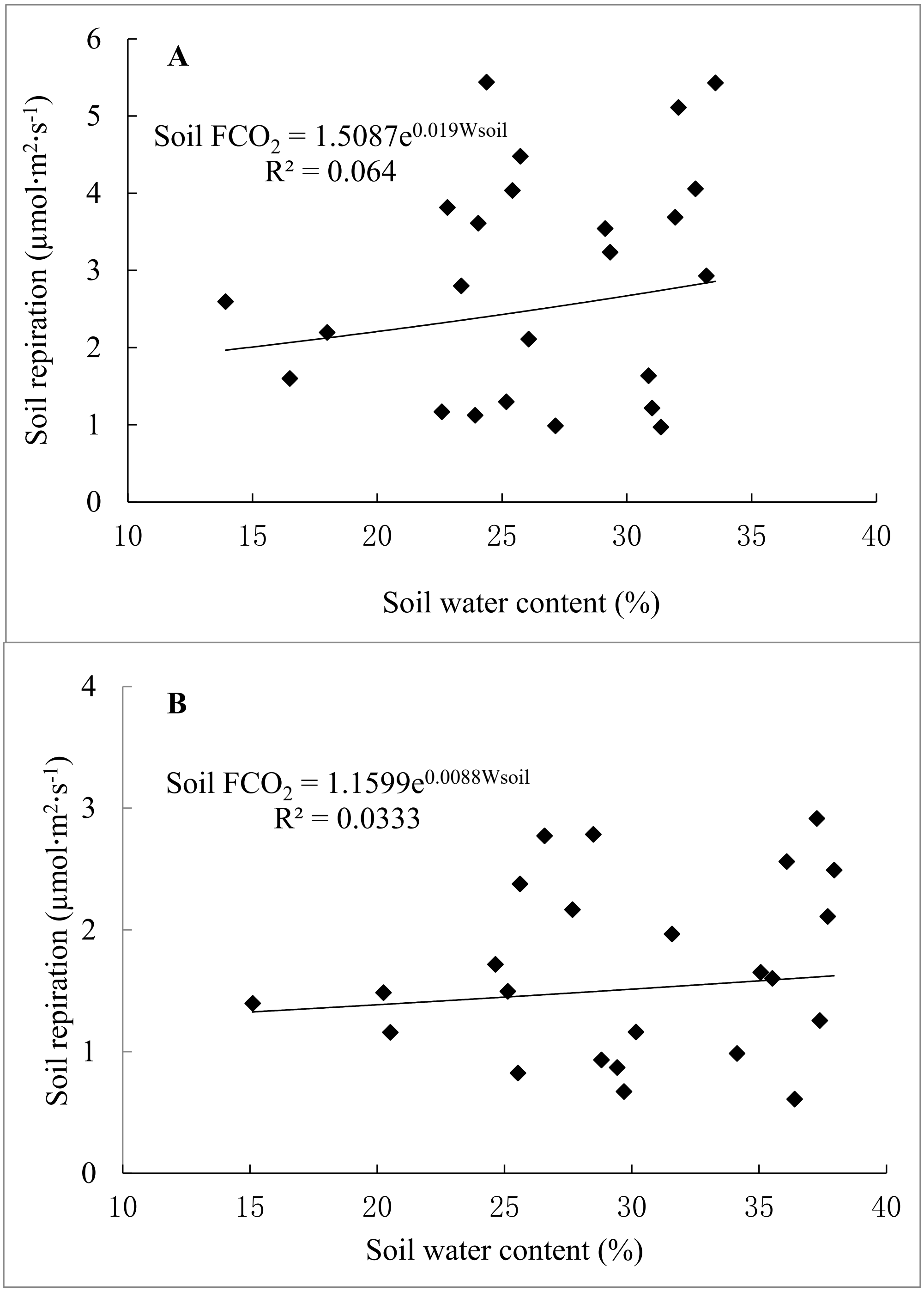

Figure 3. The relationships between soil respiration rates and soil water content (W_{soil}) in un-trenched plots (**A**) and trenched plots (**B**) in the Camphor forest over the study period.

4. Discussion

Trenched plots in Camphor forests exhibited a substantial reduction in soil respiration rates (R_s) over two years compared to un-trenched control plots. On average, R_s rates in trenched plots decreased by approximately 42% compared to control plots. Similar observations of R_s reduction due to root exclusion were reported in other studies. For instance, a nearby Chinese fir forest showed a 28% decrease in R_s in trenched plots than in un-trenched plots. One study observed a 39% reduction in R_s rates one year after trenching in a lowland tropical forest [31]. In a 30-year-old beech stand, there was a decrease of around 36% in the annual soil carbon efflux observed in the trenched plots compared to control plots. Additionally, in subtropical evergreen broad-leaved forests, trenching reduced soil FCO_2 by approximately 17% over a three-year period [32]. This reduction in annual soil FCO_2 in trenched plots was primarily associated with root exclusion, as R_a is a significant component of total soil respiration in forest ecosystems [29]. These findings highlight the consistent impact of root exclusion on reducing soil respiration rates in various forest types, emphasizing the importance of considering root contributions in assessing soil C dynamics [33]. The results from the current study indicate a relative contribution of 42% for R_a to R_s in evergreen broad-leaved Camphor forests, which aligns well with the ranges previously reported for subtropical forests (Table 3).

Table 3. Comparison of R_a component contribution (%) to R_s in different subtropical forest types.

Forest Type	R_a/R_s Mean (Range)	References
Camphor forest	41.9 (19.0–55.0)	This study
Chinese fir forest (5 years old)	27.1	[34]
Chinese fir forest (22 years old)	32.6 (13.3–55.7)	[29]
Chinese fir forest	40.3	[35]
Natural evergreen forest	47.8	[35]
Broadleaf and needle leaf mixed forest	26.75	[36]
Bamboo forest	10.98	[36]
Monsoon evergreen broad-leaf forest (about 400 years old)	22.1–35.4	[37]
Pine forest (about 60 years old)	18.1–26.1	[37]
Pine and broad-leaf mixed forest (~60 years old)	20.0–29.1	[37]
Evergreen broad-leaved forest (20–120 years old)	21.4–32.3	[34]
Moist forest	33	[32]

Note: R_a: autotrophic respiration, R_s: total soil respiration.

Further research indicates that both R_a and R_h are influenced by temperature and precipitation. Studies analyzing global patterns found that an increase in mean annual temperature led to higher R_a and R_h rates, with increases of 12.9 and 16.1 g C m^{-2} $year^{-1}$, respectively, for every 1 °C rise [38]. R_a was found to increase by 44.5 g C m^{-2} $year^{-1}$ for every 100 mm increase in mean annual precipitation (MAP) when MAP was <1000 mm, while R_h increased linearly by 15.0 g C m^{-2} $year^{-1}$ for every 100 mm increase in MAP [38]. The study suggested that the fractional contribution of R_a to R_s may be greater in boreal forests than in temperate forests, reflecting regional differences in ecosystem dynamics [39]. These study findings contribute to our understanding of the variation in R_a and R_h contributions to R_s, highlighting a multitude of factors influencing these dynamics with the potential to exhibit regional distinctions [40].

Bond–Lamberty et al. [1] established a relationship between R_a and R_s, expressed as $RC = -0.66 + 0.16 \times \ln (R_s)$, indicating that R_a contribution may vary depending on R_s. By employing this model, we estimated the root contribution (RC) of our study site. The calculated RC value averaged 30.1%, ranging from 17.6 to 37.0% across the Camphor forests under investigation. These estimated values were slightly lower than our field measurements, where the RC averaged 41.9% with a range of 25.5–51.4% (Table 2). It is worth noting that this variation may be attributed to limitations in the data sources used to develop the model. The data sources were primarily derived from 54 forest sites, with a significant focus on boreal and temperate forests, a minimal representation of tropical forests, and none from subtropical regions [41]. As a result, the RC–RS relationship, while potentially reliable globally, may show significant deviations at a local scale [42]. This finding may be due to a myriad of biotic and abiotic factors, including T_{soil}, W_{soil}, soil nutrients, soil microbial composition, tree species, and forest types, which can have specific influences on R_a at local or site-specific scales [21]. Therefore, R_a–R_s relationships developed at a regional level may not provide precise estimates of the respective contributions of R_a and R_h components within a specific site [4,38,39]. R_a appeared to be predominantly governed by physiological activities associated with root growth [9], below-ground C allocation [39], and phenological characteristics of tree species [37]. On the other hand, R_h appeared to be primarily regulated by substrate availability and biophysical conditions within the soil [43]. This seasonal pattern aligns with findings that reported a similar trend in R_a dynamics, reaching its highest value in late July due to maximal fine-root biomass and living fungal biomass during the summer and autumn [44]. During the growing season, R_a comprises both maintenance respiration and growth respiration, whereas, in the dormant season, R_a primarily consists of maintenance respiration [45]. Additionally, the positive relationship between maintenance respiration and temperature can lead to higher maintenance respiration during summer (the growing season) when temperatures are elevated, in contrast to winter (the dormant season) when temperatures are lower [46].

Previous studies have demonstrated that both T_{soil} and W_{soil} are crucial factors controlling R_a, R_h, and R_s [47,48]. Soil CO_2 effluxes closely followed seasonal and diurnal variations in T_{soil}, as indicated by our findings (Figure 1). T_{soil} accounted for over 80% of the seasonal variation in soil FCO_2 in the Camphor forest, showcasing a strong correlation between soil FCO_2 and T_{soil}. This observation aligns with the results of previous studies [29]. However, it is worth noting that most R_s–T_{soil} relationships may not accurately reflect the actual temperature response of R_s. Therefore, these temperature response functions are likely inadequate for predicting the effects of climate change on R_s [49]. In addition, climate change is expected to affect water availability by comprehensively altering the amount, distribution, and frequency of precipitation and evaporation [50]. To gain a better understanding of R_s in changing environments, considering both biotic and abiotic interactions is essential [49].

In our experiment, we observed that W_{soil} consistently remained higher in trenched plots compared to control plots (Figure 1). This finding is likely attributable to trenching, which increased W_{soil} by reducing evapotranspiration [30] and root transpiration [29]. Notably, we observed that the correlations between soil FCO_2 and W_{soil} were not statistically significant ($p > 0.05$), which is consistent with previous research on Chinese fir forests [29], an old-growth coniferous forest [51], and boreal forests [30]. In reality, the soil FCO_2–W_{Soil} relationship is complex, and the influence of W_{soil} on soil FCO_2 rates is often modulated by the T_{soil}–soil FCO_2 relationship under a threshold value of W_{soil} [48]. When the threshold value of W_{soil} is reached, it creates conditions in the soil that promote the diffusion of both oxygen and soluble substrates, thereby enhancing soil FCO_2 rates [52]. However, if W_{soil} falls significantly below or rises above this threshold value, it can impede biological processes and alter the relationship between W_{Soil} and soil FCO_2. For instance, it was reported that when soil exceeded 0.11 $m^3\ m^{-3}$, soil FCO_2 rates were positively correlated with T_{soil} in a temperate Douglas fir forest, but when W_{soil} was below this threshold, the soil FCO_2-T_{soil} relationship became largely decoupled [53]. Additionally, one of the authors of this study conducted research in a wet–dry savanna in Northern Australia and observed similar trends in the T_{soil}–soil FCO_2 relationship and the threshold value of W_{soil} [54]. In this wet–dry savanna, the threshold value of W_{soil} was about 0.07 $m^3\ m^{-3}$, with soil FCO_2 rates showing a significant positive correlation with T_{soil} when W_{soil} was above this threshold and a weak relationship when W_{soil} was below 0.07 $m^3\ m^{-3}$ [43]. This weak relationship between soil FCO_2 and T_{soil} under lower W_{soil} conditions can be attributed to limitations in the soluble substrate [52,54]. Furthermore, the status of W_{soil} directly affects the composition and activity of the soil microbial community, which can significantly influence the T_{soil}–soil FCO_2 relationship [55]. Different microbial communities have distinct optimal W_{soil} conditions for their survival, growth, and development. Changes in W_{soil} conditions can create different habitats for soil microbial communities, which directly impacts R_h and R_s [56]. A meta-analysis indicates that the response of organism respiration to water stress varies widely across functional types, such as soil fauna, bacteria, and fungi [57].

Although we did not observe a tight relationship between soil FCO_2 and W_{soil} in the present study, it is plausible that W_{soil} indirectly affects soil FCO_2 rates through Q_{10} regulation [53]. We found that the temperature sensitivity of R_s was reduced in trenched plots (Q_{10} = 1.73) compared to un-trenched plots (Q_{10} = 2.02) in the current study. This observation suggests that the temperature sensitivity of R_h was less pronounced than that of R_s. Such findings indirectly support the conclusion that Q_{10} values derived from field measurements, including R_a, could potentially overestimate the response of R_h to temperature changes on a future, warmer Earth [38].

5. Conclusions

In summary, this study has shown that R_h plays a significant role, contributing approximately 60% to the annual R_s in Camphor forests. Our estimates of the relative contributions of R_s components align with those reported in subtropical forests. T_{soil} is the primary factor controlling the seasonal variability of R_s, R_h, and the R_h/R_s ratio. The proportion of R_a to R_s reaches its peak during the growing season and is at its lowest when the trees are dormant. Considering the significant concentration of the R_h component in the soil respiration (R_s) of the studied forests, the formulation of suitable management practices focusing on the biophysical environment and microbial community of soil in subtropical forests becomes imperative. Such practices can significantly help reduce CO_2 emissions from soils, mitigating rising CO_2 concentrations in the atmosphere.

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