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Dynamic Characteristics of Soil Respiration in Park Green Spaces in Qingdao City

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Abstract: Urban green spaces play an essential role in maintaining the carbon cycle and mitigating climate change in urban ecosystems. In order to gain more carbon sinks from urban green ecosystems, it is essential to determine the carbon sequestration statuses and soil respiration rates of dominant green spaces, especially park green spaces. However, in comparison to natural ecosystems, the dynamic characteristics of soil respiration in artificial park green spaces remain unclear. This study investigated the soil respiration rates for three forest communities (dominated by *Prunus serrulata* var. *lannesiana*, *Cedrus deodara*, *Ginkgo biloba*, respectively), a shrub community (dominated by *Aucuba japonica* var. *variegata*) and a lawn community (dominated by *Poa pratensis*) in the Qingdao Olympic Sculpture and Culture Park. We used the CRIAS-3 portable photosynthesis system in combination with the SRC-1 soil respiration chamber to measure the soil respiration rate from July 2022 to June 2023 and analyzed the dynamic variations in the soil respiration rate for these specific plant communities. Our results showed that the diurnal variation in soil respiration presented a unimodal curve for the five plant communities, and it peaked at midday or in the early afternoon. They also exhibited a significant seasonal difference in the soil respiration rate, which was characterized by higher rates in summer and lower rates in winter. The lawn community exhibited significantly higher soil respiration rates compared to the woody plant community. The mean annual soil respiration rate (R_S) was, respectively, 2.88 ± 0.49 μmol·m^{-2}·s^{-1}, 1.94 ± 0.31 μmol·m^{-2}·s^{-1}, 1.43 ± 0.21 μmol·m^{-2}·s^{-1}, 1.24 ± 0.14 μmol·m^{-2}·s^{-1} and 1.05 ± 0.11 μmol·m^{-2}·s^{-1} for the lawn community, *Ginkgo biloba* community, *Prunus serrulata* var. *lannesiana* community, shrub community and *Cedrus deodara* community. The soil temperature at a 10 cm depth (T_{10}) accounted for 67.39–86.76% of the variation in the soil respiration rate, while the soil volumetric water content at a 5 cm depth (W_5) accounted for 9.29–44.01% of the variation for the five plant communities. The explained variance for both T_{10} and W_5 ranged from 67.8% to 87.6% for the five plant communities. The Q_{10} values for the five different communities ranged from 1.97 to 2.75. Based on these findings, this paper concludes that the factors influencing the soil respiration process in urban green spaces are more complicated in comparison to natural ecosystems, and it is essential to comprehensively analyze these driving factors and key controlling factors of soil respiration across urban green spaces in future studies.

Keywords: soil respiration; soil CO_2 emission; park green space; soil temperature; plant community

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1. Introduction

The substantial increase in the concentrations of greenhouse gases in the atmosphere, especially CO_2, has resulted in global warming and a series of ecological problems [1,2]. Soil respiration is an integral ecosystem activity, including the respiration of plant roots and heterotrophic organisms, which continuously emit a great deal of CO_2 into the atmosphere [3]. Soil respiration has been confirmed as one of the essential sources of CO_2 in the atmosphere. It is estimated that approximately 20% of the atmospheric CO_2 originates from the pedosphere, which is ten times greater than the anthropogenic CO_2 emissions [4].

Nissan et al. [4] stated that soil heterotrophic respiration has been increasing since the 1980s at a decadal rate of around 2% globally. Because of the vast soil surfaces (mineral and organic) involved in the global carbon cycle, human and natural disturbances in soil, e.g., land cover change [5], and prescribed burning and thinning treatments [6] bring about noteworthy fluctuations in soil respiration and alternations in the atmospheric CO_2 concentrations. Thus, expanding the research on and deepening our understanding of soil respiration would contribute to unveiling the role of diverse ecosystems in the global carbon cycle.

In the last two decades, there have been a great number of studies on forest soil respiration, which consider the intensity and spatiotemporal patterns of soil respiration, as well as its influencing factors [7,8]. For example, Joo et al. [7] investigated the temporal variations in soil respiration in a cool temperate oak forest and found a significant seasonal variation in line with the temperature; specifically, it was high in summer and low in winter. Cai et al. [8] collected nearly a hundred field observation studies and found that the spatial variation in soil respiration within forest ecosystems varied significantly at the global scale. With regard to Chinese forest ecosystems, Song et al. [9] assembled annual forest soil respiration flux and Q_{10} values from 90 published studies and concluded that the mean annual soil respiration rate was 33.65 t CO_2 hm^{-2} $year^{-1}$ across these ecosystems. Generally, soil respiration in forest ecosystems has been widely and intensively studied in the past few decades.

According to the World Bank, about 56% of the world's population lives in urban areas at present, and this is expected to double by 2050. In urban areas, the urban green space system is generally regarded as the foremost natural carbon sink, and it plays an important role in the urban carbon cycle. In addition, urban green spaces are more susceptible to human disturbances and environmental changes, e.g., pruning, artificial watering, fertilizing and trampling [10,11]. Hence, the magnitude of soil respiration inevitably differs from that in natural forests. In particular, in the context of the low-carbon city and carbon-neutral city [12,13], revealing the characteristics of carbon sequestration and emissions would help to improve our predictions of soil carbon pools in urban green spaces. However, knowledge in this field remains largely absent [3,13–15].

In this study, we investigated the soil respiration rates for three forest communities (dominated by *Prunus serrulata* var. *lannesiana*, *Cedrus deodara*, *Ginkgo biloba*, respectively), a shrub community (dominated by *Aucuba japonica* var. *variegata*) and a lawn community (dominated by *Poa pratensis*) in the Qingdao Olympic Sculpture and Culture Park, which is a representative urban park green space in downtown Qingdao City. We used the CRIAS-3 portable photosynthesis system in combination with the SRC-1 soil respiration chamber (PP Systems, Amesbury, MA, USA) to measure the soil respiration rate from July 2022 to June 2023 and analyzed the dynamic variations in the soil respiration rate for these five specific plant communities. Our objectives in this study were to explore (i) the temporal dynamics of soil respiration across the five plant communities in urban park green spaces and (ii) the key ecological factors affecting the temporal variability in soil respiration.

2. Materials and Methods

2.1. Overview of the Study Area

This study was undertaken in the Qingdao Olympic Sculpture and Culture Park (36°20′ N, 120°12′ E, 14 m a.s.l.), Chengyang District, Qingdao City, China (Figure 1). Qingdao City is located on the southern coast of the Shandong Peninsula (35°35′–37°09′ N, 119°30′–121°00′ E), and it is well known as a coastal tourism city, characterized by red tiles, green trees and clear blue skies. Qingdao City covers an area of 11,282 km^2, and it consists of seven urban districts and three suburb county-level cities. Chengyang District is situated in the north of the urban districts in Qingdao City, covering an area of 583.68 km^2.

The Qingdao Olympic Sculpture and Culture Park was built in 2003, and it is the largest urban park green space in Chengyang District, with an area of 430,000 m^2 (Figure 1). The climate in this region is typical of a warm temperate monsoon continental climate, and

the mean annual air temperature is 12.6 °C. The minimum air temperatures are always in January, and the monthly mean temperature is −2 °C. The maximum temperature is often in August, with the monthly mean air temperature of 25.7 °C. The mean annual precipitation is about 700 mm, mostly falling in summer (i.e., June–August), and there is little rainfall in autumn (i.e., September–November), winter (i.e., December–February) and spring (i.e., March–May). The soil of the park is dominated by brown soil based on the Chinese Soil Taxonomy (Haplic Luvisol in FAO classification). About 300 plant species are planted in the park, with a total of 1.1 million standing trees and shrubs distributed throughout its grounds.

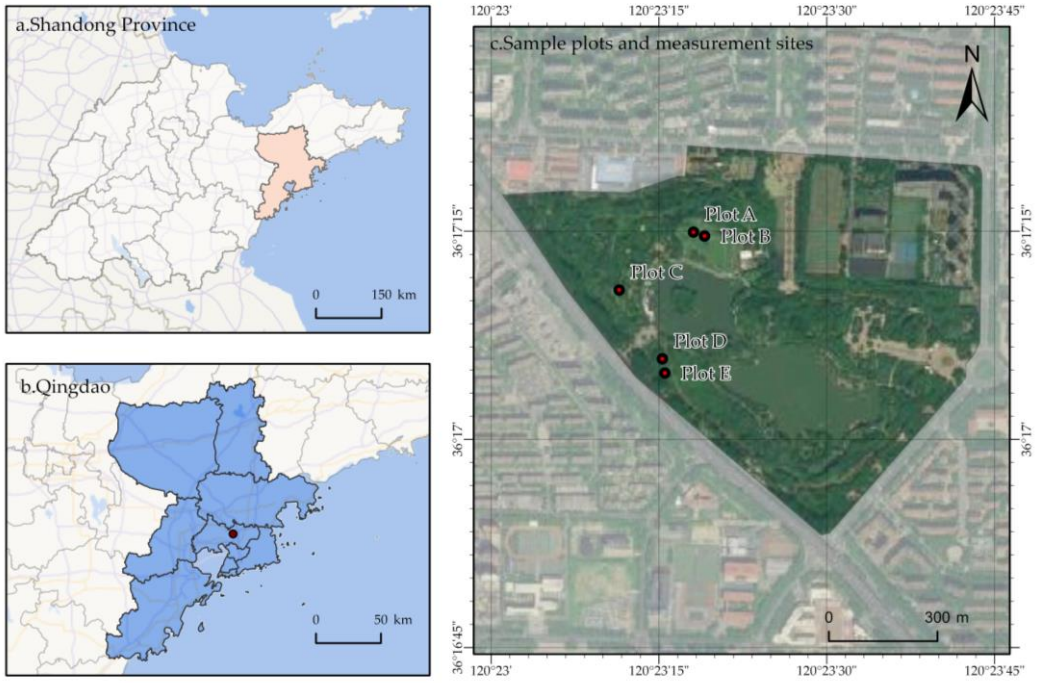


Figure 1. Location of the study area. Plot A, Plot B, Plot C, Plot D and Plot E indicate the *Prunus serrulata* var. *lannesiana* community, *Cedrus deodara* community, *Ginkgo biloba* community, *Poa pratensis* community and *Aucuba japonica* var. *variegate* community, respectively.

2.2. Experimental Design

Firstly, we zoned patches of the park green space according to the dominant plant species. Then, based on the area proportions of the dominant plant communities, three dominant tree species, i.e., *Prunus serrulata* var. *lannesiana*, *Cedrus deodara* and *Ginkgo biloba*, were selected as representative woody communities (Figure 1). In addition, a shrub community dominated by *Aucuba japonica* var. *variegate* and a lawn community dominated by *Poa pratensis* were selected as typical communities (Figure 1). In terms of these five dominant plant communities, sample plots of 20 m × 20 m were set up, and four measurement sites were randomly established as replicates within each sample plot.

2.3. Soil Respiration, Temperature and Moisture Measurements

In July 2022, we installed a polyvinylchloride (PVC) collar at each measurement site before conducting the measurements. The PVC collar was 5 cm in height and 10.5 cm in internal diameter, with 3 cm of the collar inserted into the soil layer. In order to reduce the soil disturbance, the collars remained in situ throughout the whole monitoring period. Furthermore, all plants and litterfall within the PVC collars were removed, and any regrowth was cleared away throughout the whole measurement period.

The measurement was conducted from July 2022 to June 2023. In the middle of each month, we selected three sunny days to measure the soil respiration by means of the

CRIAS-3 portable photosynthesis system connected to the SRC-1 soil respiration chamber (PP Systems, Amesbury, MA, USA). It should be pointed out that the SRC-1 soil respiration chamber needs to be seamlessly integrated with PVC collars when conducting measurements. Measurements were performed at a two-hour intervals from 7:00 to 19:00 at four measurement sites within each sample plot. Additionally, the soil moisture at a depth of 5 cm was measured using a HH2 moisture meter (Delta-T Devices Ltd., Cambridge, UK), and the soil temperature at a depth of 10 cm was recorded with a portable soil thermometer 6310 (Spectrum Technologies Inc., Plainfield, IL, USA).

2.4. Data Processing

We assembled a dataset on the soil respiration rate, soil temperature and soil moisture. Then, soil respiration rates beyond the range of -1 μmol·m^{-2}·s^{-1} to 15 μmol·m^{-2}·s^{-1} were regarded as outliers [16]. Moreover, outliers were removed in the event that the specific monitoring value exceeded -3 or +3 standard deviations from the data distribution center [16,17].

The soil temperature regulates soil respiration by affecting processes such as root growth, microbial activity and organic matter decomposition. The temperature sensitivity of soil respiration (Q_{10}) is an indicator by which the soil respiration is multiplied when the temperature increases by 10 °C [18,19], and it is an essential indicator in predicting the effects of global temperature rises on the soil carbon flux. Furthermore, the relationship between the two variables can be described by a linear, exponential or quadratic function [18,20,21]. An exponential function is widely employed to determine the Q_{10} as follows:

$$R_S = ae^{bT_{10}} \quad (1)$$

$$Q_{10} = e^{10b} \quad (2)$$

where R_S is the soil respiration rate (μmol·m^{-2}·s^{-1}), Q_{10} is the temperature sensitivity of soil respiration (unitless), T_{10} is the soil temperature (°C) at a 10 cm depth and a and b are the parameters to be determined.

The relationship between the soil respiration rate and the hydrothermal factors (i.e., soil temperature and soil volumetric water content) were assessed through regression analysis, including multiple linear regression and power-exponential regression, across the five plant communities in terms of sample plots [22,23]. It can be obtained from the following equation:

$$R_S = ae^{bT_{10}}W_5^c \quad (3)$$

$$R_S = a + bT_{10} + cW_5 \quad (4)$$

where R_S is the soil respiration rate (μmol·m^{-2}·s^{-1}), T_{10} is the soil temperature at a 10 cm depth (°C), W_5 is the soil volumetric water content at a 5 cm depth (%), and a, b and c are the regression coefficients to be determined.

Data preprocessing was conducted using Microsoft Excel 2019, while the IBM SPSS Statistics software (Version 25.0, IBM Corp., Armonk, NY, USA) was utilized to conduct a correlation analysis (Pearson's correlation coefficient) and analysis of variance (ANOVA) in regard to the plant community and inter-monthly and seasonal variation. A significance level of $p = 0.05$ and $p = 0.01$ was set for these analyses.

3. Results

3.1. Soil Hydrothermal Characteristics

Figure 2 illustrates the soil hydrothermal characteristics (T_{10}, W_5) of the three forest communities (dominated by *P. serrulata* var. *lannesiana*, *C. deodara*, *G. biloba*, respectively), the shrub community (dominated by *A. japonica* var. *variegata*) and the lawn community (dominated by *P. pratensis*). T_{10} presented a unimodal distribution for these five plant communities over the year. However, there were no significant differences in the T_{10} changes across the five plant communities, with the exception of the lawn community

dominated by *P. pratensis*, and T_{10} ranged from 2.14 °C to 29.73 °C (Figure 2a). In particular, the monthly mean T_{10} was the lowest in December and the highest in July, where it was below 5 °C and above 25 °C, respectively. W_5 demonstrated complex changes for the five plant communities, and W_5 was largely influenced by both human activities and precipitation (Figure 2b). W_5 showed notable increases in spring, when irrigation was conducted to boost new leaf sprouting. During the entire monitoring period, W_5 ranged from 1.74% to 34.34%. Overall, both T_{10} and W_5 exhibited remarkable seasonal variations across the five plant communities, reflecting the climatic characteristics of the urban park green spaces in Qingdao City.

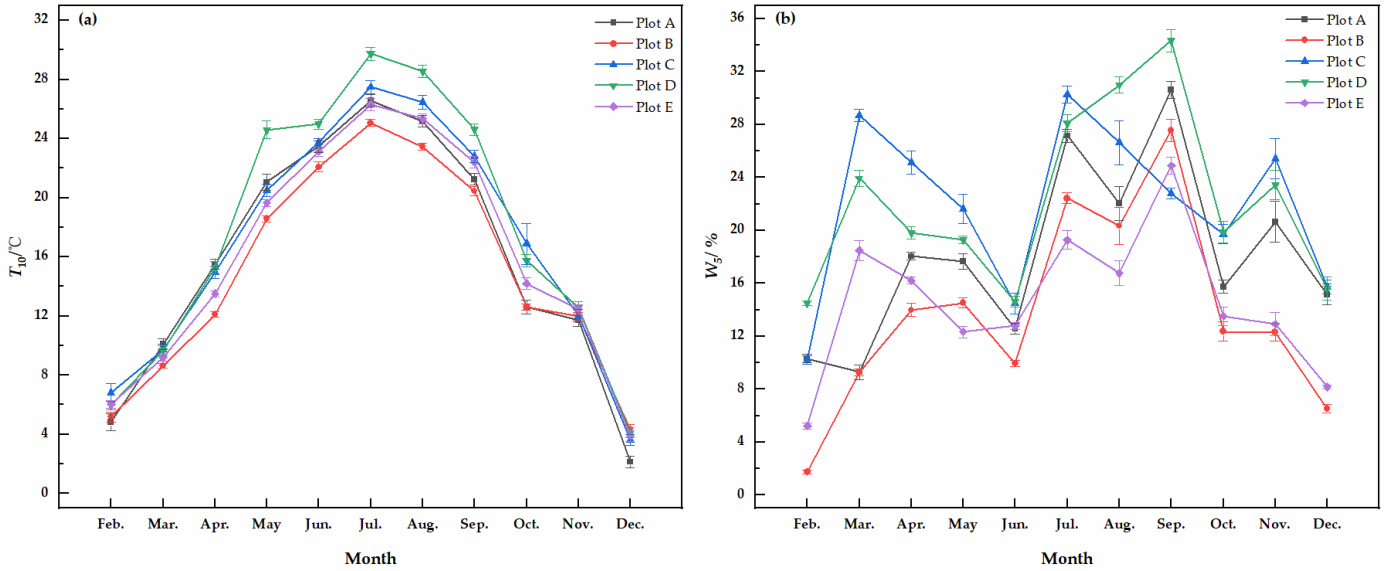


Figure 2. Monthly variations in T_{10}, W_5 for the five plant communities. (**a**) Monthly variation in T_{10}, (**b**) monthly variation in W_5. Plot A, Plot B, Plot C, Plot D and Plot E indicate the *Prunus serrulata* var. *lannesiana* community, *Cedrus deodara* community, *Ginkgo biloba* community, *Poa pratensis* community and *Aucuba japonica* var. *variegate* community, respectively.

3.2. Variations in Soil Respiration Rate and Its Response to Soil Hydrothermal Factors

The results demonstrated obvious seasonal patterns in R_S for the five plant communities, and it exhibited similar trends to T_{10} and W_5 (Figure 3a). The monthly mean R_S ranged from 0.25 μmol·m^{-2}·s^{-1} to 8.60 μmol·m^{-2}·s^{-1} for these plant communities, and the maximum and minimum values of the monthly mean R_S were recorded in July and in February, with the values of 4.67 μmol·m^{-2}·s^{-1} and 0.33 μmol·m^{-2}·s^{-1}, respectively. The next highest month for R_S was in June, with an average of 3.20 μmol·m^{-2}·s^{-1}. Strong seasonal variation in R_S was observed across the five communities, and they all exhibited the highest R_S in summer (Figure 3b). In summer, the mean R_S for the lawn community was three times higher than that in the *C. deodara* community. According to the plant communities, the lowest monthly mean R_S was presented in the *C. deodara* community, averaging 1.06 μmol·m^{-2}·s^{-1} (Figure 3c). Nevertheless, the highest monthly mean R_S was recorded in the lawn community, with an average of 3.19 μmol·m^{-2}·s^{-1}. The annual mean R_S was 2.88 μmol·m^{-2}·s^{-1}, 1.94 μmol·m^{-2}·s^{-1}, 1.43 μmol·m^{-2}·s^{-1}, 1.24 μmol·m^{-2}·s^{-1} and 1.05 μmol·m^{-2}·s^{-1} for the lawn, *G. biloba* community, *P. serrulata* var. *lannesiana* community, shrub community and *C. deodara* community, respectively.

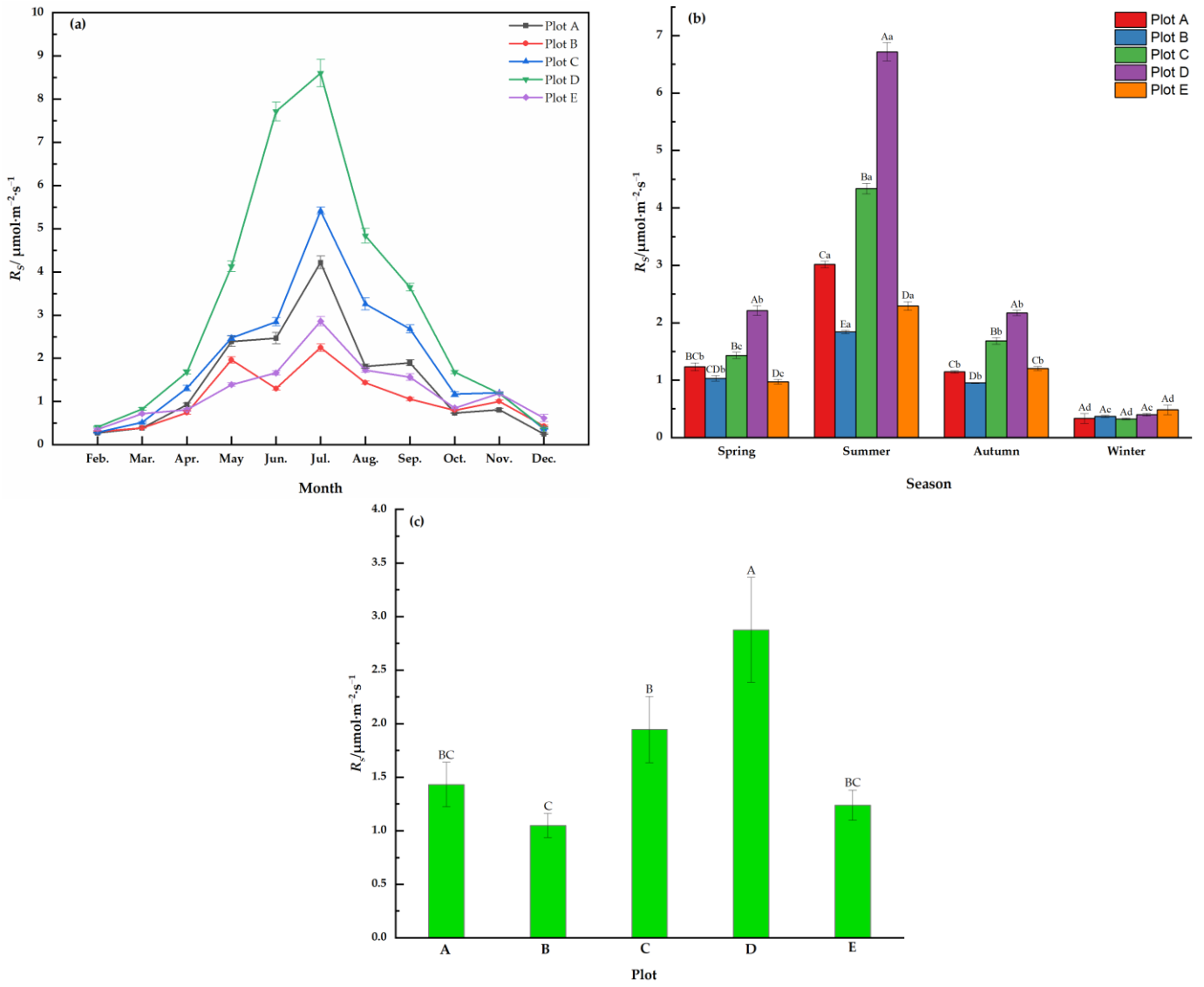


Figure 3. Seasonal changes and variations in soil respiration for the five plant communities. (**a**) Monthly variation in R_S, (**b**) seasonal changes of R_S, (**c**) comparison of annual mean R_S. Plot A, Plot B, Plot C, Plot D and Plot E indicate the *Prunus serrulata* var. *lannesiana* community, *Cedrus deodara* community, *Ginkgo biloba* community, *Poa pratensis* community and *Aucuba japonica* var. *variegate* community, respectively. Different uppercase letters indicate significant differences in the same season for the different communities ($p < 0.05$); different lowercase letters indicate significant differences between seasons for the same communities ($p < 0.05$).

With regard to the daily R_S of the *P. serrulata* var. *lannesiana*, *C. deodara*, *G. biloba*, lawn and shrub communities, its values increased in the early morning, reached the respective maximum at about noon (11:00–15:00) and subsequently decreased (Figure 4). In comparison, the daily value of R_S for the *C. deodara* community presented smaller variation, and larger variation was found for the lawn, *P. serrulata* var. *lannesiana*, *G. biloba* and shrub communities.

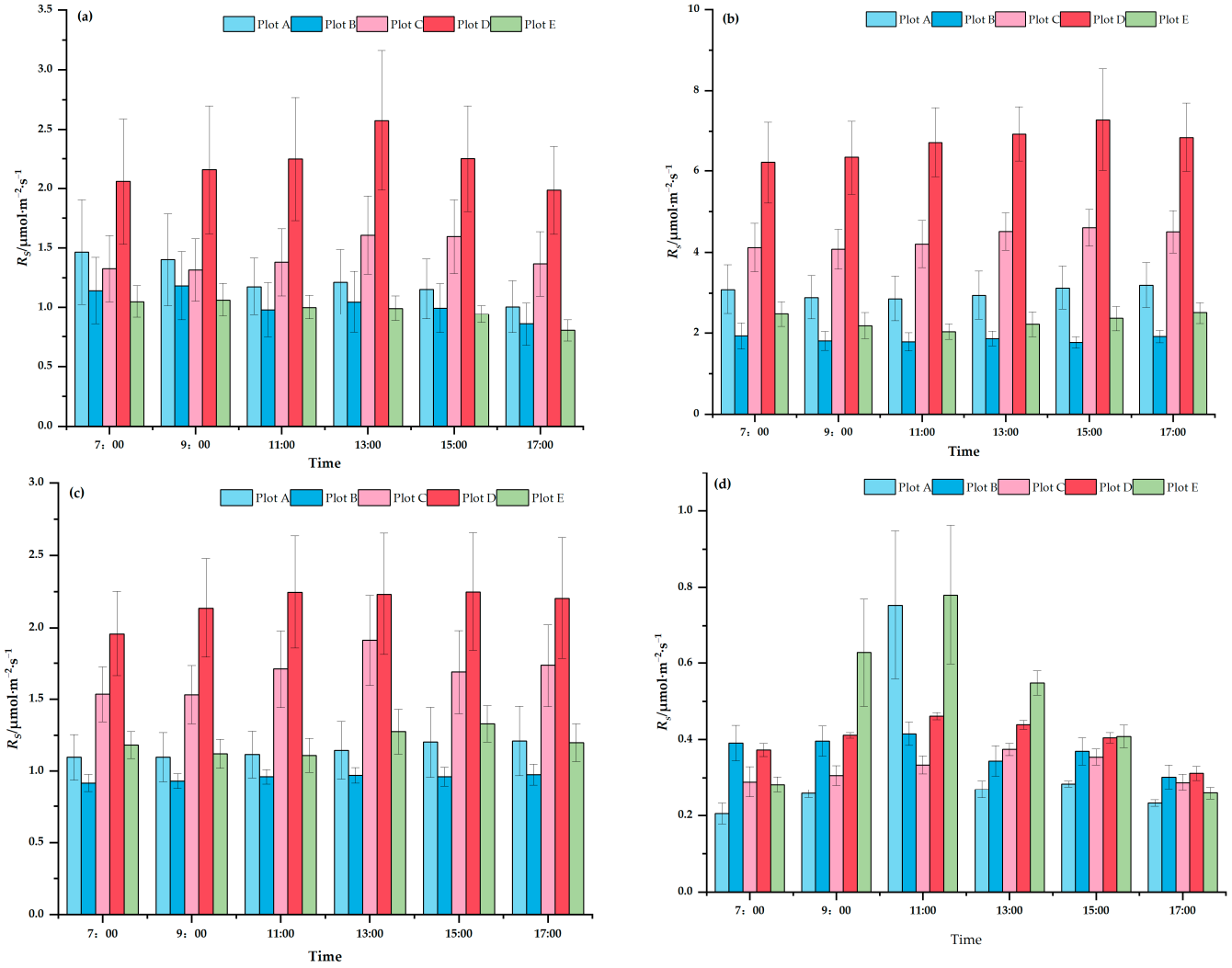


Figure 4. Daily variation in soil respiration for the five plant communities. (**a**) Spring, (**b**) summer, (**c**) autumn, (**d**) winter. Plot A, Plot B, Plot C, Plot D and Plot E indicate the *Prunus serrulata* var. *lannesiana* community, *Cedrus deodara* community, *Ginkgo biloba* community, *Poa pratensis* community and *Aucuba japonica* var. *variegate* community, respectively.

As depicted in Figures 2 and 3, R_S increased with the increase in T_{10}. Hence, there was a significant positive correlation ($p < 0.01$) between R_S and T_{10} for the three vegetation types. It was found that the exponential equation ($R_S = ae^{bT}{}_{10}$) was the most appropriate model to describe the response of R_S to T (Figure 5). The regression analysis results indicated that T_{10} could account for 76.72%, 67.39%, 86.76%, 76.51% and 73.35% of the variation in R_S for the *P. serrulata* var. *lannesiana* community, *C. deodara* community, *G. biloba* community and lawn and shrub communities, respectively.

However, the relationship between R_S and W_5 for the five plant communities was relatively less apparent (Figure 6). In comparison, cubic curves were more suitable in describing their relationship, although they could only explain 30.99%, 44.01%, 16.25%, 9.29% and 26.64% of the variation in R_S for the *P. serrulata* var. *lannesiana*, *C. deodara*, *G. biloba*, lawn and shrub communities, respectively.

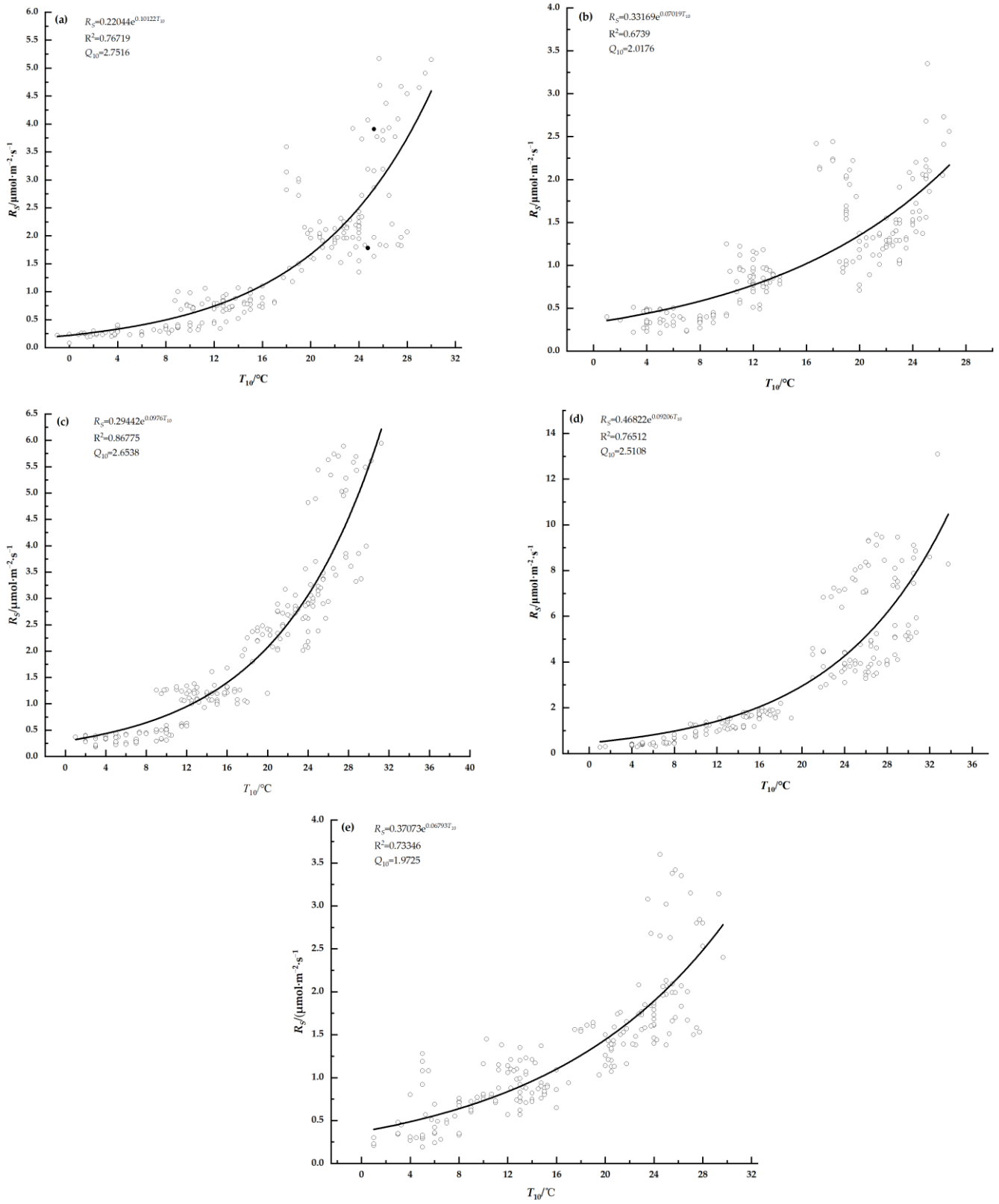


Figure 5. Relationships between R_S and T_{10}. (**a**) *Prunus serrulata* var. *lannesiana* community, (**b**) *Cedrus deodara* community, (**c**) *Ginkgo biloba* community, (**d**) *Poa pratensis* community, (**e**) *Aucuba japonica* var. *variegate* community.

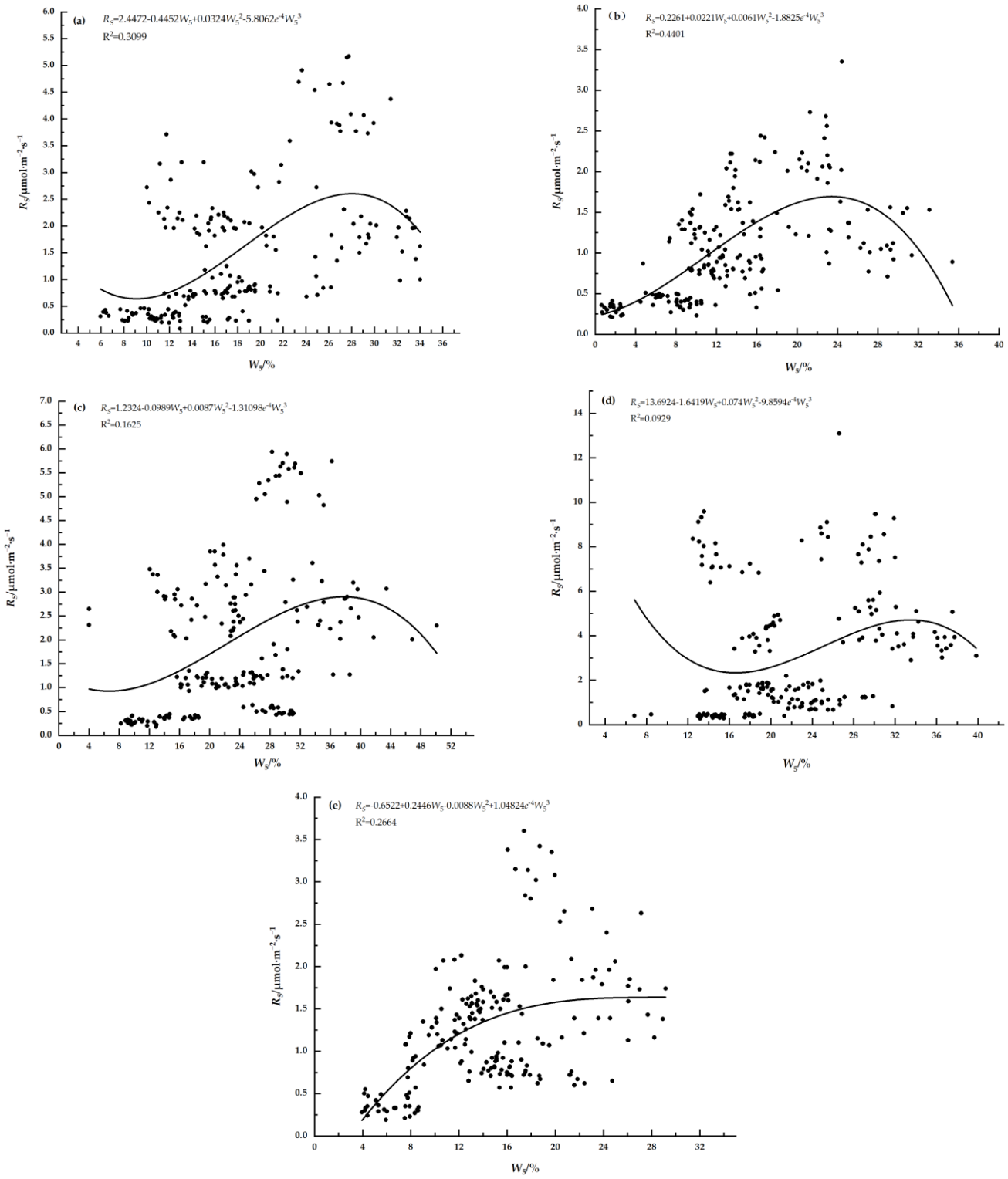


Figure 6. Relationships between R_S and W_5. (**a**) *Prunus serrulata* var. *lannesiana* community, (**b**) *Cedrus deodara* community, (**c**) *Ginkgo biloba* community, (**d**) *Poa pratensis* community, (**e**) *Aucuba japonica* var. *variegate* community.

Changes in the soil respiration rate are primarily regulated by the soil temperature and soil moisture. In this study, a bivariate regression model, $R_S = ae^{bT}{}_{10}W_5{}^C$, was employed to characterize the relationships among R_S, T_{10} and W_5 (Table 1). The results underscored the significance of T_{10} and W_5 as influential factors for soil respiration. The bivariate regression

model could explain up to 67.8–87.6% of the monthly variation in R_S. In terms of the model, parameters *b* and *c* represented the sensitivity coefficient of the soil respiration temperature and the sensitivity coefficient of the soil water content, respectively. Positive temperature sensitivity coefficients were observed across all five plant communities, indicating a stable and positive correlation between R_S and T_{10}. The moisture sensitivity factor for the lawn was negative, suggesting a negative correlation between R_S and W_5 when the differences in T_{10} were not substantial. Across the five planted communities, the moisture sensitivity of soil respiration followed the order *P. serrulata* var. *lannesiana* community > *G. biloba* community > shrub community > *C. deodara* community > lawn community.

Table 1. Fitting models for soil respiration (R_S), soil temperature (T_{10}) and soil volumetric water content (W_5). Plot A, Plot B, Plot C, Plot D and Plot E indicate the *Prunus serrulata* var. *lannesiana* community, *Cedrus deodara* community, *Ginkgo biloba* community, *Poa pratensis* community and *Aucuba japonica* var. *variegate* community, respectively. LF and PEF indicate the linear function and power-exponential function, respectively.

Plot	Model	Regression Equation	R^2	*p*
A	LF	$R_S = -0.788 + 0.114T_{10} + 0.025W_5$	0.711	<0.01
	PEF	$R_S = 0.1089e^{0.0953T_{10}}W_5^{0.2793}$	0.786	<0.01
B	LF	$R_S = -0.28 + 0.75T_{10} - 0.02W_5$	0.678	<0.01
	PEF	$R_S = 0.2797e^{0.0649T_{10}}W_5^{0.1003}$	0.681	<0.01
C	LF	$R_S = -0.996 + 0.168T_{10} + 0.06W_5$	0.802	<0.01
	PEF	$R_S = 0.1856e^{0.0954T_{10}}W_5^{0.1609}$	0.876	<0.01
D	LF	$R_S = -0.254 + 0.307T_{10} - 0.91W_5$	0.777	<0.01
	PEF	$R_S = 2.329e^{0.1048T_{10}}W_5^{-0.6111}$	0.829	<0.01
E	LF	$R_S = -0.38 + 0.76T_{10} + 0.04W_5$	0.699	<0.01
	PEF	$R_S = 0.2717e^{0.0646*T_{10}}W_5^{0.1380}$	0.740	<0.01

3.3. Temperature Sensitivity of Soil Respiration

The exponential model was utilized to determine the Q_{10} values for these plant communities (Figure 5). It was proven that the soil temperature had a significant and positive impact on soil respiration; specifically, R_S increased significantly with the increasing soil temperature. The exponential model, depicting the relationship between these two factors, could explain 67.39% to 86.77% of the seasonal variation in R_S. The Q_{10} values for the five different communities ranged from 1.97 to 2.75, all falling within a reasonable range. Q_{10} increased in the order of shrub community < *C. deodara* community < lawn community < *G. biloba* community < *Prunus serrulata* var. *lannesiana* community, implying that the vegetation types play a role in influencing the temperature sensitivity.

4. Discussion

4.1. Seasonal and Daily Changes in Soil Respiration Rate (R_S)

Previous research indicates that the R_S values of various land ecosystems exhibit distinct seasonal variations [5,9,15]. In this study, the R_S of five communities presented a unimodal distribution, with noticeable seasonal fluctuations. Generally, the seasonal variation in R_S primarily reflects changes in external environmental factors. During the dry season, characterized by low temperatures and drought, the soil microbial activity was reduced and this inhibited soil respiration, resulting in R_S being maintained at a low level. Conversely, in the rainy season, with higher temperatures and heavier rainfall, the respiration of plant roots and heterotrophic organisms increased, and R_S stayed at a higher level. Additionally, it was found that the minimum R_S generally occurred during winter, while the maximum R_S generally appeared in summer [16,22]. The findings of this study reveal that the R_S for the five communities peaked in July and reached its lowest value in February. With regard to the daily variation, all R_S values exhibited a unimodal seasonal variation pattern, and the maximum was presented between 11:00 and 15:00 during the day. Furthermore, the seasonal average R_S displayed a decreasing trend of summer > spring >

autumn > winter. This seasonal and daily trend has been reported elsewhere; see, e.g., an urban forest ecosystem in Beijing, China [16]; tree-covered urban green spaces in Helsinki, Finland [24]; and a forest in Southern Brazil [25].

4.2. Relationships Between Soil Respiration and Environmental Variables

In this study, R_S varied from 0.25 to 8.60 $\mu mol \cdot m^{-2} \cdot s^{-1}$ across the five plant communities in the urban park green space Significant differences were observed in R_S across these five plant communities, with the *C. deodara* community exhibiting a significantly lower R_S in comparison with the other communities (Figure 3). The trends in R_S and T were similar across the five plant communities, displaying a unimodal distribution. This finding aligns with previous studies by Niu et al. [26], which found a unimodal temperature response with a peak in respiration at an optimal temperature (T_{opt}), with T_{opt} values of 40–60 °C at the leaf and plant level, 11–46 °C at a microbial level and 6.5–33.3 °C at the global scale. For the whole observed period, both the air and soil temperatures were within the range of optimal temperatures. Hence, it was found that R_S presented a unimodal distribution over the whole period (Figure 3).

Previous research has indicated that R_S is primarily influenced by the combination of the soil temperature and soil water content [16,24,26]. In particular, under unrestricted soil moisture conditions, R_S demonstrated a significant positive correlation with the soil temperature, and this relationship is generally characterized by an exponential equation for forest ecosystems [18,21]. However, the association between the soil water content and soil respiration is quite complicated, and the conclusions differ according to variations in the plant community and site conditions (Figure 6). For instance, the seasonal pattern of soil respiration in a temperate urban forest in Beijing was influenced by the vegetation area index, soil moisture and nitrate nitrogen in the growing season [15]; however, irrigation was a key factor that altered the R_S in tree-covered urban green spaces in Finland [24]. In this study, a bivariate model, incorporating the soil respiration rate, soil temperature and soil water content, was established by means of exponential regression. The results indicated that the soil temperature and soil water content accounted for 67.8% to 87.6% of the seasonal variation in the soil respiration rate (Table 1). This finding is consistent with research on the soil respiration of urban green spaces in Tianjin, China [27], which found that the effective values of the soil temperature at a 10 cm depth (T_{10}) and soil moisture at a 5 cm depth (M_5) for R_S were 45.4–64.8% and 21.1–52.2%, respectively.

4.3. Temperature Sensitivity (Q_{10}) of Soil Respiration

Unveiling the temperature sensitivity (Q_{10}) of soil respiration is of vital importance in understanding the potential responses of regional and global terrestrial soil carbon fluxes to climate change [9,28]. In our study, the Q_{10} values for the five plant communities ranged from 1.97 to 2.75 (Figure 5), indicating great variations among the vegetation types in the same urban park. Yang et al. [28] predicted that Q_{10} varied from 1.54 to 4.17 with an average of 2.52 across China by means of machine learning [28], and Song et al. [9] concluded that the mean Q_{10} value was 1.28 for forest ecosystems across China. Thus, the Q_{10} values fell within the ranges presented by previous studies [9,28].

Soil respiration is an integral ecosystem activity, and Q_{10} is influenced by various ecological factors. Meta-analyses have demonstrated a significant correlation between vegetation activity and Q_{10} and highlighted the ecological linkage between plant physiological processes and soil processes [21]. However, at a large spatial scale, Yang et al. [28] argued that soil organic carbon (SOC) was the most important driving factor of the variation in Q_{10}, while Song et al. [9] indicated that the Q_{10} values significantly decreased with the mean annual temperature (MAT) but increased with the elevation and latitude when assembling 90 published studies across Chinese forest ecosystems. In this study, distinct discrepancies in the soil respiration rates were observed among the vegetation types, with the soil temperature and soil moisture exerting significant influences. A bivariate regression model, incorporating these two variables, explained 67.8% to 87.6% of the monthly variation in R_S.

Fundamentally, the impact of the vegetation type on soil respiration is multifold. Besides the direct effects of the vegetation characteristics and soil nutrient content, the vegetation type also alters the soil environment, soil structure and human activity, resulting in shifts in carbon partitioning and microbial metabolic processes [21,24]. However, our study did not investigate factors such as soil nutrients, microbial communities or human activity. Soil respiration is a dynamic and complicated process, and controlled experiments and long-term investigations are essential for a comprehensive understanding of the variation in Q_{10} across different vegetation types.

5. Conclusions

The soil respiration rates of the urban green spaces in the Qingdao Olympic Sculpture and Culture Park were significantly influenced by the soil temperature and soil water content. During summer, the soil respiration rate was higher and showed noticeable variation. The soil respiration rates were, respectively, 2.86–3.19 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 1.77–1.93 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 4.08–4.61 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 6.22–6.93 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 2.03–2.50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for the *P. serrulata var. lannesiana* community, *C. deodara* community, *G. biloba* community, lawn community and shrub community. The soil temperature and soil water content significantly influenced soil respiration. The exponential model adequately represented the relationship between the soil temperature (T_{10}) and soil respiration rate (R_S), with the soil temperature explaining 67.39% to 87.76% of the variation in R_S, and the soil water content accounting for 9.29% to 44.01% of the variation. The soil temperature and soil water content exerted essential influences on the soil respiration process. The bivariate model comprising the soil temperature and soil water content accounted for 67.80% to 87.60% of the variation in R_S. This study focused on the impacts of the soil temperature and soil water content on the seasonal variation in R_S in urban green spaces. However, the factors influencing the soil respiration process in urban green spaces are complicated, and ecological factors such as the soil organic matter content, soil compaction, vegetation biomass allocation and human activity (e.g., irrigation, fertilizer) may also have significant effects on soil respiration. Therefore, it is essential to comprehensively analyze these driving factors and key controlling factors of soil respiration across urban green spaces in future studies.

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