

ENVIRONMENTAL INTERPRETATION OF SEASONAL VARIATIONS IN SOIL RESPIRATION IN DIFFERENT FOREST STANDS OF THE ZHEGAO RIVER WETLANDS

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Abstract. To investigate the influences of environmental factors on wetland soil respiration, seasonal variations in soil respiration (Rs), heterotrophic respiration (Rh), and autotrophic respiration (Ra) were analyzed in *Populus × canadensis* Moench (PCM), *Salix matsudana* Koidz (SMK), *Metasequoia glyptostroboides* Hu (MGH), and *Pinus elliottii* Engelm (PEE) forests located in the Zhegao River wetlands. The results indicated that the Rs of different woodlands was highest in summer and lowest in winter. The annual mean Rs values were highest in MGH and lowest in PEE, where the contribution of Rh was > 57.9%. Seasonal changes in Rh were significant in MGH and PEE, and negligible in SMK, while the Ra in PEE reached the highest flux in autumn, and other woodlands had the highest fluxes in summer. Correlations between soil respiration and soil temperature were higher than those with soil moisture across the four forest stands. Furthermore, the temperature sensitivity coefficients (Q_{10}) were greater in all three deciduous forests compared with the coniferous forest (PEE). The synergistic impacts of soil temperature and moisture on soil respiration were greater than their individual effects.

Keywords: soil respiration, stand type, CO₂ flux, soil temperature, soil moisture

Introduction

Wetlands comprise transitional zones between terrestrial and aquatic ecosystems, which exhibit high primary productivity, redox capacity, and carbon storage in the form of organic matter. Thus, they possess the capacity to reduce the greenhouse effect and play a critical role in the global carbon cycle (Amani et al., 2022; Sen et al., 2017). As an essential component of wetland ecosystems, vegetation plays an invaluable role in their restoration (Cao et al., 2014). The soil CO₂ release profiles of various classes of forests are intimately related to local vegetation species, which influence soil structures, microbe activities, organic matter, and root respiration rates (Li et al., 2024). Global data studies revealed that the median CO₂ fluxes of wetland soils exceeded those of forests, grasslands, bare ground, and farmlands. This meant that the soil respiration of wetlands was distinct from that of other ecosystems to a certain extent (Oertel et al., 2016), which warranted further investigation.

Soil respiration refers to the full range of metabolic processes that generate CO₂ in undisturbed soils (Bond-Lamberty and Thomson, 2010). Primary CO₂ emission pathways in the soil encompass the decomposition of organic matter, respiration of soil animals, microorganisms, vegetative roots, and inter-root organisms, as well as the oxidation of carbon containing compounds (Li et al., 2014; You et al., 2013). These respiration levels determine the soil carbon turnover rate, where small changes in their intensity translate to significant impacts on the concentrations of CO₂ in the ambient atmosphere. As a key ecological process in wetland ecosystems, soil respiration is

directly correlated with the carbon cycle and greenhouse gas emissions (Zhou et al., 2016). However, it is complex and susceptible to the influences of apoplastic quantity and quality, fine root biomass, the effectiveness of temperature and water, etc. (Zhang et al., 2011), in conjunction with their interactions. Consequently, the investigation of soil respiration and its influencing factors under global warming and the quantification of the relationship between the two, can effectively predict changes in soil carbon fluxes and their impacts on the carbon pool of the Zhegao River wetland ecosystem.

Lake wetlands store copious amounts of carbon within sediments and lakeshore wetland peat, which have long-term carbon storage capacities (Cole et al., 2007). Despite their accounting for only ~1/3 of lake areas (Buffam et al., 2011) they can store > 80% of their total carbon pools (Benoy et al., 2007), which contributes significantly to regional carbon cycles. Lakeshore wetlands serve as transition zones between lake waters and land, with unique hydrological and biogeochemical cycles and ecological characteristics (Wang et al., 2014). The Zhegao River Wetland Park is a typical lakeshore wetland located on the north shore of Chaohu Lake. There have been no investigations into the soil respiration of this wetland to date; thus, its atmospheric carbon balance profile remains unclear. For this study, the soil respiration was measured in four typical woodlands in the Zhegao River Wetland Park. The heterotrophic and autotrophic soil respiration was distinguished, while the seasonal soil respiration dynamics were elucidated, compared, and analyzed for different vegetation types to determine the causes of these variations. The complexity of soil respiration at seasonal scales was explored to provide basic theoretical data and scientific support for the accurate assessment of soil respiration in lakeshore wetlands.

Materials and methods

Study area

The study area is located in the Zhegao River Wetland (31°35'58"-31°39'36"N, 117°43'39"-117°49'12"E), in Chaohu City, of Anhui Province, China (Fig. 1). It is distributed along Chaohu Lake in a belt-like configuration with a total area of 446.65 hm². The wetland portion comprises 323.87 hm² with the wetland rate reaching 72.51%. This region is home to a subtropical humid monsoon climate, with an average annual temperature of 15.7°C and precipitation of 1,000 mm. The soil in the area is dominated by rice soil and yellow-brown loam, with a pH that ranges from 4.9 to 6.7. The trees in the wetland sample area are primarily *Populus×canadensis* Moench (PCM), *Salix matsudana* Koidz (SMK), *Metasequoia glyptostroboides* Hu (MGH), and *Pinus elliottii* Engelm (PEE), etc., each of which are pure forests. The basic soil conditions of the sample sites are listed in Table 1. The soil pH of the SMK forests is 4.9, which is lower than those of the PCM, MGH, and PEE forests.

Table 1. Basic properties of soils in different forest stands

Stand type	pH	EC (ms·m ⁻¹)	BD (g·cm ⁻³)	TN (g·kg ⁻¹)	TP (g·kg ⁻¹)
PCM	6.71 ± 0.04a	90.7 ± 8.94b	2.29 ± 0.11a	1.09 ± 0.24b	0.73 ± 0.03c
SMK	4.89 ± 0.30b	100.43 ± 16.11b	2.23 ± 0.08a	1.01 ± 0.26b	0.87 ± 0.04b
MGH	6.72 ± 0.21a	110.6 ± 10.43b	2.38 ± 0.02a	0.54 ± 0.08c	1.90 ± 0.05a
PEE	6.46 ± 0.36a	257.33 ± 21.59a	2.37 ± 0.08a	1.92 ± 0.09a	0.55 ± 0.07d

Different lowercase letters after data in the same column indicate significant differences (p < 0.05). Same as below

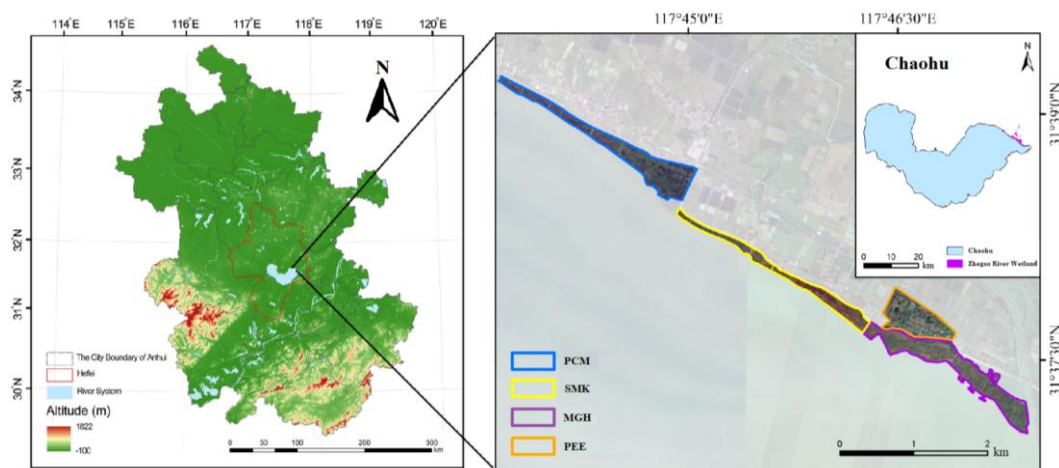


Figure 1. Location of sample plots in the study area

Establishment of sample plots

From April 2023 to January 2024, survey soil samples were extracted from the PCM, SMK, MGH, and PEE forests, wherein 20 m × 20 m sample plots were selected with a standard sample plot spacing of > 100 m. A total of 24 sampling points were established in each sample plot, where six representative sample sites (1 m × 1 m) were selected following an 's' shape. For each sample site special static boxes were installed, with three being non-derooted and the remaining three being derooted. The non-derooted and de-rooted sample sites were adjacent, with the distance between them at > 5 m. The soil respiration and environmental factors were quantified for all sample squares. As it was necessary to dig up the sample plots to separate the heterotrophic and autotrophic soil respiration samples, new sample sites were selected within the plots prior to each measurement.

Soil respiration measurements

The total soil respiration (R_s) was determined using an optical cavity decay spectroscopy (CRDS) technique for CO_2 concentrations in syringes, using a greenhouse gas analyzer (Picarro G2131-i, USA). The soil CO_2 fluxes were measured in the PCM, SMK, MGH, and PEE forests of the Zhegao River Wetland, on sunny rain-free days and between 9 am and 11 am, which was considered to best represent the average soil respiration over the course of a day. Gas samples (150 mL) were obtained using a syringe with a three-way valve at 10 min intervals for a total of four times. For each instance, once the three-way valve was closed the air, box, and soil temperatures, as well as soil moisture at a depth of 5 cm were recorded during the measurement period. Subsequently, the syringes were transferred to the laboratory for concentration measurements using a greenhouse gas analyzer, which were calculated using a static box gas flux formula (Tong et al., 2012; Hanson et al., 2000):

$$F = \rho \cdot \frac{V}{A} \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} \cdot \frac{\Delta C}{\Delta t}$$

where F is the CO_2 emission flux ($mgCO_2 \cdot m^{-2} \cdot h^{-1}$); p is the CO_2 density at the standard state ($mg \cdot m^{-3}$); V is the volume of the headspace of the static box (m^3); A is the area

covered by the bottom of the static box (m^2); P is the barometric pressure (Pa), P_0 is the standard atmospheric pressure (Pa); T is the air temperature during the measurement period (K), T_0 is the absolute air temperature at the standard state (K); and $\Delta C/\Delta t$ is the slope of the gas concentration in the static box over time ($\text{ppm} \cdot \text{min}^{-1}$), calculated by the least squares method.

Following the determination of R_s , the soil heterotrophic respiration (R_h) was quantified using a root removal technique (Hanson et al., 2010). Once the roots were removed, the R_h gas samples were obtained after 48 h of standing, and the balance of the procedure was performed as described above. The difference between the R_s value of the non-derooted sample and the R_h value of the derooted sample was the soil autotrophic respiration (R_a) value. Meanwhile, the soil temperature and moisture were measured simultaneously via an automatic soil temperature and moisture recorder in the 5 cm layer of the soil, with three replicate measurements being made for each sample type.

Soil sample collection and measurement

In mid-August 2023, three small sample squares ($5 \text{ m} \times 5 \text{ m}$) were selected in each sample plot of the different forest stand types, from which soil samples (0-10 cm) were extracted according to the 'Z' shape 5-point sampling method. Subsequently the soil samples of five points from each square were mixed evenly to form a composite sample, which was placed in a sterile bag, sealed, and transferred to the laboratory. Any gravel, residual plant roots, etc., were then removed, after which the fresh composite soil sample was divided into two portions. One portion was refrigerated at 4°C pending the quantification of the dissolved organic carbon (DOC) and dissolved organic nitrogen (DON). The other portion was naturally air-dried and sifted through a 100-mesh sieve to facilitate the analysis of the total organic carbon (TOC), total carbon (TC), total nitrogen (TN), and other parameters.

The bulk density (BD) was measured using the ring knife method (Panagos et al., 2024); the soil pH by the potentiometric technique (Fraser et al., 2024); and electrical conductivity (EC) via the electrode method (Lin et al., 2005). The total phosphorus (TP) was determined using the sulfuric acid decoction-molybdenum antimony resistance method (Potdar et al., 2021), which involved leaching followed by measurement using a fully automated intermittent chemical analyzer. Further, the total nitrogen (TN) was determined by the Kjeldahl-distillation method (Huang et al., 2015), while the total carbon (TC) was quantified through the dry combustion method. The total organic carbon (TOC) content was measured using the potassium dichromate oxidation technique (Pearse et al., 2018; Gu et al., 2016). Finally, the dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) concentrations were quantified using the deionized water extraction method (Wang et al., 2016).

Statistical analysis

A model fitting analysis of the soil respiration with temperature, humidity, and temperature-humidity synergies was performed.

Soil respiration (R_s) consists of both soil autotrophic respiration (R_a) and heterotrophic respiration (R_h).

A split calculation of soil respiration components is:

$$R_s = R_a + R_h \quad (\text{Eq.1})$$

The contribution of each soil respiration component to the total respiration (%) was obtained by dividing the respiration rate value of each component by Rs multiplied by 100.

The relationships between soil temperature, soil moisture, and respiration were analyzed by means of commonly used models (Li et al., 2006, 2018), while the functional relationships between soil respiration and temperature were fitted using an exponential function model, as well as the calculation of the value of the temperature sensitivity (Q_{10}) of soil respiration using the equations below:

$$R = ae^{bT} \quad (\text{Eq.2})$$

$$Q_{10} = e^{10b} \quad (\text{Eq.3})$$

The relationships between soil respiration and soil moisture were modeled using a linear function model:

$$R = c \cdot W + d \quad (\text{Eq.4})$$

The functional relationships between the soil temperature-moisture and soil respiration were modeled using a multivariate linear functional model:

$$R = a + b \cdot T + c \cdot W \quad (\text{Eq.5})$$

where R is the soil respiration flux ($\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$); T represents the 5 cm soil temperature ($^{\circ}\text{C}$); W represents the soil humidity at 5 cm (%); and a, b, c are the undetermined parameters in the model. The temperature sensitivity (Q_{10}) of the respiratory flux was determined by an exponential model (Eq. 2), where b is the constant b obtained from the exponential model and plotted with Origin 2021.

The mean and standard deviations of the measurements were calculated using SPSS 26.0. One-way ANOVA was employed to compare the soil respiration variability, while significance was tested using Duncan's multiple comparison method. Multiple regression models were applied to analyze the relative importance of hydrothermal factors on soil respiration. Redundancy analysis was performed using Canoco 5 software to determine the key factors that induced variabilities in soil respiration. Finally, graphs were completed using Prism 9.5 and Origin 2021 software.

Results

Annual soil respiration variations in different forest stands of Zhegao River wetlands

Soil respiration in the PCM, SMK, MGH, and PEE forests exhibited significant quarterly variations ($p < 0.05$), with high summer and low winter fluxes. As depicted in Figure 2 the Rs varied significantly ($p < 0.05$) between the different forest stands, with the highest mean annual flux in the MGH stand and the lowest in the PEE. The mean annual Rs values for the PCM, SMK, MGH, and PEE forests were 348.7, 343.3, 360.5, and 288.9 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, respectively.

Differences in the mean annual Rh between the various forest stands were significant in the PEE forest ($p < 0.05$), while they were negligible in the PCM, SMK, and MGH

forests ($p > 0.05$). The highest mean annual flux was in the PCM forests with the lowest in the PEE forests. The mean annual values of Rh in PCM, SMK, MGH, and PEE forests were 239.7, 198.9, 232.4, and 178.6 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, respectively. Further, the highest mean annual contribution of Rh was found in the PCM forests with the lowest in the PEE. The average annual contributions of Rh from PCM, SMK, MGH, and PEE forests were ~68.7%, 57.9%, 64.5%, and 61.8%, respectively.

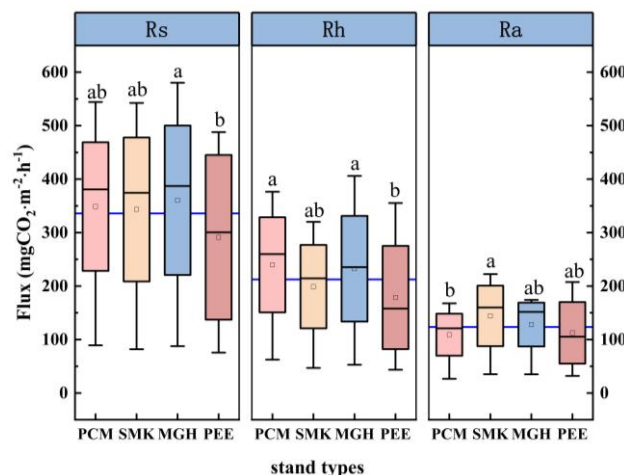


Figure 2. Mean annual fluxes of soil respiration in the different forest stands. PCM refers to *Populus × canadensis* Moench; SMK refers to *alix matsudana* Koidz; MGH refers to *Metasequoia glyptostroboides* Hu; PEE refers to *Pinus elliottii* Engelm; Rs refers to soil respiration; Rh refers to soil heterotrophic respiration; Ra refers to soil autotrophic respiration; and the same below

The Rh varied significantly ($p < 0.05$) between the different forest stand types, with annual mean Ra values of 109.0, 144.4, 128.1, and 110.3 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ for the PCM, SMK, MG, and PEE forests, respectively. Further, the mean annual contributions to Rs were ~31.3%, 42.1%, 35.5%, and 38.2%, respectively.

Seasonal changes in soil respiration of different forest stands

As shown in Figure 3, the soil respiration flux characterized the strength of the capacity of soil to release CO₂. The Rs values of the four different forest stands were characterized by obvious seasonal variations ($p < 0.05$), which initially increased and then decreased. The change pattern revealed an obvious single-peak curve trend, with all forests peaking during the growing season. The mean seasonal flux was highest in the MGH forests and lowest in the PEE. The mean seasonal fluxes of the PCM, SMK, MGH, and PEE forests ranged from 89.3 to 544.1 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, 81.9 to 542.4 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, 87.7 to 580.2 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, and 75.5 to 487.8 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, respectively.

The seasonal Rh dynamics were consistent with the general Rs trend, which showed a single-peak curve change, with the highest flux in summer and the lowest in winter. However, the mean seasonal fluxes of Rh varied significantly ($p < 0.05$) between different forest stand types, with larger Rh variations in the MGH and PEE forests, and smaller variations in the SMK forests. The ranges of mean seasonal fluxes in the PCM, SMK, MGH, and PEE forests were 62.6-376.4 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, 46.8-320.1 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, 52.8-405.9 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ and 43.5-355.2 $\text{mgCO}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, respectively.

The R_a was calculated from the R_s and R_h . The summer R_a change trends of the PCM, SMK, and MGH forests were equivalent to that of R_s and R_h , with the highest flux value in summer and the lowest in winter. However, the soil R_a of PEE forests had the highest flux value in autumn and the lowest in winter. Among them, the R_a varied greatly in PEE forests, while the R_a was mostly stable in the MGH forests. The mean seasonal flux variations in the PCM, SMK, MGH, and PEE forests ranged from 26.7 to 167.7 $\text{mgCO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, 35.1 to 222.3 $\text{mgCO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, 34.9 to 174.3 $\text{mgCO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, and 32.3 to 207.4 $\text{mgCO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, respectively.

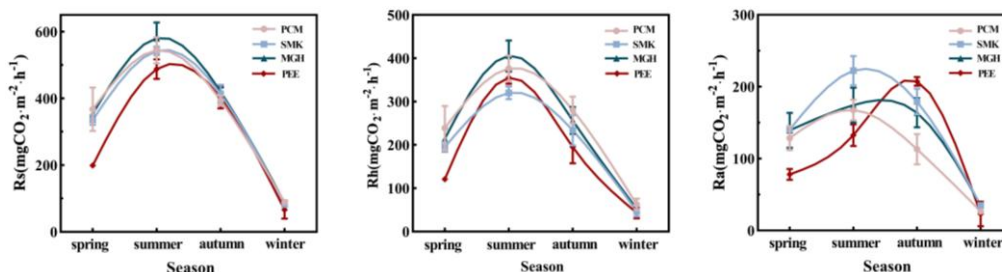


Figure 3. Soil respiration and component respiration in different stands

Seasonal changes in soil hydrothermal factors for different forest stands

The soil temperature and moisture of the four forest stands under study exhibited significant seasonal variations. Among them, the soil temperature was highest in summer and lowest in winter (*Fig. 4*). Seasonal variations in the soil temperatures of the four forest stand types differed significantly ($p < 0.05$), which was consistent with the seasonal variation rule of soil respiration. This suggested that changes in the soil temperature had a greater impact on soil respiration, with an exponentially increased relationship between the two as their fluxes intensified with soil temperature. The average seasonal variations in soil temperature of the PCM, SMK, MGH, and PEE forests ranged from 6.8–27.0°C, 5.8–27.6°C, 6.1–29.2°C, and 4.8–26.7°C, respectively. The soil moisture of the different stand forest types was high during autumn and winter and low in the spring and summer, with the seasonal differences in soil moisture being significant ($p < 0.05$). The average seasonal soil moisture changes in the PCM, SMK, MGH, and PEE forests ranged from 13.3 to 43.1%, 24.8 to 39.0%, 24.2 to 39.0%, 12.3 to 29.7%, and 12.3 to 29.7%, respectively.

Relationships between soil respiration, soil hydrothermal factors, and temperature sensitivity coefficients

The R_s , R_h , and R_a of the four forest stand types were significantly positively correlated ($p < 0.01$) with the soil temperature (*Fig. 5*). The soil temperatures of the PCM, SMK, MGH, and PEE forests explained 88.92%, 92.15%, 88.59%, and 84.16%, respectively, of the seasonal dynamics of R_s ; 94.85%, 91.56%, 83.93%, and 84.95%, respectively, of the seasonal dynamics of R_h ; and 69.27%, 86.25%, 95.37%, and 66.36%, respectively, of the seasonal dynamics of R_a . PCM forests were the most sensitive to soil temperatures, while PEE forests were the least sensitive. As shown in *Table 2* the temperature sensitivity coefficients (Q_{10}) for the R_s of PCM, SMK, MGH, and PEE forests were 2.14, 2.00, 1.75, and 1.69, respectively; 2.50, 1.91, 2.01, and 1.76, respectively, for the R_h ; and 1.72, 1.81, 2.16, and 1.57, respectively, for the R_a .

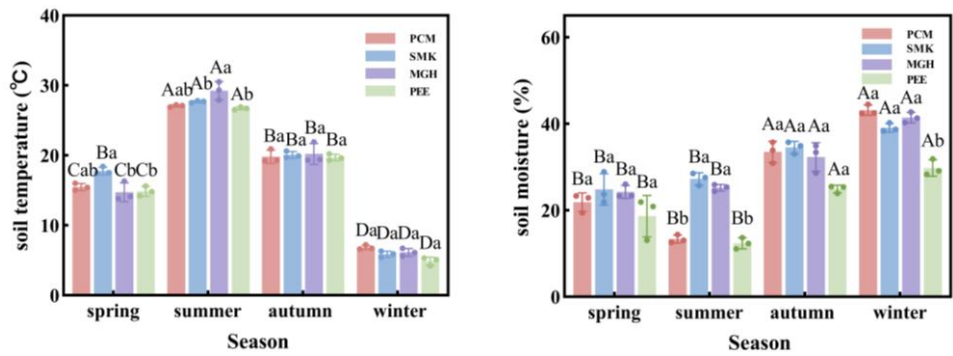


Figure 4. Seasonal changes in soil hydrothermal factors for different forest stands. Different uppercase letters indicate significant differences between seasons in the same stand ($p < 0.05$); different lowercase letters indicate significant differences between stands in the same season ($p < 0.05$)

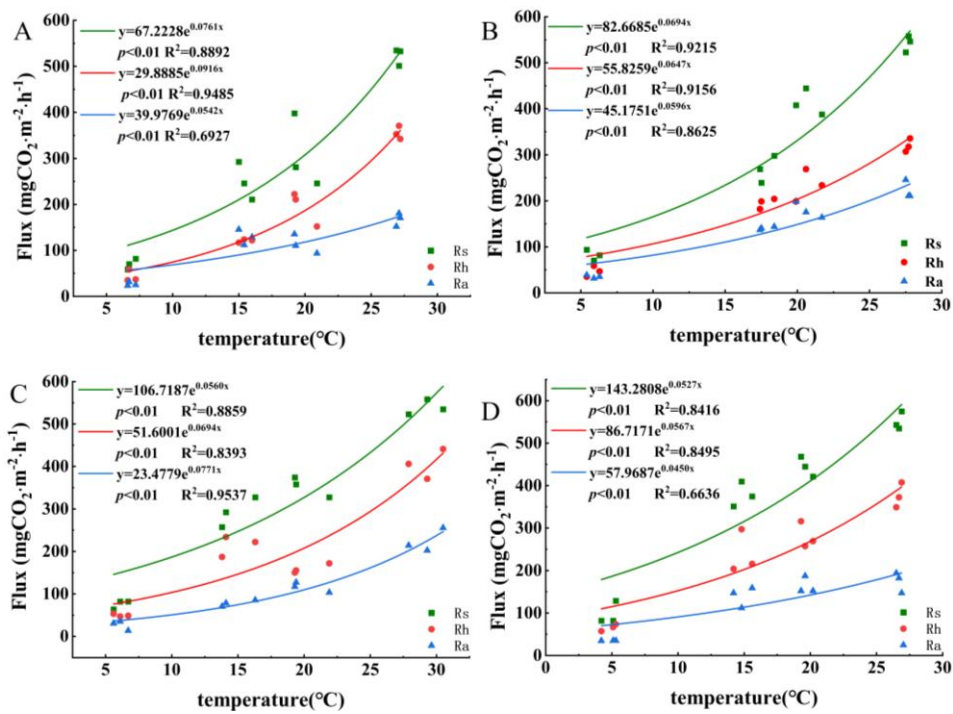


Figure 5. Temperature fitting equations for the different forest stands. (A) PCM; (B) SMK; (C) MGH; (D) PEE

Table 2. Q_{10} values for the different stands

Component	PCM	SMK	MGH	PEE
Rs	2.14	2.00	1.75	1.69
Rh	2.50	1.91	2.01	1.76
Ra	1.72	1.81	2.16	1.57

From the results of fitting the soil temperature to respiration, it was observed that the fit of temperature to Rs ranged from 84.2% to 92.2%, to Rh from 83.9% to 94.9%, and

to Ra from 66.4% to 95.4% for each stand. The respiration of each component of the SMK forests had the best correlation with temperature ($p < 0.01$), while the respiration of each component of the PEE forests showed a poorer correlation with temperature ($p < 0.01$). Overall, most of the soil respiration components increased exponentially with temperature in each stand. However, different forest stands potentially altered the sensitivity of soil respiration to temperature, as well as the correlations between them. This difference was associated with the internal physical and biochemical environments of the soils, differences in vegetation, and community distributions.

The equations for fitting the components of soil respiration to soil moisture in the four different forest stands are shown in Figure 6. The soil component respiration was not significantly correlated with the soil moisture in the PCM forests ($p > 0.05$), while the Rs, Rh, and Ra were significantly positively correlated with the soil moisture in the SMK, MGH, and PEE forests ($p < 0.01$). The correlation between the Rs and soil moisture was stronger than that of component respiration in the SMK and PEE forests. The correlation between Ra and the soil moisture was stronger than Rs and Rh in the MGH forests. The soil water content of the PCM, SMK, MGH, and PEE forests explained 39.71%, 63.82%, 50.71%, and 73.19%, respectively, of the seasonal dynamics of Rs; 39.61%, 53.52%, 50.50%, and 68.44%, respectively, of the seasonal dynamics of Rh; and 31.40%, 52.58%, 71.25%, and 67.64%, respectively, of the seasonal dynamics of Ra. The PEE forests were the most sensitive to moisture, while the PCM forests were less sensitive.

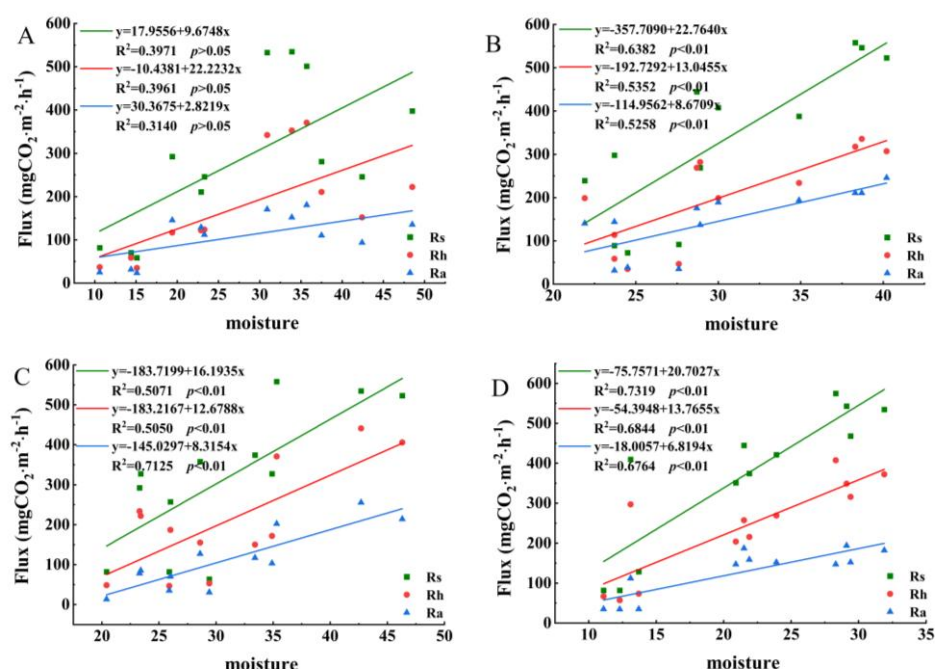


Figure 6. Fitted equations for soil moisture at 5 cm depth in the different forest stands. (A) PCM; (B) SMK; (C) MGH; (D) PEE

Multiple linear regression equations were fitted with the soil temperature and humidity to describe the synergistic effects of soil temperature and humidity on soil respiration. The results revealed that there was a high degree of goodness of fit after

fitting the soil respiration, temperature, and humidity with the two composite models, with the correlation reaching a highly significant level ($p < 0.001$). The decision coefficients of the two-factor model were higher than those of the one-factor model for temperature and wetland. As seen in *Table 3*, both the soil temperature and humidity could explain from 89.5% to 95.7% of the variation in R_s ; from 83.3% to 92.4% of the variation in R_h ; and from 77.1% to 95.3% of the variation in R_a . It was observed that the two-factor composite model had high accuracy in projecting soil respiratory fluxes in the different forest stand types.

Relationship between soil respiration and soil physical and chemical properties

The soil pH was highest in sequoia forests and lowest in SMK forests, with an overall range of from 4.89 to 6.72 (*Table 4*). The TOC content was highest in MGH forests and lowest in PEE forests, with an overall range of from 14.69 to 39.48 $\text{g}\cdot\text{kg}^{-1}$. The DOC/DON content varied significantly between the different forest stands, both of which were highest in PCM forests and lowest in PEE forests, with overall ranges of from 62.14 to 157.26 $\text{mg}\cdot\text{kg}^{-1}$ and from 10.24 to 35.04 $\text{mg}\cdot\text{kg}^{-1}$, respectively. Further, the TC content was highest in PCM forests and lowest in MGH forests, with an overall range of from 7.31 to 15.10 $\text{g}\cdot\text{kg}^{-1}$. Finally, TN content was highest in PEE forests and lowest in MGH forests, with an overall range of from 0.54 to 1.92 $\text{g}\cdot\text{kg}^{-1}$.

Table 3. Results of multiple linear regression of hydrothermal factors with soil respiration

Component	PCM	SMK	MGH	PEE
R_s	$y = -74.231 + 23.340T - 1.493W$ $R^2 = 0.895$ $p < 0.001$	$y = -137.213 + 18.574T + 4.321W$ $R^2 = 0.954$ $p < 0.001$	$y = -18.470 + 19.528T - 0.322W$ $R^2 = 0.957$ $p < 0.001$	$y = 48.013 + 23.091T - 2.893W$ $R^2 = 0.944$ $p < 0.001$
R_h	$y = -75.250 + 16.409T - 1.070W$ $R^2 = 0.896$ $p < 0.001$	$y = -57.749 + 11.370T + 1.755W$ $R^2 = 0.833$ $p < 0.001$	$y = -11.183 + 14.935T - 1.463W$ $R^2 = 0.827$ $p < 0.001$	$y = 35.900 + 16.846T - 3.449W$ $R^2 = 0.924$ $p < 0.001$
R_a	$y = 1.753 + 7.245T + 0.645W$ $R^2 = 0.771$ $p < 0.001$	$y = -8.944 + 8.930T - 0.196W$ $R^2 = 0.953$ $p < 0.001$	$y = -97.354 + 6.436T + 3.168W$ $R^2 = 0.934$ $p < 0.001$	$y = 13.005 + 5.785T + 0.907W$ $R^2 = 0.812$ $p < 0.001$

Table 4. Physicochemical properties of soils in the different forest stands

Stand type	pH	TOC ($\text{g}\cdot\text{kg}^{-1}$)	DOC ($\text{mg}\cdot\text{kg}^{-1}$)	DON ($\text{mg}\cdot\text{kg}^{-1}$)	TC ($\text{g}\cdot\text{kg}^{-1}$)	TN ($\text{g}\cdot\text{kg}^{-1}$)
PCM	6.71 $\pm$ 0.04a	12.49 $\pm$ 3.54bc	157.26 $\pm$ 2.82a	35.04 $\pm$ 2.84a	15.10 $\pm$ 0.03a	1.09 $\pm$ 0.09b
SMK	4.89 $\pm$ 0.30b	19.03 $\pm$ 6.97ab	110.47 $\pm$ 10.35b	15.83 $\pm$ 1.13b	12.51 $\pm$ 0.04b	1.01 $\pm$ 0.26b
MGH	6.72 $\pm$ 0.21a	22.90 $\pm$ 2.85a	121.84 $\pm$ 3.45b	11.19 $\pm$ 1.12c	7.31 $\pm$ 0.05d	0.54 $\pm$ 0.08c
PEE	6.46 $\pm$ 0.36a	8.52 $\pm$ 3.41d	62.14 $\pm$ 7.28c	10.24 $\pm$ 0.16c	9.60 $\pm$ 0.07c	1.92 $\pm$ 0.24a

Different lowercase letters indicate significant differences ($p < 0.05$)

As can be seen in *Figure 7* the two axes together explained 65.46% of the information in the data set (64.34% in the first axis and 1.12% in the second axis). The soil respiration and its component respiration were significantly correlated with the TOC content ($p < 0.05$), while no significant correlation ($p > 0.05$) was shown with any other soil physicochemical factors.

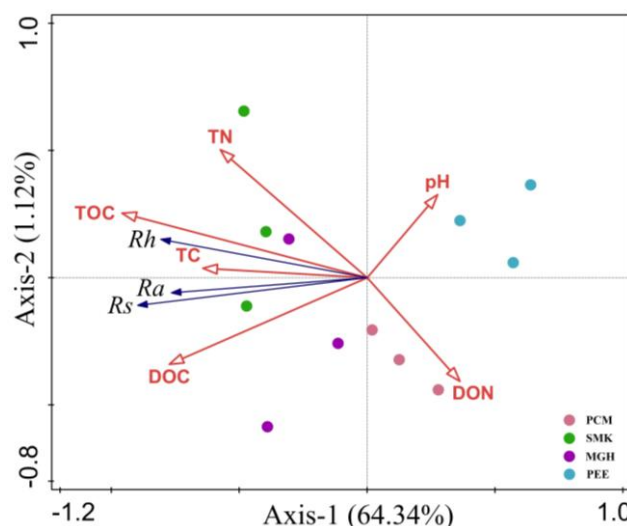


Figure 7. RDA analysis of soil respiration with soil physicochemical properties

Discussion

Causes of differences in the soil respiration of the various forest stands

For the different forest stands, the surface litter and soil properties of the vegetation zones were distinct. The plant root growth and soil microbial activities also differed, which in turn influenced the CO₂ emissions (Shen et al., 2022). At the seasonal scale, the total soil respiration of the four stand types exhibited high flux in summer and low flux in winter. This characteristic seasonal change was consistent with the results of preceding studies (Yang et al., 2022), and its change pattern showed an obvious single-peak curve trend. Correlations between the soil respiration and environmental factors varied significantly between the different stand types, and there were also significant differences between the same forest stand types (Yuste et al., 2004). This may have been due to the plant community composition affecting soil respiration through a combination of factors such as the regulation of microbial species and activities, and altering plant litter inputs (Mauritz et al., 2021; Upadhyay et al., 2021). In this study, soil respiration was highest in *Metasequoia glyptostroboides* Hu (MGH) forests and lowest in *Pinus elliottii* Engelm (PEE) forests. The rationale for this may have been that there was a higher concentration of substances (e.g., lignin and phenols) in the litter material of coniferous species (Li et al., 2018). This translated to a slower decomposition rate of litter material, lower carbon source required for microbial activities, and relatively decreased forest floor soil respiration (Joshi et al., 2024). Furthermore, *Populus × canadensis* Moench (PCM), *Salix matsudana* Koidz (SMK), and *Metasequoia glyptostroboides* Hu (MGH) forests are deciduous species. The surface litter material cover was easier to decompose, and the soil respiration was higher than that of PEE forests. This indicated that the litter material of deciduous species contributed more to soil respiration than that of coniferous species.

Effects of soil hydrothermal factors on respiration

In this experiment, soil respiration was significantly positively correlated with environmental hydrothermal factors at each forest site, which agreed with most of the findings of Zhang et al. (2018) and Zhao et al. (2023). As microbial activities play a key

role in soil respiration processes, soil temperature has traditionally been widely regarded as a major environmental factor that affects soil respiration (Liu et al., 2024; Niklinska et al., 1999). The effects of soil temperature on its respiration is more pronounced under conditions of adequate soil moisture, which ensures root and microbial activities (Wildung et al., 2021). When soil is subject to extreme drought or waterlogged conditions, soil moisture becomes the primary factor that affects respiration (Davidson et al., 2000). In this study, autotrophic soil respiration (R_a) peaked in autumn in the PEE forests, while it peaked in summer for the PCM, SMK, and MGH forests. PEE forests had the lowest temperature sensitivity (Q_{10}) in contrast to the other three forest types, which made them the least sensitive to temperature. Because soil moisture is low during the summer months, it is the primary influence on R_a in PEE forests. Changes in soil moisture impact plant root growth, soil metabolic activities, soil microbial community structures and activities, as well as soil permeability and gas diffusion; thus, the intensity of soil respiration (Xu et al., 2004). Consequently, R_a is inhibited in PEE forests by soil moisture during summer, which results in its low flux, while the intensity of soil R_a increases in autumn as the soil moisture increases and the flux peaks.

Soil respiration in the four typical forest stands of this study exhibited significant positive correlations with the soil temperature and humidity. However, its correlation with soil temperature was higher, which may have been attributed to the fact that increased soil temperature not only promoted the growth and development of vegetation and enhanced root respiration, but also effectively enhanced the activities of soil microbes and enzymes, accelerated the decomposition of organic matter, and promoted CO_2 emissions (Shi et al., 2011). The outcomes revealed that the two-factor fitting with soil temperature-moisture was better than the one-factor fitting with soil temperature or soil moisture. This was similar to the results of Meng et al. (2008) and Han et al. (2017), that is, the interpretation of soil respiration was stronger when using two-factor co-fitting.

Effects of soil physicochemical properties on soil respiration

The content of soil organic carbon affects soil properties such as its permeability, water content, fertility, etc.; thus, soil organic carbon is a key aspect of soil respiration (Sikora et al., 1990). In this study, we found that among the four forest types under investigation, the MGH forests possessed the highest total organic carbon (TOC) content. This provided sustenance materials for microbes and increased the populations and activities of microorganisms, which improved the soil respiration intensity. In contrast, the PEE forests had the lowest TOC content, which did not contain sufficient substrates for respiration; thus, weakening the soil respiration intensity. These results suggested that the high contribution of organic carbon played a critical role in the ecological functions of wetland soils. Its availability directly influenced microbial activities and the soil respiration rate; thus, it is generally believed that a higher TOC content is favorable for soil respiration (Francioni et al., 2019; Qu et al., 2010).

Conclusion

For this study, a comprehensive analysis of the soil respiration attributes of four typical forest stands in the Zhegao River wetland concluded that, except for the PEE forests (where the R_a showed a higher flux in autumn and a lower flux in winter), the remainder of the soil respiration and component respiration exhibited high fluxes in

summer and low fluxes in winter with a single-peak curve pattern, and the contribution rate of R_h to R_s was higher. Furthermore, the effects of soil temperature and humidity on the fluxes of soil respiration components were not separate but worked simultaneously. The interactions of the two had a higher synergistic effect on soil respiration than the effects of temperature and humidity alone. In addition to the influences of hydrothermal factors on soil respiration, the TOC content affected soil respiration. Among the different forest stand types, MGH forests released the most soil CO_2 , while PEE forests released the least. Therefore, planting *Pinus elliottii* in lakeshore wetlands is more conducive to reducing carbon emissions and increasing carbon sequestration.

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APPENDIX

Schedule 1. One-way ANOVA for basic physical and chemical properties of soils in different stand types

Factor	ph		EC		BD		TN		TP	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Stand type	35.395	0.000	81.47	0.000	2.111	0.177	28.968	0.000	401.943	0.000