Variation Characteristics of Carbon Flux in Schrenk Spruce Forests in the Middle Section of the Northern Slope of the Tianshan Mountains and Their Response to Environmental Factors

Cui Yirui¹, Jiang Yan¹, Li Jimei^{2,3}, Zhang Yutao^{2,3}

2026-06-18

ChinaRxiv

Abstract

The Tianshan Mountains are an important ecological security barrier and carbon sequestration site in western China. As the dominant species of Tianshan forests, Picea schrenkiana has a carbon sink function that directly affects the regional carbon storage pattern and cycling processes, making it a key factor in the carbon balance of the Tianshan forest region. To clarify the characteristics and influencing factors of carbon fluxes in Tianshan spruce forests, carbon flux observations were conducted in May 2023-2024 at the Xinjiang Tianshan Forest Ecosystem National Observation and Research Station based on the eddy covariance method. The results showed that: (1) the spruce forest on the northern slope of the middle Tianshan Mountains in Xinjiang generally functioned as a carbon sink, with an annual carbon sink of 635.633 μmol · m-2, and the diurnal variation in CO2 flux showed a "U" -shaped pattern, ranging from −36.82 to 13.02 μmol · m-2 · s-1; (2) the flux contribution area was concentrated from the northwest to the southwest, consistent with the prevailing wind direction and vegetation-covered areas, indicating that the spatial distribution of fluxes was jointly regulated by biological and meteorological factors; (3) temperature was the key environmental factor regulating the carbon source/sink status of this system. On the monthly scale, air temperature and photosynthetically active radiation jointly dominated changes in net ecosystem exchange, whereas on the daily scale, the dynamics of net ecosystem exchange were driven by soil temperature through regulation of the diurnal rhythm of ecosystem respiration. This study provides data support for accurately assessing the carbon sink capacity of the Tianshan Picea schrenkiana ecosystem.

Full Text

DOI: 10.13866/j.azr.2026.04.11
CSTR: 32277.14.AZR.20260411

Variation Characteristics of Carbon Flux in Schrenk Spruce Forests in the Middle Section of the Northern Slope of the Tianshan Mountains and Their Response to Environmental Factors

Cui Yirui1, Jiang Yan1, Li Jimei2,3, Zhang Yutao2,3

(1. College of Agronomy, Shihezi University, Shihezi, Xinjiang 832003; 2. Institute of Forest Ecology, Xinjiang Academy of Forestry Sciences, Urumqi, Xinjiang 830063;
3. National Station for Positioning Observation and Research of the Tianshan Forest Ecosystem, Urumqi, Xinjiang 830000)

Abstract: The Tianshan Mountains are an important ecological security barrier and carbon-sink site in western China. As the dominant tree species of Tianshan forests, Schrenk spruce directly affects the regional pattern of carbon storage and cycling processes through its carbon-sink function, and is a key factor in the carbon balance of the Tianshan forest region. To clarify the carbon-flux characteristics of Tianshan Schrenk spruce forests and their influencing factors, carbon-flux observations were conducted in May 2023–2024 at the National Station for Positioning Observation and Research of the Tianshan Forest Ecosystem in Xinjiang using the eddy covariance method. The results show that: (1) the Schrenk spruce forests in the middle section of the Tianshan Mountains in Xinjiang generally functioned as a carbon sink, with an annual carbon sink of 635.633 $\mu\text{mol} \cdot \text{m}^{-2}$. The diurnal variation in CO_2 flux was "U" -shaped, ranging from -36.82 to 13.02 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; (2) the flux contribution area was concentrated from the northwest to the southwest, consistent with the prevailing wind direction and vegetation-covered area, indicating that the spatial distribution of flux was jointly regulated by biological and meteorological factors. (3) Temperature was the key environmental factor regulating the carbon source/sink status of this system. On the monthly scale, air temperature and photosynthetically active radiation jointly dominated changes in net ecosystem exchange; on the daily scale, the dynamics of net ecosystem exchange were driven by the diurnal rhythm of ecosystem respiration regulated by soil temperature. This study provides data support for accurately evaluating the carbon-sequestration capacity of Tianshan Schrenk spruce ecosystems.

Keywords: eddy covariance; Schrenk spruce forest; carbon flux; environmental factors; Tianshan Mountains

Accurately quantifying the carbon sources and sinks of terrestrial ecosystems is the scientific basis for predicting future climate-change trends and formulating effective emission-reduction strategies[1]. Since the Industrial Revolution, atmospheric CO_2 concentration has risen from $0.495 \sim 0.511$ $\text{mg} \cdot \text{L}^{-1}$ to above 0.747 $\text{mg} \cdot \text{L}^{-1}$. This change has intensified global warming through the greenhouse effect, making research on ecosystem carbon cycling a focus[2-3]. Among terrestrial ecosystems, mountain ecosystems, because of their high complexity and diversity, exhibit strong spatial heterogeneity and uncertainty in carbon-cycling processes, and have an influence on the global carbon cycle that cannot be ignored[3-4]. Therefore, revealing the laws of carbon cycling in mountain ecosystems has become a key field in current global carbon-cycle research[5].

The eddy covariance method can conduct continuous, non-destructive, long-term observations of material and energy exchange at the vegetation–atmosphere interface, making it a key technique for directly quantifying net ecosystem exchange (NEE) and its components–gross primary productivity (GPP) and ecosystem respiration (ER)–at the ecosystem scale[6]. Based on this technique, scholars have made important progress in revealing the response patterns of forest carbon flux to environmental factors. For example, studies have shown that carbon exchange in boreal and subalpine forests is mainly driven by energy factors such as temperature and photosynthetically active radiation[7], whereas carbon fluxes in coastal mangrove forests and other ecosystems are more strongly regulated by moisture conditions, such as saturated vapor pressure deficit and precipitation[8], revealing differences in the driving mechanisms of different ecosystems. However, most studies have mainly focused on humid and semi-humid climatic regions; understanding of the spatiotemporal characteristics of forest carbon flux and its dominant influencing factors in arid regions such as Xinjiang remains insufficient, which seriously constrains in-depth understanding of forest carbon-cycle mechanisms in arid regions.

Forests can absorb and fix atmospheric CO_2, serving as sinks, reservoirs, and buffers for atmospheric CO_2. As key carriers of carbon sinks, the carbon-sequestration efficiency of forests has irreplaceable strategic value for achieving the global carbon-neutrality target[9]. The forest area of Xinjiang is 9.01×10^6 hm^2, and it is an important component of the northern forest belt of Central Asia and the Eurasian continent, mainly distributed in the Altai Mountains, the Tianshan Mountains, and major river valleys[10]. Schrenk spruce is a characteristic evergreen tree species of the Tianshan Mountains and plays an important role in carbon sequestration and water conservation[11–12]. As the dominant tree species of the Tianshan forest region, dynamic changes in its carbon source/sink potential play a key regulatory role in carbon storage and cycling in the Tianshan Mountains[13]. Therefore, analyzing the spatiotemporal dynamics of carbon exchange in Schrenk spruce forests and their influencing factors, and quantifying their carbon budget,

Received: 2025-08-26; **Revised:** 2025-11-05
Funding project: Response of ecosystem carbon exchange in *Rosa* communities in the shallow mountain belt of the northern slope of the Tianshan Mountains to coppicing mode (2023D01A90)
Author profile: Cui Yirui (2000–), female, master' s student, mainly engaged in research on ecosystem carbon cycling. E-mail: cuiyirui1216@163.com
Corresponding author: Jiang Yan. E-mail: jiangyan098@163.com

Clarifying the carbon sequestration potential of Xinjiang' s forests is of great significance, and can also help China achieve its dual-carbon goals and actively respond to climate change.

Accordingly, this study takes the *Picea schrenkiana* forest of the Tianshan Mountains in Xinjiang as the research object. Based on eddy covariance observations, it aims to address the following questions: (1) reveal the spatiotemporal variation patterns of carbon fluxes in the Tianshan *Picea schrenkiana* forest; (2) clarify the characteristics of carbon uptake/release by the *Picea schrenkiana* forest and the environmental influencing factors at different temporal scales. The results will provide a scientific basis for deeper understanding of forest carbon cycling mechanisms in arid regions, and for accurately evaluating the carbon sink capacity of the Tianshan *Picea schrenkiana* ecosystem.

1 Materials and Methods

1.1 Overview of the Study Area

The Xinjiang Tianshan Forest Ecosystem Station is affiliated with the National Forestry and Grassland Administration' s forest ecosystem positioning research network. It is located at 87°27′–87°29′E, 43°24′–43°26′N, and administratively belongs to Banfanggou Forest Farm, Urumqi City. The site has an elevational gradient of 1908–2710 m and a typical temperate continental climate. The annual mean temperature is 2.0 ℃; historical extreme temperatures are −30.2 ℃ (minimum) and 30.5 ℃ (maximum); the active accumulated temperature $ $10 ℃ is 1170.5 ℃ · d; the annual frost-free period (>0 ℃) is 89.3 d; annual precipitation is 572.7 mm; and the maximum snow depth is 65 cm. This region has been jointly influenced over geological history by mountain-building movements, Quaternary glaciation, and bioclimatic factors, leading to the development of a cold-temperate montane coniferous forest ecosystem dominated by *Picea schrenkiana*.

1.2 Instrumentation

The flux tower at the Xinjiang Tianshan Forest Ecosystem Station can be used to observe net ecosystem CO_2 exchange (NEE) in the *Picea schrenkiana* forest. It mainly consists of an open-path eddy covariance flux monitoring system and a micrometeorological observation system. The flux observation tower is installed at a height of 35 m and is equipped with an open-path CO_2/H_2O analyzer (LI-7500, LI-COR, USA) and a three-dimensional ultrasonic anemometer (CAST-3, Campbell, USA). Raw data are synchronously collected at a sampling frequency of 10 Hz. The data are stored in real time by a CR3000 data logger (Campbell, USA), and 30 min mean flux parameters are calculated online based on the eddy covariance algorithm, including CO_2 flux (F_c), friction velocity (u^*), and others.

1.3 Flux Data Processing

This study used data from January 2023 to April 2024. Based on the 10 Hz high-frequency raw data, the built-in LI-7500DS module EddyPro 7.0.6 (LI-COR, USA) was used for online processing, automatically performing outlier removal, terrain correction, and QA/QC flagging, and finally outputting a 30 min flux dataset to analyze the diurnal cycle and seasonal dynamics of carbon fluxes.

For flux data quality control, EddyPro software classified flux results into three quality classes according to the "0–1–2" quality evaluation method and in combination with turbulence stationarity: class 0 (high quality), class 1 (medium quality), and class 2 (low quality) [14]; class 2 data were removed. Further processing was also required: (1) remove negative nighttime data, because at night only soil and vegetation respiration occur, and CO_2 flux cannot be negative; (2) remove data that are clearly different from normal values through spectral analysis; (3) according to previous experience and research results [15], this study selected 0.2 $m \cdot s^{-1}$ as the critical threshold for u^*, and removed observational data with friction velocity $u^* < 0.2\ m \cdot s^{-1}$. For missing data, if the missing period was less than 2 h, linear interpolation was used; if it exceeded 2 h, the mean diurnal variation method (MDV) was applied, using the observational mean value at the same time period within an adjacent interval to replace the missing value, thereby ensuring the accuracy and completeness of the data and providing reliable data support for subsequent research.

Subsequent data processing and figure preparation were conducted in Excel, SPSS, and Origin.

1.4 Calculation Method

Net ecosystem carbon exchange (NEE) was calculated as follows [16]:

$$\mathrm{NEE} = \mathrm{ER} - \mathrm{GPP}$$

In the formula: when ecosystem respiration (Ecosystem Respiration, ER) > gross primary productivity (Gross Primary Productivity, GPP), the NEE value is positive, indicating that vegetation releases CO_2 to the atmosphere and that the forest ecosystem is a carbon source; when ER < GPP, the NEE value is negative, indicating that vegetation absorbs CO_2 from the atmosphere and that the forest ecosystem is a carbon sink; when GPP = 0, vegetation is not undergoing photosynthesis, and at this time NEE = ER.

2 Results and Analysis

2.1 Variation Characteristics of Environmental Factors

Observational data from January 2023 to April 2024 were selected as the research object. Among them, the meteorological factors (Fig. 1) included air temperature (T_a), 5 cm soil temperature (T_s), precipitation ($RAIN$), soil volumetric water content (SWC), relative humidity (RH), photosynthetically active radiation (PAR), and wind speed (WS). Seasonal variation in air temperature and soil temperature was relatively pronounced (Fig. 1a). Air temperature and 5 cm soil temperature showed similar seasonal trends. Air temperature was highest from June to August, at 28.05-32.69 ℃, and the annual mean air temperature was 2.71 ℃. Soil temperature reached its maximum in July and August, at 16.01-17.61 ℃, and the annual mean soil temperature was 3.49 ℃. In winter (October to the following January), air temperature and soil temperature reached their lowest values, and soil temperature was higher than air temperature. Precipitation was mainly concentrated from June to September each year, while in other months overall precipitation was scarce and of low intensity (Fig.

Fig. 1 Variation characteristics of environmental factors

Visible figure labels:
(a) Air temperature; soil temperature.
(b) Soil volumetric water content; precipitation.
(c) Relative humidity; photosynthetically active radiation.
Time / year-month-day.

Fig. 1b); the corresponding soil water content was low and stable in late winter and early spring, rose rapidly in spring because of snowmelt, fluctuated at high values in summer, and declined in autumn and winter (Fig. 1b). Relative humidity (Fig. 1c) increased markedly in summer, reaching its maximum in July–August ($> 90\%$), which was related to precipitation. As shown in Fig. 1c, photosynthetically active radiation exhibited obvious seasonal variation, with a unimodal fluctuation pattern characterized by high values in summer and low values in winter. The highest daily mean value in June reached 716.10 μmol$\cdot$m$^{-2}\cdot$ s^{-1} on June 27, and the lowest daily mean value in December was 53.60 μmol $\cdot$ m^{-2} $\cdot$ s^{-1} on December 25. The annual mean wind speed at the observation station was 2.02 m $\cdot$ s^{-1}. The prevailing wind directions were northwest, south, and north; among them, southerly winds accounted for 21.27% of the annual wind directions, followed by northwesterly and northerly winds, accounting for 19.46% and 19.34%, respectively (Fig. 2).

2.2 Spatiotemporal variation in carbon flux

2.2.1 Spatial distribution of CO_2 flux

The average distance between the 90% flux-contribution source area and the flux tower ranged from 283.02 to 436.41 m. The maximum CO_2 flux occurred in the northwest direction, and the minimum occurred in the south direction (Fig. 3a). The farthest points of the flux-contribution area were relatively concentrated, with a maximum distance of 463.632 m from the flux-tower observation point; the flux measurements mainly originated from the northwest, northeast, and southwest directions (Fig. 3b). The CO_2 flux map for each wind direction (Fig. 3c) quantified these differences: fluxes were highest in the northwest, southwest, and northeast directions (the darkest gray), whereas fluxes were lowest in the southeast direction. The directional differences in nighttime CO_2 flux fluctuated less, and the differences were mainly dominated by the daytime period (Fig. 3d).

Fig. 2 Wind direction frequency distribution

Visible figure labels: wind frequency / %; $WS/(\mathrm{m}\cdot\mathrm{s}^{-1})$; wind-speed classes: ≥ 4, 3–4, 2–3, 1–2, 0–1.

2.2.2 Temporal variation in CO_2 flux

The diurnal variation trends of monthly F_c in 2023 were generally similar, all showing a "U" -shaped pattern (Fig. 4). Carbon sinks mainly occurred during 8:00–18:00, with a fluctuation range of -1.4×10^{-5} to -0.018 μmol $\cdot$ m^{-2} $\cdot$ s^{-1}. The minimum value occurred at 11:00 in July, and the maximum value occurred at 8:00 in March. Carbon sources were mostly concentrated from 20:00 to 07:00 the next day, with a fluctuation range of 13.02 to 0.26 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The maximum value occurred at 23:00 in July, and the minimum value occurred at 17:00 in January. The carbon source–sink transition periods differed among months; among them, July had the longest daily mean carbon-sequestration duration, reaching 12 h, whereas January had the shortest, only 6 h.

2.2.3 Temporal variation in NEE, GPP, and ER

The *Picea schrenkiana* forest ecosystem in the Tianshan Mountains overall showed a significant net carbon sink (Figs. 5-6), with an annual carbon sequestration of 11.44 $\text{Mg C} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$. Net ecosystem exchange NEE exhibited strong seasonality: from February to April, ecosystem respiration was relatively strong ($ER > GPP$), and the *Picea schrenkiana* forest acted as a carbon source ($NEE > 0$); from May to October, it remained a carbon sink ($NEE < 0$), with the strongest carbon-sequestration capacity in August. The annual cumulative NEE, GPP, and ER were -635.63 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$, 1125.50 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$, and 489.87 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$, respectively.

2.3 Temporal dynamic distribution of carbon sources/sinks

From the temporal distribution pattern of carbon sources/sinks throughout 2023 (Fig. 7), carbon sinks were mainly concentrated in the range of -5 to 0 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, totaling 206 d; carbon sources were mainly concentrated in the range of 0 to 3 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, totaling 111 d. It can be seen that the number of carbon-sink days far exceeded the number of carbon-source days. Carbon dynamics were relatively stable, with no long-term, high-intensity tendency toward a single carbon-sink or carbon-source state, indicating that the internal carbon-cycle regulation mechanism was relatively effective.

2.4 Correlation between carbon flux and meteorological factors

2.4.1 Influencing factors of carbon sources and carbon sinks

To explore the driving effects of environmental factors, stepwise regression was used to analyze air temperature (T_a), light

(a) Legend: 90% contribution source-area range. Axis: 90% contribution source-area range / m.

(b) Legend: distribution of the farthest points of the flux footprint. Axis: distribution of the farthest points of the flux footprint / m.

(c) Legend: CO_2 flux in each wind direction. Axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1})$.

(d) Legends: daytime carbon flux; nighttime carbon flux. Axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1})$.

Fig. 3 Flux footprint and sector-wise CO_2 flux distribution

photosynthetically active radiation (PAR), 5-cm soil temperature (T_s), 5-cm soil moisture (SWC), and precipitation ($RAIN$) on carbon sources and sinks (Table 1). Changes in the carbon sink were jointly affected by T_s, T_a, and SWC; the total explanatory power of these three environmental factors reached 50.4%. Among them, T_s explained 48.2% and showed a significant negative correlation with the carbon sink ($P < 0.001$). The dominant factor controlling the carbon source was soil temperature, which explained 29% and was positively correlated with the carbon source ($P < 0.001$).

2.4.2 Influencing factors of NEE, GPP, and ER at different temporal scales

To identify the key environmental driving factors, correlation coefficients between factors such as air temperature (T_a), photosynthetically active radiation (PAR), 5-cm soil temperature (T_s), 5-cm soil moisture (SWC), and precipitation ($RAIN$) and each component of carbon flux were calculated at different temporal scales (Fig. 8). The results showed that, at the daily scale, NEE in the Tianshan *Picea schrenkiana* forest ecosystem was negatively correlated with T_s, T_a, and RH ($P < 0.01$), with the strongest negative correlation occurring with T_s ($R = -0.28$). GPP and ER were negatively correlated with PAR and positively correlated with all other environmental factors, among which their correlations with T_s and RH were the strongest. At the monthly scale, NEE in the Tianshan *Picea schrenkiana* forest ecosystem was mainly significantly negatively correlated with T_a, T_s, and PAR ($P < 0.01$), with values of -0.87, -0.93, and -0.77, respectively. GPP was most strongly affected by T_a and T_s, with R values of 0.9 and 0.94, respectively, followed by PAR and RH. The R values between ER and T_a and T_s were 0.84 and 0.83, respectively.

3 Discussion

The Xinjiang *Picea schrenkiana* forest overall functioned as a carbon sink, with an annual sink amount of 635.633 $\mu\text{mol} \cdot \text{m}^{-2}$. The diurnal variation in CO_2 flux of the *Picea schrenkiana* forest showed a "U" shape, with a daily variation range of -36.82 to 13.02 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Under the same forest type (Table 2) [8, 17–20], the carbon-flux variation of the *Picea schrenkiana* forest···

Fig. 4. Diurnal variation of carbon fluxes by month

- **(a)** Legend: March, April, May.
  y-axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1})$; x-axis: Time.
- **(b)** Legend: June, July, August.
  y-axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1})$; x-axis: Time.
- **(c)** Legend: September, October, November.
  y-axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1})$; x-axis: Time.
- **(d)** Legend: January, February, December.
  y-axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1})$; x-axis: Time.

Fig. 5. Dynamics of NEE, GPP, and ER in the spruce forest during the period from January 2023 to May 2024

Legend: ER, GPP, NEE.
y-axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1})$; x-axis: Days/d.

Fig. 7. Temporal dynamics of carbon source and carbon sink in spruce forests in 2023

Top labels: Carbon sink; Carbon source.
y-axis: Days/d; x-axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1})$.

Fig. 6. Monthly dynamics of spruce forests in 2023

Legend: NEE, GPP, ER.
y-axis: $F_c/(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{month}^{-1})$; x-axis: Month.

The variation is pronounced. The latitude of the Xueling spruce forest is higher than that of other mixed forests. Because high-latitude forests have short growing seasons but concentrated light energy, they often exhibit more extreme diurnal amplitudes in carbon flux, whereas low-latitude forests maintain relatively steady photosynthesis throughout the year and show smaller amplitudes. Second, owing to the distinctive climatic characteristics of arid regions, the diurnal temperature range exceeds 15 °C, and low nighttime temperatures strongly suppress respiration, thereby improving the efficiency of net carbon accumulation. Therefore, unlike the other forest ecosystems in Table 2 that may be dominated by moisture or phenology, this study reveals that the Tianshan Xueling spruce forest is a typical "soil-temperature-regulated" ecosystem.

carbon sink; its sharp flux variations fundamentally arise from the distinctive mechanism whereby GPP is highly sensitive to changes in soil temperature.

Table 1 Stepwise regression analysis between carbon source, sink and environmental factors

Carbon flux	Independent variables	Regression equation	Adjusted R^2	P
Carbon sink	Ts	NEE = $-2.915 - 0.902Ts$	0.482	<0.001
Carbon sink	Ts, SWC	NEE = $-0.728 - 0.906Ts - 13.641SWC$	0.496	<0.001
Carbon sink	Ts, SWC, Ta	NEE = $-0.907 - 0.688Ts - 12.142SWC - 0.135Ta$	0.504	<0.001

Carbon flux	Independent variables	Regression equation	Adjusted R^2	P
Carbon source	Ts	NEE = $1.095 + 0.166Ts$	0.29	<0.001
Carbon source	Ts, SWC	NEE = $0.857 + 0.166Ts + 1.153SWC$	0.291	<0.001

The spatial distribution of CO_2 fluxes shows that 90% of the carbon flux mainly comes from the northwest, northeast, and southwest directions. Combined with the year-round wind-direction distribution, it can be seen that the study area is dominated by northwesterly, southwesterly, and northerly winds, indicating that the spatial distribution characteristics of CO_2 fluxes are affected to some extent by wind direction and wind speed. Zhang et al. [21] also considered wind direction and wind speed to be among the main factors influencing flux contribution areas. In addition, the magnitude of CO_2 flux values in different directions is also related to vegetation coverage within their contributing source areas [22]. In combination with the findings of Chang Mengdi et al. [23], the vegetation coverage in the northwest and southwest directions of the flux observation tower in this study was found to be 80%-90%. During the daytime, directional differences in CO_2 fluxes are significant, mainly due to the spatial heterogeneity of vegetation distribution and wind speed; whereas at night, the convergence of fluxes results from stable vegetation respiration [22,24]. This indicates that the spatial pattern of ecosystem carbon fluxes is jointly regulated by biotic and meteorological factors.

Fig. 8 Temporal-scale dependent correlation analysis of carbon flux and environmental factors in coniferous forests

Visible panel labels: (a) daily scale; (b) monthly scale; color scale: correlation coefficient. Variables shown include Ta, Ts, PAR, RH, SWC, $RAIN$, NEE, GEP, GPP, and ER.

Table 2 Research findings of flux studies across different regions

Site	Climate type	Forest type and stand age	Research scale	Range of CO_2 flux variation / (mol · m^{-2} · s^{-1})	Research focus	Source
Jinyun Mountain, Chongqing(106°17′–106°24′E,29°41′–29°52′N)	Subtropical monsoonal humid climate	Mixed coniferous and broad-leaved forest(35 a)	Year-round	−22–8.64	Energy closure, flux characteristics, correlation analysis	[8]
Qilian Mountains, Qinghai(102°22′E, 37°08′N)	Plateau continental climate	Cold-temperate coniferous forest(60–70 a)	Growing season	−16.1–1.82	Flux characteristics, correlation analysis	[17]
Fengyang Mountain, Zhejiang(119.21°E, 27.93°N)	Subtropical warm humid climate	Mixed coniferous and broad-leaved forest(40 a)	Year-round	−11.4–19.1	Flux characteristics, correlation analysis	[18]
Dinghu Mountain, Guangdong(112°30′–112°33′E,23°09′–23°11′N)	Southern subtropical climate	Mixed coniferous and broad-leaved forest(76 a)	Year-round	−26.8–8.41	Flux characteristics, correlation analysis	[19]
Damaojian Mountain, Zhejiang(119.51°E, 28.58°N)	Subtropical monsoon climate	Mixed coniferous and broad-leaved forest	Year-round	−27.27–20.23	Energy closure, flux characteristics, correlation analysis	[20]

Site	Climate type	Forest type and stand age	Research scale	Range of CO_2 flux variation / (mol · m^{-2} · s^{-1})	Research focus	Source
Tianshan Mountains, Xinjiang(87°27′-87°29′E,43°24′-43°26′N)	Temperate continental climate	Cold-temperate coniferous forest	Year-round	−36.82-13.02	Flux characteristics, correlation analysis	This study

From the perspective of influencing factors, enhanced plant photosynthesis increases gross primary productivity and fixes more CO_2; a reduction in ecosystem respiration (ER) decreases the amount of CO_2 released to the atmosphere. Together, these two processes define the direction of NEE. Temperature is a key factor regulating the carbon-sink function of forest ecosystems [25–26]. This study likewise confirms this finding: at both daily and monthly scales, soil temperature (Ts) and air temperature (Ta) were significantly positively correlated with gross primary productivity (GPP) and ecosystem respiration (ER). This indicates that, when moisture conditions are suitable, high daytime temperatures directly promote photosynthesis and lead to a sharp increase in GPP, whereas abrupt nighttime cooling directly suppresses ER and causes it to decrease sharply [27]. Meanwhile, soil warming significantly promotes ER by enhancing plant respiration and microbial metabolism. These results are consistent with the findings of Zhu Jingbin [28] and Ping et al. [29].

Regression analysis showed that Ts and Ta were significantly negatively correlated with NEE, and that NEE was mainly driven by Ts [30]. This reveals that, under the conditions of this study, the promoting effect of temperature increase on GPP exceeded its promoting effect on ER, thereby causing the ecosystem carbon-sink capacity (i.e., an increase in the negative value of NEE) to strengthen with rising temperature. In addition, this temperature effect is condition-dependent: under drought stress, an increase in soil temperature (Ts) may intensify water evaporation, induce water stress, and indirectly inhibit GPP; in this case, the net effect of temperature on NEE may weaken or even reverse

31–32

. The relative contribution of RH was lower than that of temperature and photosynthetically active radiation, and RH was negatively correlated with NEE. On the one hand, an increase in RH raises stomatal conductance and increases GPP

33–34

; on the other hand, a decrease in RH suppresses microbial activity and weakens ER

35

. When the two act synergistically, the gain in photosynthetic carbon fixation and the reduction in respiratory carbon release form a positive superposition, driving NEE toward an enhanced carbon-sink state.

4 Conclusions

Based on carbon-flux data from the Tianshan Forest Ecosystem Station from January 2023 to May 2024, this study analyzed the dynamic variation of carbon fluxes and their influencing factors. The main conclusions are as follows:

(1) The *Picea schrenkiana* forest ecosystem on the northern slope of the middle Tianshan Mountains in Xinjiang exhibited a significant carbon-sink function, with an annual net carbon sink of 635.633 $\mu\text{mol} \cdot \text{m}^{-2}$. The diurnal variation in CO_2 flux showed a typical "U" -shaped distribution, with a daily mean range of -36.82 to 13.02 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

(2) In terms of spatial pattern, the flux contribution areas were mainly distributed to the northwest, northeast, and southwest, highly coinciding with the prevailing wind direction and areas of high vegetation coverage. This indicates that terrain-induced water redistribution and local microclimate play important regulatory roles in the spatial distribution of carbon fluxes.

(3) Soil temperature (Ts) was identified as the core environmental control factor for carbon source/sink transition in this system, and its increase significantly suppressed the intensities of both carbon sink and carbon source. The carbon-sink function was jointly regulated by air temperature (Ta) and soil water content (SWC); together, the three factors explained 50.4% of the variation in carbon flux. In addition, the regulatory mechanisms of environmental factors exhibited significant time-scale dependence: at the daily scale, NEE was mainly dominated by Ts, which regulated the diurnal

fluctuation of ecosystem respiration; at the monthly scale, NEE shifted to being jointly controlled by temperature and photosynthetically active radiation (PAR), reflecting the decisive influence of seasonal hydrothermal and light-temperature combinations on the carbon-sink pattern.

In summary, this multi-scale regulatory mechanism reveals the complexity of the responses of mountain forests in arid regions to moisture and thermal factors, and provides important scientific evidence for accurately assessing the carbon-sink potential of Tianshan forests under the background of climate change.

References

1

Wang J, Feng L, Palmer P I, et al. Large Chinese land carbon sink estimated from atmospheric carbon dioxide data

J

. Nature, 2020, 586(7831): 720-723.

2

Etheridge D M, Steele L P, Langenfelds R L, et al. Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn

J

. Journal of Geophysical Research-Atmospheres, 1996, 101(D2): 4115-4128.

3

WMO Greenhouse Gas Bulletin. The State of Greenhouse Gases in the Atmosphere Based on Global Observations Through 2021

R

. No.18, World Meteorological Organization, Geneva, 2022.

4

Nagy L, Eller C B, Mercado L M, et al. South American mountain ecosystems and global change–a case study for integrating theory and field observations for land surface modelling and ecosystem management

J

. Plant Ecology & Diversity, 2023, 16(1-2): 1-27.

5

Dainese M, Crepaz H, Bottarin R, et al. Global change experiments in mountain ecosystems: A systematic review

J

. Ecological Monographs, 2024, 94(4): e1632.

6

Chen Shiping, You Cuihai, Hu Zhongmin, et al. Eddy covariance technique and its applications in flux observations of terrestrial ecosystems

J

. Chinese Journal of Plant Ecology, 2020, 44(4): 291-304.

7

Wang Jingyu, Li Guodong, Ren Xiaojuan, et al. Carbon flux characteristics and responses to environmental factors in the evergreen-deciduous broadleaf mixed forest of the north-south transitional zone

J

. Acta Ecologica Sinica, 2024, 44(14): 6243-6253.

8

Wang Songnian, Wang Yunqi, Wang Kai, et al. Eddy covariance applicability and carbon flux variation characteristics of coniferous and broad-leaved mixed forests in Jinyun Mountain

J

. Forest Research, 2022, 35(4): 93-102.

9

Zhang Xin, Zhang Qiuliang, Sun Shoujia, et al. Carbon exchange

characteristics and their environmental effects in the northern forest ecosystem of the Greater Khingan Mountains in China[J]. Science of the Total Environment, 2022, 838: 156056.

[10] Zan Mei. Spatiotemporal variation characteristics of forest carbon fluxes and carbon stocks in Xinjiang and their main influencing factors[D]. Nanjing: Nanjing University, 2016. [Zan Mei. Dynamics of Carbon Fluxes and Stocks of Forests and Underlying Driving Factors in Xinjiang, China[D]. Nanjing: Nanjing University, 2016.]

[11] Qiu Xunxun, Cao Guangchao, Zhang Jinhu, et al. Distribution characteristics of carbon density in Qinghai spruce forests on the southern slope of the Qilian Mountains with altitude[J]. Arid Zone Research, 2023, 40(4): 615-622. [Qiu Xunxun, Cao Guangchao, Zhang Jinhu, et al. Distribution characteristics of carbon density in the arbor and soil layers of Qinghai spruce forest on the southern slope of Qilian Mountains with altitude[J]. Arid Zone Research, 2023, 40(4): 615-622.]

[12] Tian Shengchuan, Zhao Shanchao, Zheng Xinjun, et al. Water sources of *Picea schrenkiana* at different altitudes in the Tianshan Mountains during the growing season[J]. Arid Zone Research, 2023, 40(3): 436-444. [Tian Shengchuan, Zhao Shanchao, Zheng Xinjun, et al. Water source of spruce (*Picea schrenkiana*) at different altitudes in the Tianshan Mountains during the growing season[J]. Arid Zone Research, 2023, 40(3): 436-444.]

[13] Zhou Honghua, Chen Yaning, Zhu Chenggang, et al. Warming increases the carbon sequestration capacity of *Picea schrenkiana* in the Tianshan Mountains, China[J]. Forests, 2021, 12(8): 1066.

[14] Papale D, Reichstein M, Aubinet M, et al. Towards a standardized processing of net ecosystem exchange measured with eddy covariance technique: Algorithms and uncertainty estimation[J]. Biogeosciences, 2006, 3(4): 571-583.

[15] Song Ruipeng, Yang Qifan, Zheng Zhiheng, et al. Effects of three understory vegetation types on soil organic carbon and its component characteristics in *Cunninghamia lanceolata* plantations[J]. Ecology and Environmental Sciences, 2022, 31(12): 2283-2291. [Song Ruipeng, Yang Qifan, Zheng Zhiheng, et al. Effects of three understory vegetation types on soil organic carbon and its components in *Cunninghamia lanceolata* plantation[J]. Ecology and Environmental Sciences, 2022, 31(12): 2283-2291.]

[16] Wang Xingchang, Wang Chuankuan. A review of fundamental concepts and field measurement methods of carbon cycling in forest ecosystems[J]. Acta Ecologica Sinica, 2015, 35(13): 4241-4256. [Wang Xingchang, Wang Chuankuan. Fundamental concepts and field measurement methods of carbon cycling in forest ecosystems: A review[J]. Acta Ecologica Sinica, 2015, 35(13): 4241-4256.]

[17] Pei Weiwei, Yang Zhe, Wang Yunying, et al. Carbon sink characteristics and regulatory factors of Qinghai spruce forests in the Qilian Mountains[J]. Journal of Agricultural Science and Technology, 2024, 26(1): 226-233. [Pei Weiwei, Yang Zhe, Wang Yunying, et al. Carbon sink characteristics and regulatory factors of Qinghai spruce forests in the Qilian Mountains[J]. Journal of Agricultural Science and Technology, 2024, 26(1): 226-233.]

[18] Ji Xiaofang, Lu Jianbing, Yang Jun, et al. Variation characteristics of carbon flux and its influencing factors in a coniferous and broad-leaved mixed forest in Fengyang Mountain[J]. Journal of Northeast Forestry University, 2019, 47(3): 49-55. [Ji Xiaofang, Lu Jianbing, Yang Jun, et al. Carbon flux variation characteristics and its influencing factors in coniferous and broad-leaved mixed forest

in Fengyang Mountain[J]. Journal of Northeast Forestry University, 2019, 47(3): 49–55.]

[19] Huang Jun, Mai Boru, Deng Xuejiao, et al. Variation characteristics of CO_2 concentration and flux in a coniferous and broad-leaved mixed forest in Dinghu Mountain[J]. Guihaia, 2019, 39(2): 261-274. [Huang Jun, Mai Boru, Deng Xuejiao, et al. Characteristics of CO_2 flux and concentration in coniferous and broad-leaved mixed forest in Dinghu Mountain[J]. Guihaia, 2019, 39(2): 261–274.]

[20] Sun Yankun, Zhang Yinzhou, Yao Weijie, et al. Analysis of CO_2 flux characteristics in the evergreen broadleaf forest ecosystem of Damaojian Mountain, Zhejiang[J/OL]. China Environmental Science, 1–9[2025-11-03]. https://doi.org/10.19674/j.cnki.issn1000-6923.20240022.004. [Sun Yankun, Zhang Yinzhou, Yao Weijie, et al. Analysis of CO_2 flux characteristics in the evergreen broadleaf forest ecosystem of Damaojian Mountain, Zhejiang[J]. China Environmental Science, 1–9[2025-11-03]. https://doi.org/10.19674/j.cnki.issn1000-6923.20240022.004.]

[21] Zhang Kun, Wang Yu, Mamtimin Ali, et al. Variation characteristics and influencing mechanisms of CO_2 flux from grassland ecosystem in the central Tianshan Mountains, China[J]. Ecological Indicators, 2025, 170: 113069.

[22] Liu Xiaoman, Cheng Xueling, Hu Fei. Gradient characteristics of carbon dioxide concentration and flux in urban Beijing—Part I: concentration and virtual temperature[J]. Chinese Journal of Geophysics, 2015, 58(5): 1502–1512. [Liu Xiaoman, Cheng Xueling, Hu Fei. Gradient characteristics of CO_2 concentration and flux in Beijing urban area part I: Concentration and virtual temperature[J]. Chinese Journal of Geophysics, 2015, 58(5): 1502–1512.]

[23] Chang Mengdi, Wang Xinjun, Yan Linan, et al. Dynamic changes in the spatiotemporal pattern of vegetation cover and management-measure factors in the mountainous area of the middle section of the northern slope of the Tianshan Mountains[J]. Journal of Agricultural Resources and Environment, 2022, 39(4): 836–846. [Chang Mengdi, Wang Xinjun, Yan Linan, et al. Temporal and spatial pattern dynamic variations of vegetation cover and management factors in the middle of the northern slope of Tianshan Mountains[J]. Journal of Agricultural Resources and Environment, 2022, 39(4): 836–846.]

[24] Zhao Lu, Wang Xiaoke, Yao Yang, et al. Diurnal variation patterns of carbon flux and their influencing factors in a complex urban environment[J]. Acta Ecologica Sinica, 2023, 43(11): 4549–4560. [Zhao Lu, Wang Xiaoke, Yao Yang, et al. The diurnal variation and influencing factors of carbon dioxide fluxes in an urban complex area[J]. Acta Ecologica Sinica, 2023, 43(11): 4549–4560.]

[25] Ci Hui, Zhang Qiang, Zhang Jianghui, et al. Spatiotemporal characteristics of extreme precipitation events in Xinjiang from 1961 to 2010[J]. Geographical Research, 2015, 33(10): 1881–1991. [Ci Hui, Zhang Qiang, Zhang Jianghui, et

al. Spatiotemporal variations of extreme precipitation events within Xinjiang during 1961-2010[J]. Geographical Research, 2014, 33(10): 1881-1891.]

[26] Shi Yafeng, Shen Yongping, Hu Ruji. Preliminary discussion of the signals, impacts, and prospects of the climatic shift from warm-dry to warm-humid in Northwest China[J]. Journal of Glaciology and Geocryology, 2002, 24(3): 219-266. [Shi Yafeng, Shen Yongping, Hu Ruji. Preliminary study on signal, impact and foreground of climatic shift from warm-dry to warm-humid in Northwest China[J]. Journal of Glaciology and Geocryology, 2002, 24(3): 219-226.]

[27] Bruhn D. Activity-dependent nocturnal decrease in leaf respiration[J]. Plant Physiology, 2023, 191(4): 2167-2169.

[28] Zhu Jingbin, Zhang Fawei, Li Hongqin, et al. Response of growing-season CO_2 flux to the diurnal temperature range in an alpine meadow on the southern slope of the Qilian Mountains from 2002 to 2016[J]. Chinese Science Bulletin, 2021, 66(1): 85-95. [Zhu Jingbin, Zhang Fawei, Li Hongqin, et al. The response of CO_2 fluxes to the amplitude of diurnal temperature in alpine meadow during growing season from 2002 to 2016 at the

southern foot of Qilian Mountains[J]. Chinese Science Bulletin, 2021, 66(1): 85-95.]

[29] Ping Jiaye, Cui Erqian, Du Ying, et al. Enhanced causal effect of ecosystem photosynthesis on respiration during heatwaves[J]. Science Advances, 2023, 9(43): ead6395.

[30] Gao Yulian, Liu Jinbao, Liu Weiyang, et al. Study on the spatiotemporal variation characteristics of surface evapotranspiration and drought in the oasis region of southern Xinjiang over the past 14 years[J]. Arid Land Geography, 2019, 42(4): 830-837. [Gao Yulian, Liu Jinbao, Liu Weiyang, et al. The response of CO_2 fluxes to the amplitude of diurnal temperature in alpine meadow during growing season from 2002 to 2016 at the southern foot of Qilian Mountains[J]. Arid Land Geography, 2019, 42(4): 830-837.]

[31] Qu Ruosong, Liu Guanzhen, Yue Ming, et al. Soil temperature, microbial biomass and enzyme activity are the critical factors affecting soil respiration in different soil layers in Ziwuling Mountains, China[J]. Frontiers in Microbiology, 2023, 14: 1105723.

[32] Cheng Xiangfen, Zhou Yu, Hu Meijun, et al. The links between canopy solar-induced chlorophyll fluorescence and gross primary production responses to meteorological factors in the growing season in deciduous broadleaf forest[J]. Remote Sensing, 2021, 13(12): 2363.

[33] Wen Jingwen, Chen Haoxuan, Teng Yiping, et al. Variation patterns of leaf stomatal traits in *Quercus* species along an altitudinal gradient in Taibai Mountain[J]. Acta Ecologica Sinica, 2018, 38(18): 6712-6721. [Wen Jingwen, Chen Haoxuan, Teng Yiping, et al. Variation of leaf stomatal traits in Quercus species along the altitudinal gradient in Taibai Mountain, China[J]. Acta

Ecologica Sinica, 2018, 38(18): 6712-6721.]

[34] Lombardozzi D, Levis S, Bonan G, et al. Predicting photosynthesis and transpiration responses to ozone: Decoupling modeled photosynthesis and stomatal conductance[J]. Biogeosciences, 2012, 9(8): 3113-3130.

[35] Cruz-Paredes C, Tájmel D, Rousk J. Can moisture affect temperature dependences of microbial growth and respiration?[J]. Soil Biology and Biochemistry, 2021, 156: 108223.

Variation in carbon flux and its response to environmental factors in Schrenk spruce forests on the northern slopes of the central Tianshan Mountains

CUI Yirui1, JIANG Yan1, LI Jimei2,3, ZHANG Yutao2,3

(1. College of Agriculture, Shihezi University, Shihezi 832003, Xinjiang, China; 2. Institute of Forest Ecology, Xinjiang Academy of Forestry, Urumqi 830063, Xinjiang, China; 3. Xinjiang Tianshan Forest Ecosystem National Observation and Research Station, Urumqi 830000, Xinjiang, China)

Abstract: The Tianshan Mountains serve as a crucial ecological security barrier and carbon sequestration reservoir in western China. The forests in this area are dominated by *Picea schrenkiana*, which plays a key role in regional carbon storage and cycling and is thus a significant factor for the carbon balance in this region. To elucidate the variation in carbon flux in the Tianshan forest ecosystem as well as the influencing factors, we conducted continuous carbon flux measurements from 2023 to 2024 at the national positioning observation and research station of the Xinjiang Tianshan forest ecosystem using the eddy covariance technique. The key findings are as follows: (1) the *P. schrenkiana* forests on the northern slopes of the central Tianshan Mountains functioned as a net carbon sink, with an annual carbon sequestration rate of 635.633 $\mu\text{mol} \cdot \text{m}^{-2}$. The diurnal variation in CO_2 flux exhibited a U-shaped pattern, ranging from -36.82 to 13.02 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. (2) The flux footprint was predominantly concentrated between the northwestern and southwestern sectors, aligning with the prevailing wind direction and vegetation-covered area, indicating that the spatial flux distribution is co-regulated by both biological and meteorological factors. (3) Temperature was the key environmental factor regulating the carbon source/sink dynamics of this system. At the monthly scale, net ecosystem exchange (NEE) was primarily controlled by air temperature and photosynthetically active radiation. In contrast, at the diurnal scale, soil temperature governed NEE dynamics by regulating the diurnal rhythm of ecosystem respiration. This study provides critical information for accurately assessing the carbon sink capacity of the *P. schrenkiana*-dominated forest ecosystem in the

Tianshan Mountains.

Keywords: eddy covariance; *Picea schrenkiana*; carbon flux; environmental factors; Tianshan Mountains

Note: Figure translations are in progress. See original paper for figures.