Using Eddy Covariance Observations to Determine the Carbon Sequestration Characteristics of Subalpine Forests in the Qinghai-Tibet Plateau

Niu Zhu[1,2,4], Jinniu Wang[1,2], Dongliang Luo[3], Xufeng Wang[3], Cheng Shen[1,2], Ning Wu[1]

1 Chengdu Institute of Biology, Chinese Academy of Science, Chengdu 610041, China

2 Mangkang Ecological Monitoring Station, Tibet Ecological Security Barrier Ecological Monitoring Network, Qamdo 854500, China

3 Northwest Institute of Eco-environmental Resources, Chinese Academy of Sciences, Lanzhou 730000, China

4 College of Resources and Environmental Sciences, Gansu Agricultural University, Lanzhou 730070, China

Correspondence: Jinniu Wang (wangjn@cib.ac.cn)

Abstract: The subalpine forests are one of the crucial components in the carbon cycling system in the Qinghai-Tibet Plateau (QTP) in the context of climate change and ecosystem dynamics.~~The subalpine forests in the Qinghai-Tibet Plateau (QTP) act as carbon sinks in the context of climate change and ecosystem dynamics.~~ In this study, we investigated the carbon exchange dynamics for a subalpine forest on the QTP using the eddy covariance method from November 2020 to October 2022. We first revealed the seasonal characteristics of carbon dynamics in the subalpine forest, revealing the pattern of higher rates in summer and autumn and lower rates in winter and spring, and found that autumn is the peak period for carbon sequestration in the subalpine forest. Subsequently, we explored the climatic factors influencing the carbon sequestration function. The PCA analysis show that photosynthetically active radiation (PAR) was major climatic factor driving the net ecosystem exchange (NEE), significantly influencing forest and carbon absorption. The spatial distribution of NEE was significantly positively correlated with temperature, while the average annual precipitation shows a minor effect on NEE at the regional scale. At the annual scale, the subalpine forest was a strong carbon sink, with an average NEE of -342 g C m^{-2} (from November 2020 to October 2022). Despite the challenges caused by climate change, forests remain a robust carbon sink, currently, they are the ecosystems with the highest carbon sequestration capacity in the QTP, with an average annual CO_2 absorption rate of 368 gC m^{-2}. this study provides essential insights for understanding the carbon cycling mechanism in plateau ecosystems and the global carbon balance. We propose that, to positively influence global carbon cycling and promote "carbon neutrality and peak carbon," strengthening the protection and management of subalpine forests is crucial. Although our research has shown that these forest is currently playing a role in continuous carbon absorption, there are significant data gaps on the Qinghai-Tibetan Plateau. Therefore, it is essential to enhance continuous monitoring of forest carbon absorption processes in the future.~~In this study, we investigated the carbon sequestration function using the *in-situ* observations from an eddy covariance system for the subalpine forests. With two-year contiguous observations, the factors driving the seasonal variations in carbon sequestration potential were quantified. We first revealed the seasonal characteristics of carbon dynamics in the subalpine forests during the growing and dormant seasons, respectively. The diurnal carbon exchange exhibited significant fluctuations, as high as 10.78 μmol CO_2 s^{-1} m^{-2}~~

~~(12:30, autumn). The period from summer to autumn was identified as the peak in carbon sequestration rate in the subalpine forests. Subsequently, we explored the climatic factors influencing the carbon sequestration function. Photosynthetically active radiation (PAR) was found to be a major climatic factor driving the net ecosystem exchange (NEE) within the same season, significantly influencing forest growth and carbon absorption. Increasing altitude negatively impacts carbon absorption at the regional scale and the rising annual temperature significantly enhances carbon uptake, while the average annual precipitation shows a minor effect on NEE. At the annual scale, the observations at the subalpine forests demonstrated a strong carbon sequestration capability, with an average NEE of 389.03 g C m^{-2}. Furthermore, we roughly assessed the carbon sequestration status of subalpine forests in the QTP. Despite challenges caused by climate change, these forests possess enormous carbon sequestration potential. Currently, they represent the most robust carbon sequestration ecosystem in the QTP. We conclude that enhancing the protection and management of subalpine forests under future climate change scenarios will positively impact global carbon cycling and contribute to climate change mitigation. Moreover, this study provides essential insights for understanding the carbon cycling mechanism in plateau ecosystems and global carbon balance.~~

Keywords: Subalpine forest; Qinghai-Tibet Plateau; The eddy covariance system; Three Parallel Rivers Region; Carbon sinks

1 Introduction

Carbon dioxide (CO_2) is a prominent greenhouse gas, and its atmospheric concentration has reached an unprecedented high level in recent years, in May 2021, a recorded peak of 419 parts per million (ppm) was observed at the Mauna Loa Observatory in Hawaii (Stein, 2021).~~with a recorded peak of 419 parts per million (ppm).~~ The global atmospheric CO_2 concentration is rapidly increasing at a rate of 2 to 3 ppm per year， compared to pre-industrial levels, the average global temperature has already risen by 1.1°C by 2019 (World Meteorological Organization, 2019). Human activities have been the primary catalyst behind the significant surge in atmospheric CO_2 concentrations (Schweizer et al., 2020).~~Extensive research conducted by numerous scholars has consistently demonstrated that human activities have been the primary catalyst behind the significant surge in atmospheric CO_2 concentrations since the 18th century~~

~~(Stein, 2021).~~ CO_2 and CH_4 collectively contribute approximately 70% to the global warming potential among the six greenhouse gases specified in the Kyoto Protocol (Zhang et al., 2022). As atmospheric CO_2 concentrations continue to rise, global climate warming is gradually intensifying. Therefore, The Paris Agreement urges national governments to restrict the increase in global average temperature to well below 2.0 °C above pre-industrial levels and to strive to limit it to 1.5 °C. The increasing atmospheric CO_2 levels will lead to irreversible ecological disasters. For instance, the concentration of CO_2 in the atmosphere is projected to double within approximately 50 years if global consumption of fossil fuels continues to rise at the current rate~~, the concentration of CO_2 in the atmosphere is projected to double within approximately 50 years. The rise in temperatures at 80°S latitude could result in the melting of glaciers, leading to a sea-level rise of 5 m (Mercer, 1978). By the year 2040, most countries are projected to experience at least one annual disaster with a 50% or higher probability (Fortunato et al., 2022)~~. Addressing the greenhouse effect caused by carbon dioxide and reducing its impact is a crucial challenge facing human society today. Reducing regional carbon emissions or per capita carbon emissions is widely regarded as an effective approach to carbon reduction (Wang et al., 2023a). Nevertheless, countries around the world have already begun to commit to carbon reduction and carbon neutrality efforts. On September 22, 2020, during the 75th session of the United Nations General Assembly, the Chinese government announced "double carbon" goals, which aim to achieve carbon emission peaking by 2030 and carbon neutrality by 2060, in alignment with ecological conservation and sustainable development objectives (Yu, 2022). It is predicted that China's average forest carbon sequestration rate will reach 0.358 Pg C $year^{-1}$ (petagrams of carbon per year) by 2060 (Cai et al., 2022). This significant rate of carbon sequestration is expected to have a substantial impact on the environment and economy, providing negative feedback to global warming (Pan et al., 2011).

Currently, there are various methods available to accurately quantify the carbon sequestration potential of forests, each with its advantages and disadvantages.~~Forests cover approximately 30% of the earth's land surface and store around 90% of the terrestrial vegetation carbon (Le Quéré et al., 2018). However, currently, there is no method available to accurately quantify the carbon sequestration potential of forests.~~ Quantitative estimation of carbon sequestration potential still requires scientists to establish more *in-situ* sites and generate comprehensive datasets to assess a wide range of areas. Initially, individuals' biomass measurements were used to estimate forest carbon sequestration capacity (Ebermayer, 1876). However, this method was time-consuming, labor-intensive, and prone to inaccuracies due to the omission of various variables during the calculation process. The development of modeling techniques allowed for the use of simulation methods - forest management models and land ecosystem-climate interaction models, such as the Ecological Assimilation of Land and Climate Observation (EALCO), have been widely applied in this regard (Landsberg and Waring, 1997; Wang et al., 2001). Currently, remote sensing monitoring and the eddy covariance method are widely used. Remote sensing techniques can be used to extract vegetation parameters (such as NDVI) from multispectral bands and estimate the carbon sequestration of entire forests through regression analysis (Laurin et al., 2014). The eddy covariance (EC) method, allowing continuous, long-term carbon flux calculation, provides fundamental data for model establishment and calibration. It is widely applied across ecosystems, including urban areas, farmlands, grasslands, forests, and water bodies (Konopka et al., 2021; Vote et al., 2015; Du et al., 2022a; Kondo et al., 2017; Li et al., 2022).~~The theoretical foundation of the eddy covariance method was initially proposed by Swibank et al., (Swinbank, 1951). It started to be applied in carbon flux studies of forest ecosystems in the 1980s (Anderson et al., 1984). Nowadays, this method not only accurately measures the carbon exchange between forests and the atmosphere but also integrates other instruments to measure meteorological variables such as light intensity and temperature. It allows for long-term and continuous calculation of carbon flux between forests and the atmosphere. Additionally, it provides fundamental data for establishing and calibrating other models. The eddy covariance method has been widely applied in various ecosystems, including urban areas (Konopka et al., 2021), farmlands (Vote et al., 2015), grasslands (Du et al., 2022a), forests (Kondo et al., 2017), and water bodies (Li et al., 2022).~~

The forest ecosystem's Net ecosystem exchange (NEE) of carbon dioxide is influenced by multiple environmental factors~~Net Ecosystem Exchange (NEE) of carbon dioxide is a fundamental parameter in the biogeochemical feedback of the climate system (Graf et al., 2013). The carbon flux in forest ecosystems is influenced by multiple environmental factors~~. Previous studies have shown that NEE is significantly influenced by air temperature (AT), photosynthetically active radiation (PAR), vapor pressure deficit (VPD), relative humidity (RH), and soil temperature (ST) (Liu et al., 2022). For instance, temperature variables, especially annual or seasonal average temperature variations, serve as the optimal single predictor for carbon flux, explaining variations in carbon flux between 19% and 71% (Banbury Morgan et al., 2021). Photosynthetically active radiation not only influences the absorption of carbon dioxide by the forest canopy but also affects the utilization of carbohydrates by roots due to its association with canopy processes and soil respiration (Baumgartner et al., 2020). Furthermore, research suggests that the NEE is influenced by biotic factors such as NDVI (Normalized Difference Vegetation Index) and LAI (Leaf Area Index) (Tang et al., 2022). Given the projected future global warming trends, the role of forests as a vast carbon reservoir becomes highly significant and worthy of attention. The Qinghai-Tibet Plateau (QTP) is the highest and largest plateau in the world, with an extensive area of alpine forests covering approximately 2.3×10^5 km^2. These forests hold tremendous economic and ecological benefits. The southeastern region of the QTP boasts one of the world's highest-altitude alpine forest ecosystems. Research indicates that the alpine forest ecosystem in this area has a remarkable capacity to consume methane, reaching up to 5.06 kg ha^{-1} yr^{-1}, and playing a significant role in mitigating the impact of greenhouse gases (Qu et al., 2023). Since the 1960s, the QTP has experienced a faster warming rate than lowland areas. It is projected that this phenomenon will be intensified by the end of the 21^{st} century (Li et al., 2019). Currently, the QTP is considered a weak carbon sink at the overall level, but the carbon source-sink dynamics vary among different ecosystems (Chen et al., 2022). For instance, most lakes in the QTP are currently characterized by supersaturated CO_2 levels (Cole et al., 1994). Mu et al. (2023) found that the thermokarst lakes serve as significant carbon sources through carbon flux measurements in 163 thermokarst lakes during the summer and autumn seasons. Wang et al. (2021) discovered that these ecosystems act as sinks for carbon dioxide by comparing carbon fluxes in ten high-mountain ecosystems with different grassland types. Wang et al.(2021), discovered that these ecosystems act as sinks for carbon dioxide in their study comparing carbon fluxes in ten high-mountain ecosystems with different grassland types. The alpine meadows in the eastern QTP were identified as strong carbon sinks, with the highest annual average NEE recorded at -284 g C m^{-2}. Forest ecosystems play a crucial role in the south-eastern edge of the QTP, providing important support for climate regulation and forestry-based economic activities. Moreover, recent predictive studies suggest that under both current and future climate scenarios, the forested area in this region is expected to expand further, with coniferous forests continuing to grow into higher altitudes (Liu et al., 2021). Due to the extensive presence of permafrost in the QTP, forest net primary productivity exhibits a most pronounced response to surface temperatures in the continuous permafrost zone over multiple years. Therefore, the changes in permafrost in the QTP should not be overlooked, as they also have a significant impact on carbon absorption by forests (Mao et al., 2015). However, the QTP is a vast region with a widespread distribution of high-altitude and subalpine forests. Researchers need to conduct long-term monitoring to understand how these forests will respond to climate change. Furthermore, there is a significant data gap concerning the monitoring of carbon exchange capacity in the forests of the QTP, indicating the need for further data collection efforts. Based on this, we have established a carbon flux monitoring site in the subalpine ecosystem of the Three Parallel Rivers Region, which is located on the south-eastern edge of the QTP and lies in the transitional zone between the QTP and the Yunnan-Kweichow Plateau and is renowned as a global hotspot for biodiversity (Wang et al., 2022). Our research objectives are as follows:

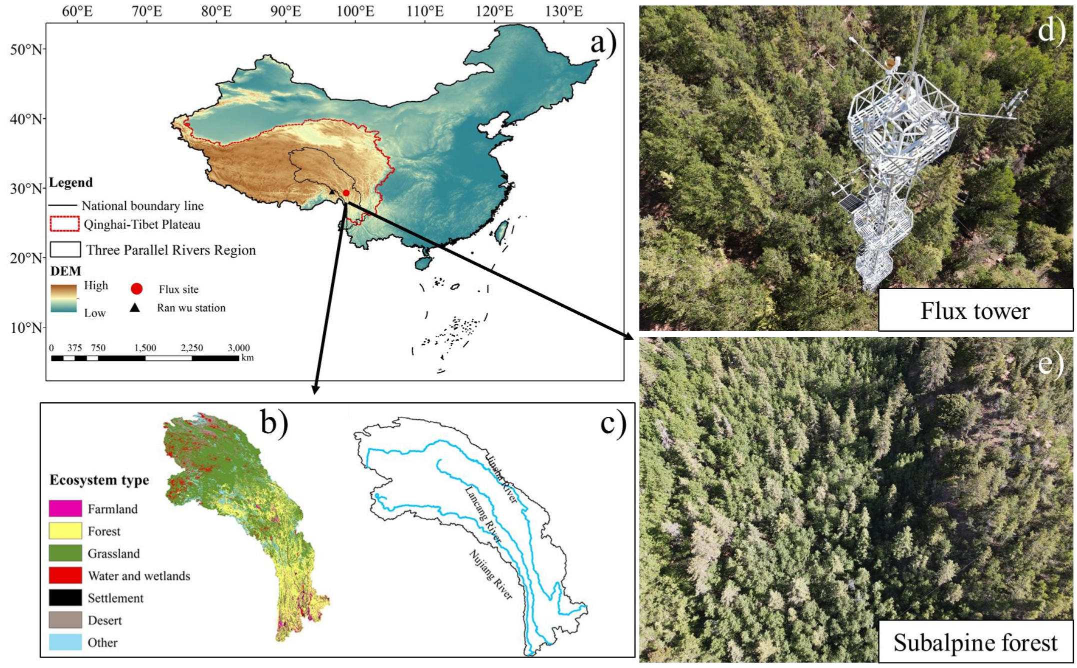
1) Determine whether the subalpine forests in the Three Parallel Rivers Region act as a carbon sink or source, and quantify the annual uptake or release of carbon dioxide;
2) Investigate the main environmental factors influencing the carbon exchange process in the subalpine forests and identify the factors with the greatest impact;
3) Since the carbon sink potential of forest ecosystems in the QTP is currently unknown, we evaluated the carbon exchange capacity of subalpine forests by comparing existing data with other ecosystems in the QTP.~~Assess the carbon exchange capacity of the subalpine forests in comparison to other ecosystems of the QTP.~~

This study will provide a data foundation and background support for accurately estimating the carbon balance of forests in high-altitude areas and for model simulations in the future.

2 Materials and Methods

2.1 Overview of the study site

The study site is located in the Hongla Mountain Yunnan Snub-nosed Monkey National Nature Reserve in Mangkang County, Tibet, China (29.28633°N, 98.69096°E), the core area of the Three Parallel Rivers (Nujiang River, Lancang River, and Jinsha River) Region. The elevation of the study site is 3755 m. The observation period was from November 2020 to October 2022. The study area experiences large diurnal temperature variations and dry conditions in winter, while the summers are warm and humid. ~~The climate of the region is characterized as a typical mountainous climate.~~ The average daily sunshine duration exceeds 10 h, with an annual average temperature of 5 °C and an average annual precipitation of around 600 mm (Niu et al., 2023). The main tree species in the area include *Picea likiangensis var. rubescens, Abies squamata, Sabina tibetica Kom,* and *Abies ernestii*. They are accompanied by the growth of some *Quercus aquifolioides, Rhododendron lapponicum,* and *Potentilla fruticosa* shrubs. The average height of the trees is below 30 meters, and the forest is in a relatively active growth phase, reaching the state of a mature forest. The vegetation coverage ranges from 70% to 80%.~~The vegetation coverage ranges from 70% to 80%, indicating rich vegetation resources.~~ The dominant soil type is yellow-brown soil. The mountainous terrain contributes to distinct vertical climate characteristics and significant variations in water and heat conditions. Characterized by numerous dry and hot river valleys and widespread distribution of canyons, the climate in the study area exhibits a clear impact from the southwest and southeast monsoons. The varying elevations give rise to diverse ecosystems, transitioning from alpine forests to mountain shrubs, and above 4000 meters, high alpine grasslands and meadows, forming a noticeable vegetation transition zone. The mountainous topography results in evident vertical climate features and significant fluctuations in water and heat conditions, with precipitation showing a pronouncedly uneven distribution throughout the region (Zemin et al., 2023).~~The study site is located in the core area of the Three Parallel Rivers (Nujiang River, Lancang River, and Jinsha River) Region. The area exhibits a complex and diverse climatic environment influenced by the southwest and southeast monsoon. The mountainous terrain contributes to distinct vertical climate characteristics and significant variations in water and heat conditions. The region is characterized by numerous dry and hot river valleys and widespread distribution of canyons.~~



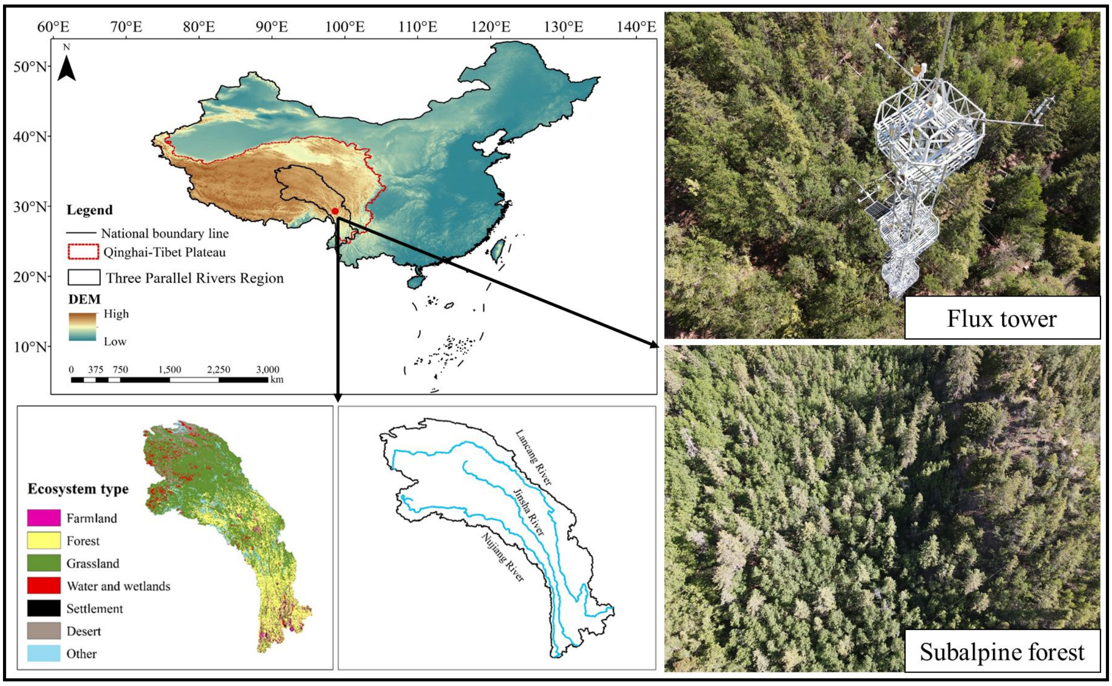


Figure 1. location of the flux site **(a)**. Ecosystem types **(b)** and main rivers **(c)** in Three Parallel Rivers Region. Flux tower **(d)** and forest top view **(e)**. (The national boundary range in the figure was retrieved from the http://bzdt.ch.mnr.gov.cn, elevation data, and ecosystem type from www.gscloud.cn.)~~Figure 1 Overview of the study area (The national boundary range in the figure comes from the http://bzdt.ch.mnr.gov.cn, elevation data from www.gscloud.cn.)~~

2.2 Eddy covariance system

The flux data in this study were collected from a 35 m-high tower located at the study site.The flux data in this study were collected from a 35 m-high tower located at the study site. At the top of the tower, a 3-D wind velocity (Wind Master, Gill, UK) and an open-path infrared CO_2/H_2O analyzer (LI-7500DS, Li-Cor, USA) were installed to measure CO_2 flux. The instruments had a measurement frequency of 10 Hz.The instruments had a response frequency of 10 Hz. Additionally, micro-meteorological sensors were placed at different heights on the tower, including sensors at 15 m for observing air temperature and humidity (HMP155A, Vaisala, Finland), sensors at -5 cm for soil temperature (TEROS11, LI-Cor, USA), and sensors at 35 m for photosynthetically active radiation (LI-190R, LI-Cor, USA),including sensors for observing air temperature and humidity (HMP155A, Vaisala, Finland), soil temperature (TEROS11, LI-Cor, USA), and photosynthetically active radiation (LI-190R, LI-Cor, USA), among other environmental variables. All data were recorded at 30-m intervals and stored in a SmartFlux 3 data logger (Li-Cor, USA) for future download.

2.3 Data processing and quality control

When considering only the turbulent transport of matter and energy in the vertical direction, the carbon dioxide flux (Fc) can be represented by the following equation (Yu and Sun, 2006; Monteith et al., 1994):Turbulent transport is the primary form of gas exchange between the near-surface and the atmosphere. In the case of a homogeneous and flat underlying surface, considering only the turbulent transport of substances in the vertical direction, the CO_2 flux *Fc* (μmol m^{-2} s^{-1} or mg m^{-2} s^{-1}) within the region can be calculated using the following.

$$F_C = \overline{W' \mathrm{CO}_2'} \quad (1)$$

Where *W'* is the vertical component of 3-D wind speed fluctuations (m s^{-1}), and CO_2' represents the fluctuations in measured CO_2 mole concentration. A positive Fc indicates carbon emissions, while a negative value represents carbon uptake.Where *W'* represents the vertical component of 3-D wind speed fluctuations (m/s), CO_2' represents the fluctuations in measured CO_2 mole concentration (μmol m^{-3}), and the overline denotes the average value over a half-hour time period. A positive value of Fc indicates carbon emissions from the underlying surface during the given time interval, while a negative value represents carbon uptake.

The acquired 10 Hz raw data was processed and corrected using the EddyPro software (EddyPro 7.06, Li-Cor, USA). The calibration process~~correction process~~ involved outlier detection for flux data, lag elimination, coordinate rotation (Jia et al., 2020), ultrasonic temperature correction (Schotanus et al., 1983), frequency correction (Moncrieff et al., 1997), and Webb-Pearman-Leuning (WPL) correction (Leuning and King, 1992), After these controls, the integrity of the effective FC raw valid data we obtained reached 92.95 %. We removed outliers caused by environmental disturbances such as power outages, rain, snow, and dust particles that interfered with the instrument. Due to the slope of the underlying surface being around 5 degrees, we also corrected from non-uniform and non-flat surfaces using EddyPro for double coordinate rotation (Cao et al., 2019). ~~We also corrected errors resulting from non-uniform and non-flat underlying surfaces (Cao et al., 2019).~~As a result, we obtained half-hourly flux data with associated data quality indicators. To evaluate the turbulence steadiness, we employed the "0-1-2" quality assessment method, which classified flux results into three quality levels: 0 for excellent data quality, 1 for moderate data quality, and 2 for low data quality (Mauder and Foken, 2011; Foken et al., 2005)~~(Mauder and Foken, 2011)~~. We removed data points labeled with a quality level of "2". We further eliminated flux data with negative values during nighttime since plants do not perform photosynthesis at night. Additionally, we conducted spectral analysis to identify and remove data points with values significantly deviating from normal. Finally, friction velocities (u*) for each of the two years were determined separately using the method of moving point, and deleted data recorded during nighttime when u* was less than 0.28 and 0.39 m s^{-1} (Reichstein et al., 2005). After excluding outliers from the data, the data integrity is 72.67%. Tovi software (Tovi, Li-Cor, USA) was used in the process.~~Finally, we utilized the friction velocity (U*) as a criterion and deleted data recorded during nighttime when U* was less than 0.28 and 0.39 m s^{-1} (Papale et al., 2006).~~

When turbulence is weak, a portion of CO_2 is stored in the vegetation canopy and the atmosphere below the measurement height. At this time, the NEE is calculated as (Zhang et al., 2018):~~NEE of CO_2 can be represented by the following:~~

$$\mathrm{NEE} = F_C + F_S \quad (2)$$

Where NEE represents the net ecosystem exchange of CO_2, F_C stands for the observed flux during a specific period, F_S represents the CO_2 storage in the forest canopy, F_S is calculated as $(\Delta c/\Delta t)\cdot h$, where Δc is the difference in CO_2 concentration between two consecutive measurements, Δt is the time interval between two consecutive measurements, and h is 35m.

We adopted the following formula as a gap-filling strategy for daytime NEE (NEE_{day}) concerning PAR, aiming to address missing values during the daytime (Falge et al., 2001):

~~Where NEE represents the net ecosystem exchange of CO_2, F_C stands for the observed flux during a specific time period, F_S represents the CO_2 storage in the forest canopy, which is assumed to be zero in this case.~~

~~We used the Michaelis-Menten model to fit the daytime NEE (NEE_{day}) with respect to PAR to fill in the missing values during the daytime (Falge et al., 2001):~~

$$NEE_{day} = \frac{\alpha \cdot PAR \cdot P_{max}}{\alpha \cdot PAR + P_{max}} - R_{day} \quad (3)$$

where: a (μmol CO_2/μmol PAR) represents the apparent photosynthetic quantum efficiency, which characterizes the maximum efficiency of converting light energy during photosynthesis. PAR (μmol m^{-2} s^{-1}) is the photosynthetically active radiation, a measure of the amount of light energy available for photosynthesis. P_{max} (μmol CO_2 m^{-2} s^{-1}) is the apparent maximum photosynthetic rate, representing the maximum CO_2 uptake rate under optimal conditions. R_{day} (μmol CO_2 m^{-2} s^{-1}) is the daytime dark respiration rate, which denotes the rate of CO_2 release during daylight hours. The parameters α,~~a,~~ P_{max}, and R_{day} are obtained through the non-linear fitting of the Michaelis-Menten model to the observed data.

During the nighttime, the NEE is modeled using an exponential function of ecosystem respiration~~respiration~~ and soil temperature to fill in the missing values of NEE during the night (NEE_{night}) (Lloyd and Taylor, 1994; Kato et al., 2006):

$$NEE_{night} = a \cdot \exp^{(bt)} \quad (4)$$

The parameters *a* and *b* are estimated values for the exponential function used in modeling NEE_{night}. The variable *t* represents the soil temperature measured at the depth of 5 cm. Origin 2023 (Originlab Corporation, USA) is the data processing software used for this analysis. For the missing data, interpolation was performed using Tovi software allows for data interpolation to fill in the gapsThe data processing software used for this analysis is Origin 2023 (Originlab Corporation, USA). For the missing data, interpolation was performed using Tovi software (Tovi, Li-Cor, USA) that allows for data interpolation to fill in the gaps and ensure a continuous dataset for further analysis (Reichstein et al., 2005). 27.33% of missing data were interpolated, The final flux data achieved a data integrity of 100%.

In flux analysis, the significance of source area contributions cannot be overlooked. In this study, the peak distances of the 90% flux contribution areas averaged over two years are 364.2 and 357.1m, respectively. Looking at seasons, the average peak distances of the 90% flux contribution areas for winter, spring, summer, and autumn over the two years are 353.9, 358.2, 350.05, and 344.34m, respectively.

2.4 Flux partitioningFlux splitting

Ecosystem respiration (RE) is the sum of plant and heterotrophic respiration in an ecosystem and is obtained by adding the measured nighttime data to the extrapolated daytime data. Gross primary productivity (GPP) is the total amount of organic carbon fixed by green plants through photosynthesis per unit of time and per unit of area:

$$RE=R_{day}+R_{night} \quad (5)$$

$$GPP=-NEE+RE \quad (6)$$

Carbon use efficiency (CUE) is a crucial parameter that reflects the ability of an ecosystem to sequester carbon. It is defined as the ratio of net ecosystem productivity (NEP) to gross primary productivity.It is defined as the ratio of net primary productivity to gross primary productivity. CUE can be expressed using the following equation:

$$CUE=\frac{NEP}{GPP}=\frac{-NEE}{GPP} \quad (7)$$

To study the variation of ecosystem respiration rates with environmental factorsenvironmental conditions, we considered the dependence of nocturnal ecosystem respiration on soil temperature (Pavelka et al., 2007; Mamkin et al., 2023):

$$Q_{10}=\exp(10\cdot\alpha) \quad (8)$$

$$\ln(NEE_{night})=\alpha\cdot T+\gamma \quad (9)$$

Where T is the soil temperature (◦C) and γ is an empirical parameter of the equation.

To clarify the carbon sink potential of forests in the QTP and to compare it with other ecosystems, a search was conducted in two authoritative databases, Web of Science and China National Knowledge Internet, for research articles on the current utilization of EC systems in the QTP. A total of 82 research results were collected from 48 studies, and their annual average environmental factors, such as air temperature, precipitation, and altitude, were obtained.

3 Results

3.1 Daily average changes in main environmental factors

During the observational period, the environmental conditions exhibited significant fluctuations. The winter and spring seasons were characterized by cold and dry conditions, while the summer and autumn seasons were warm and humid. The daily maximum air temperature (AT) recorded was 15.87 °C (on June 15, 2021), and the minimum temperature was -9.88 °C (on January 17, 2022), with an average of 5.5 °C over the two years. The relative humidity (RH) with an annual average of 55.89%. The vapor pressure deficit (VPD) with an annual average of 4.46 hPa. Soil temperature (ST) exhibited a similar trend to air temperature. The highest observed soil temperature was 13.53 °C (on June 27, 2021), while the minimum was -3.78 °C (on January 18, 2022), with an annual average of 6.11 °C. Photosynthetically active radiation (PAR) with an annual average of 447.24 mol m^{-2} s^{-1}.~~The relative humidity (RH) ranged from a maximum of 93.98% (on August 26, 2021) to a minimum of 6.74% (on April 29, 2021), with an annual average of 55.89%. The vapor pressure deficit (VPD), which represents the difference between the saturated vapor pressure and the actual vapor pressure in the air, influences plant stomatal closure and regulates physiological processes such as transpiration and photosynthesis. The highest recorded VPD was 1169.8 hPa (on July 5, 2022), and the lowest one was 60.8 hPa (on August 26, 2021), with an annual average of 446.4 hPa. Soil temperature (ST) exhibited a similar trend to air temperature and remained relatively stable over short periods. The highest observed soil temperature was 13.53 °C (on June 27, 2021), while the minimum was -3.78 °C (on January 18, 2022), with an annual average of 6.11 °C. Photosynthetically active radiation (PAR) reached a maximum value of 779.06 mol m^{-2} s^{-1} (on June 2, 2021), with an annual average of 447.24 mol m^{-2} s^{-1}. From March to October, the radiation conditions were favorable for photosynthesis, but reduction in radiation intensity was observed during rainy, snowy, and cloudy weather conditions.~~

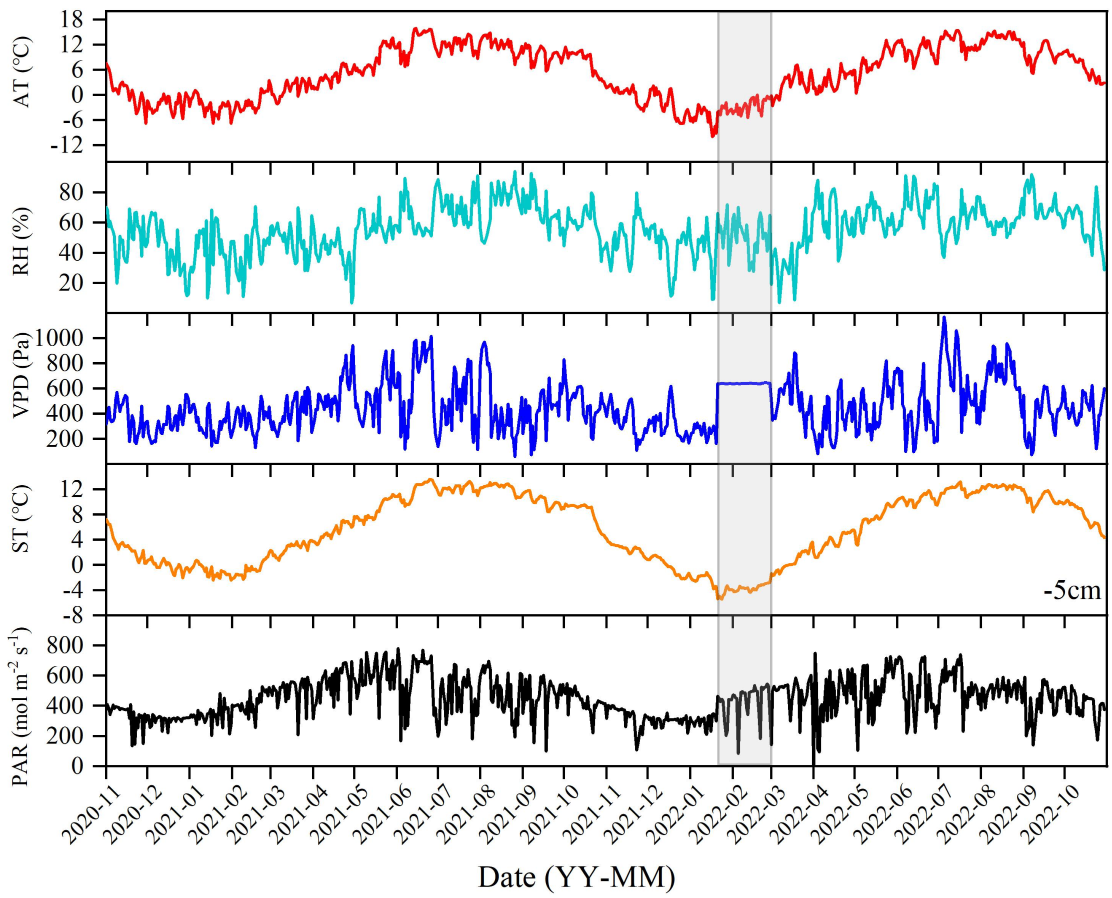
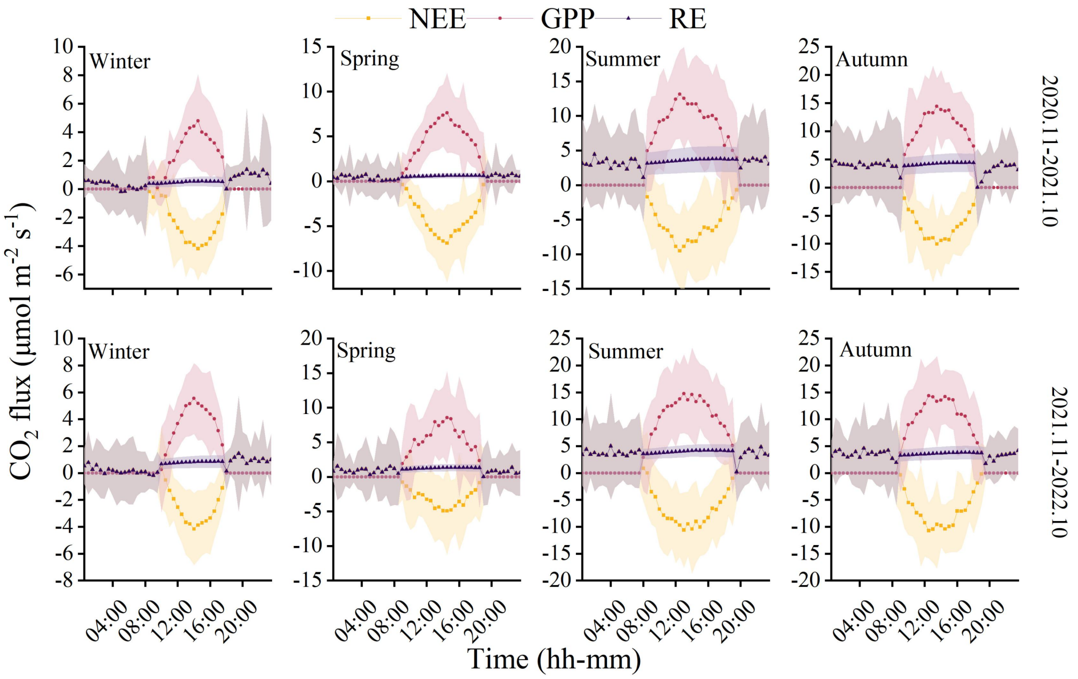


Figure 2. Daily values of main environmental factors, air temperature (AT), relative humidity (RH), vapor pressure deficit (VPD), soil temperature (ST), and Photosynthetically active radiation (PAR). (The data of the shadow part in the figure comes from the Ranwu forest site (Figure 1). Since there was no interpolated data source for VPD, the annual average was used instead.)~~(The shaded part of the figure represents the data interpolated by the nearby station)~~

3.2 The seasonal variations in NEE, RE, and GPP

The observations from the forest ecosystem indicate distinct diurnal and seasonal variations in NEE and GPP. The NEE and GPP exhibit a pronounced U-shaped curve, with significant seasonal differences. The summer and autumn are characterized by peak carbon uptake, with the maximum NEE reaching~~ -10.78 umol CO_2 m^{-2} s^{-1} (12:30, autumn)~~. During the nighttime, the ecosystem generally releases carbon, while during favorable daytime meteorological conditions, it demonstrates a carbon uptake capacity. The peak carbon absorption of the forest ecosystem occurs from 12:00 to 15:00 (Beijing time, UTC+8:00)~~(Beijing time, UTC+8:00)~~. daily carbon sequestration~~The carbon sequestration period~~ in summer and autumn is 1.5-3 hrs longer than in winter. The timing of maximum carbon sequestration capacity changes with each season. In winter, the transition from nighttime carbon release to daytime carbon uptake occurs around 08:30, which is approximately 1 hour later than in summer. GPP characterizes the forest's carbon sequestration capacity, and since photosynthesis does not occur at night, GPP is zero during nighttime. The maximum daily total productivity is recorded at 14.76 ± 7.34 μmol CO_2 m^{-2} s^{-1} during the summer of the second year, with a standard deviation indicating greater variability in GPP and NEE during the summer and autumn compared to the winter and spring. Although diurnal variations in RE are relatively small, there are significant seasonal differences. During the night, when only respiration occurs, RE equals NEE. However, as photosynthesis becomes active during the day, RE gradually increases and stabilizes. The respiratory rate of the coniferous forest is highest in autumn, being eight times greater than in winter.~~In winter, the transition from nighttime carbon release to daytime carbon uptake occurs around 08:30, while in summer, it shifts to around 07:30 (Beijing time, UTC+8:00). GPP reflects the carbon sequestration capacity of the forest, with the recorded daily total productivity highest at 14.76 umol CO_2 m^{-2} s^{-1} during summer season of second year, RE exhibits minor diurnal variations but shows significant seasonal differences, with maximum and minimum diurnal RE values of 0.73 umol CO_2 m^{-2} s^{-1} and 0.17 umol CO_2 m^{-2} s^{-1}, respectively. The respiration rate of the coniferous forest during the summer and autumn is 5-8 times higher than that in the winter and spring.~~



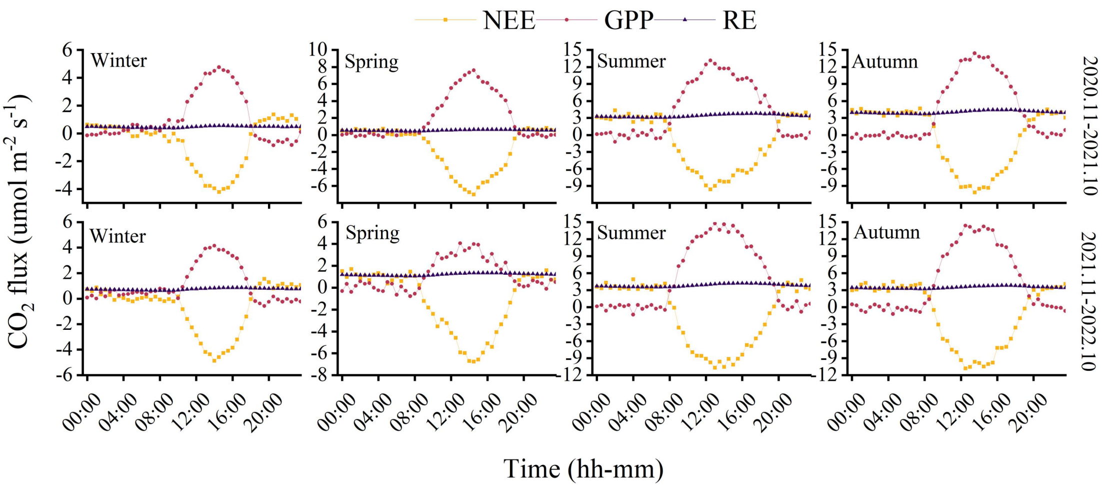
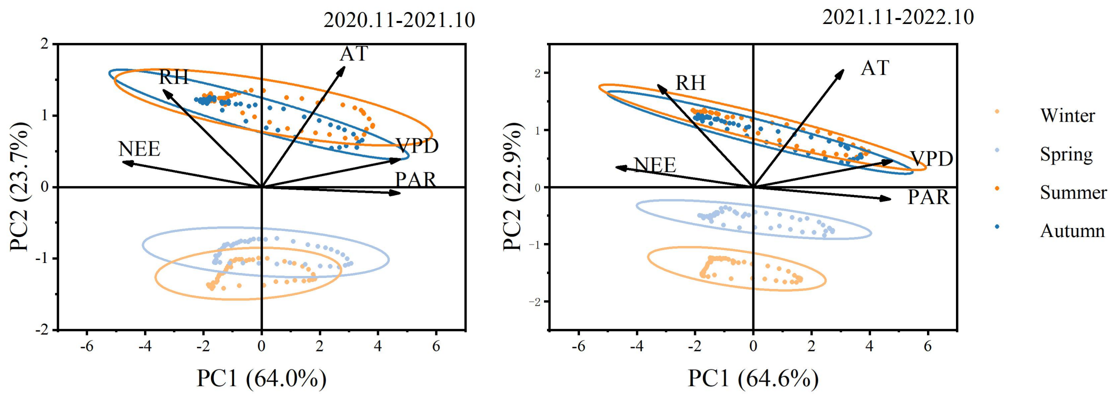


Figure 3. Monthly mean values of carbon fluxes~~Figure 3 The monthly variations in carbon fluxes~~

3.3 Relationship between NEE and main environmental factors

The PCA analysis of two years of NEE and environmental factors (Figure 4) indicates that the explanations for the first principal component (PC1) and the second principal component (PC2) are essentially the same between the two years. The total contributions of PC1 and PC2 are 87.7% and 87.5%, respectively, with PC1 accounting for 64.0% and 64.6% individually. The angle between photosynthetically active radiation (PAR) and PC1 is minimal, suggesting a strong correlation between PAR and PC1. Additionally, PAR and VPD contribute the most to PC1, while AT and RH contribute the most to PC2. The analysis results reveal a significant positive correlation between NEE and RH, while a significant negative correlation is observed with AT, VPD, and PAR. This implies that an increase in RH is unfavorable for the forest's absorption of carbon dioxide. Among these environmental factors, PAR plays a dominant role. Furthermore, the figure illustrates the relationships between environmental factors, showing a positive correlation between RH and TA, and a negative correlation with VPD and APR. The indicators exhibit some seasonality, with notable differences between the winter-spring and summer-autumn seasons, indicating limited similarity between seasons.The fitting results between NEE and environmental factors indicate that the selected environmental factors have a significant impact on NEE (*P*<0.001) (Figure 4). However, the influence of individual environmental factors on NEE varies across different seasons. RH has the smallest impact on NEE during the summer, while AT, VPD, and PAR exhibit the strongest influence on NEE during the autumn. These factors consistently have the least impact on NEE during autumn. In the same season, PAR primarily controls NEE, with an R^2 value reaching up to 0.957. Positive values of NEE indicate carbon emissions, while negative values indicate carbon uptake. Therefore, air temperature, vapor pressure deficit, and PAR all have a significant positive effect on carbon uptake, while an increase in humidity leads to a noticeable reduction in carbon uptake.



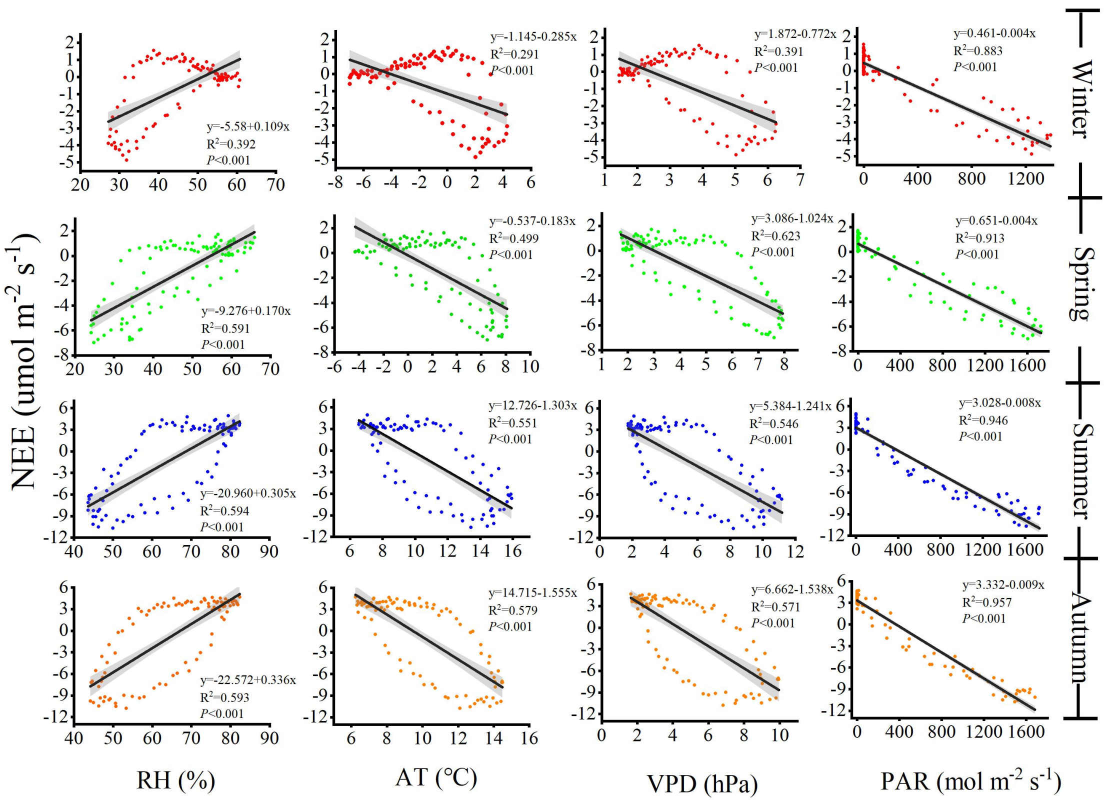
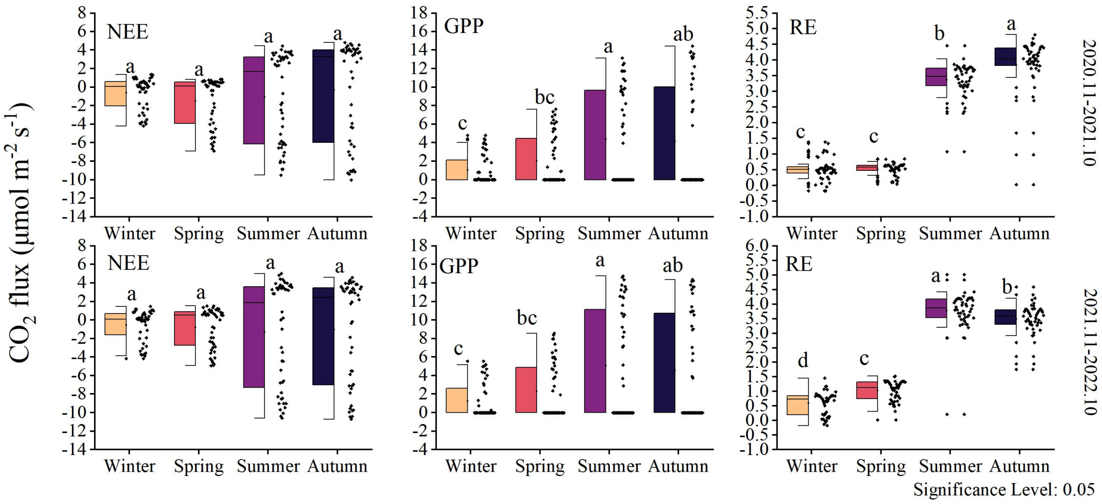


Figure 4. Principal component analysis of environmental factors and NEE~~Figure 4 Relationship between NEE and main environmental factors~~

3.4 Seasonal variation characteristics of NEE, GPP, and RE

The NEE ~~rate~~ did not show significant inter-seasonal differences (Figure 5). However, data distribution indicates that the variability in NEE rate differs across different seasons, particularly between summer-autumn and winter-spring. ~~However, data distribution indicates that the variability in NEE rate differs across different seasons, particularly between the growing seasons (summer, autumn) and the non-growing seasons (winter, spring).~~ The changes in GPP over the two years were similar, with significant differences observed between summer and winter

(P<0.05). The RE was higher during summer-autumn compared to winter-spring. The highest ecosystem respiration occurred in the first year during autumn, while in the second year, it was highest during summer. Within the same year, summer and autumn exhibited significant differences (P<0.05), while between the same seasons in different years, notable distinctions were not observed.with significant differences observed between the growing seasons and the non-growing seasons (P<0.05). The RE was higher during the growing seasons compared to the non-growing seasons. The forest ecosystem respiration rate was lowest in winter and slightly higher in spring. The highest ecosystem respiration occurred in the first year during autumn, while in the second year, it was highest during summer. This pattern is also reflected in GPP and NEE.



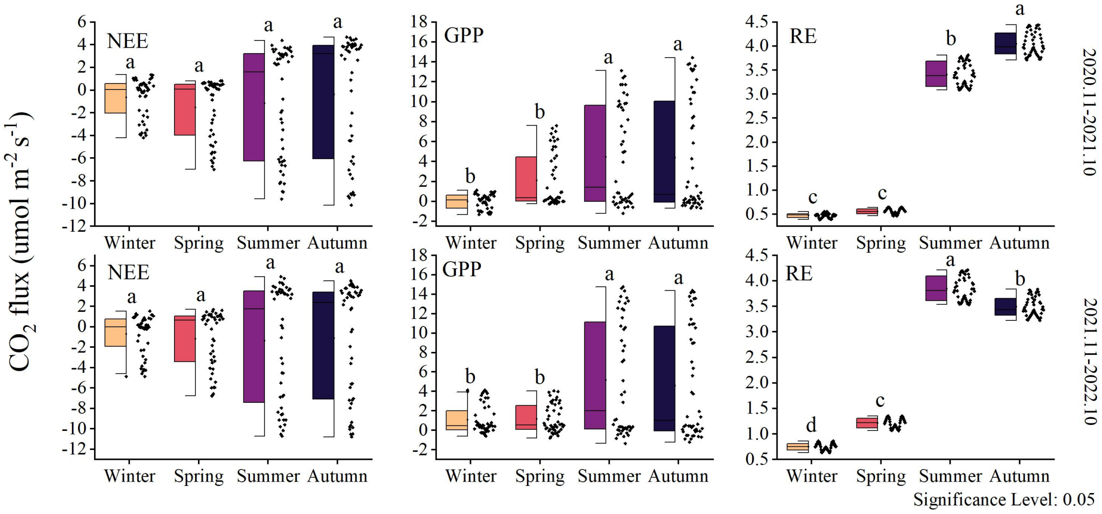
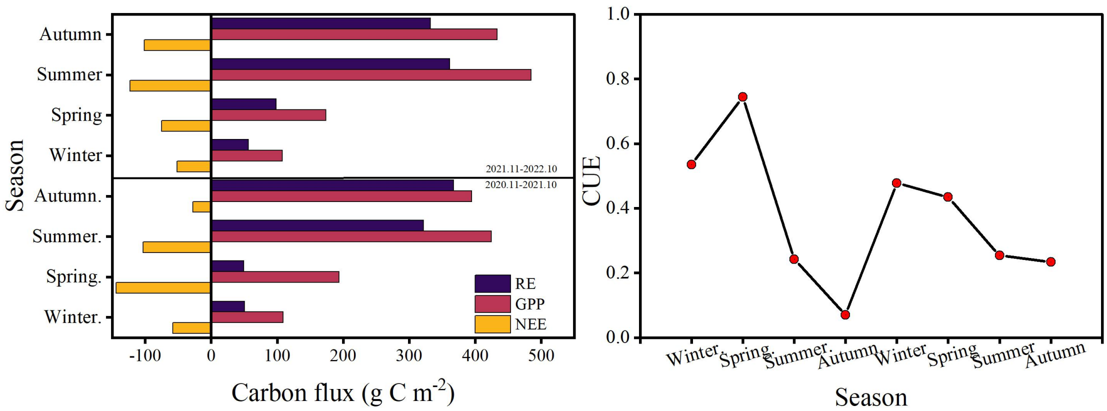


Figure 5. Seasonal variation of carbon fluxes

3.5 Changes in total NEE, GPP, RE, and CUE

The cumulative fluxes over the two years for the forest ecosystem are shown in Figure 6. NEE indicates the net carbon sequestration in each month. The cumulative respiration reached its highest value of 361 g C m^{-2} in the summer of 2022. The total NEE, GPP, and RE for the first year were -332, 1121, and 788 g C m^{-2}, respectively, and -351, 1199, and 847 g C m^{-2} for the second year, respectively. The CUE was higher during the spring and lower during the autumn, with a maximum value of 0.74 and a minimum value of 0.07. The average CUE over the two years was 0.40 and 0.35, respectively.~~The cumulative respiration reached its highest value of 363.23 g C m^{-2} in the summer of 2022. The total NEE, GPP, and RE for the first year were -358.65, 1159.60, and 802.67 g C m^{-2}, respectively, and -419.41, 1265.96, and 846.55 g C m^{-2} for the second year, respectively. The CUE was higher during the cold non-growing seasons and lower during the growing seasons, with a maximum value of 0.73 and a minimum value of 0.08. The average CUE over the two years was 0.43 and 0.41, respectively.~~



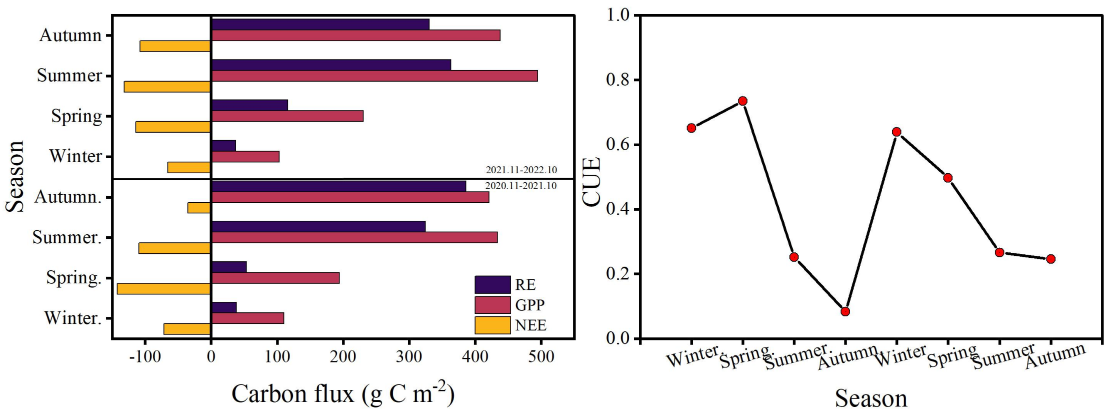
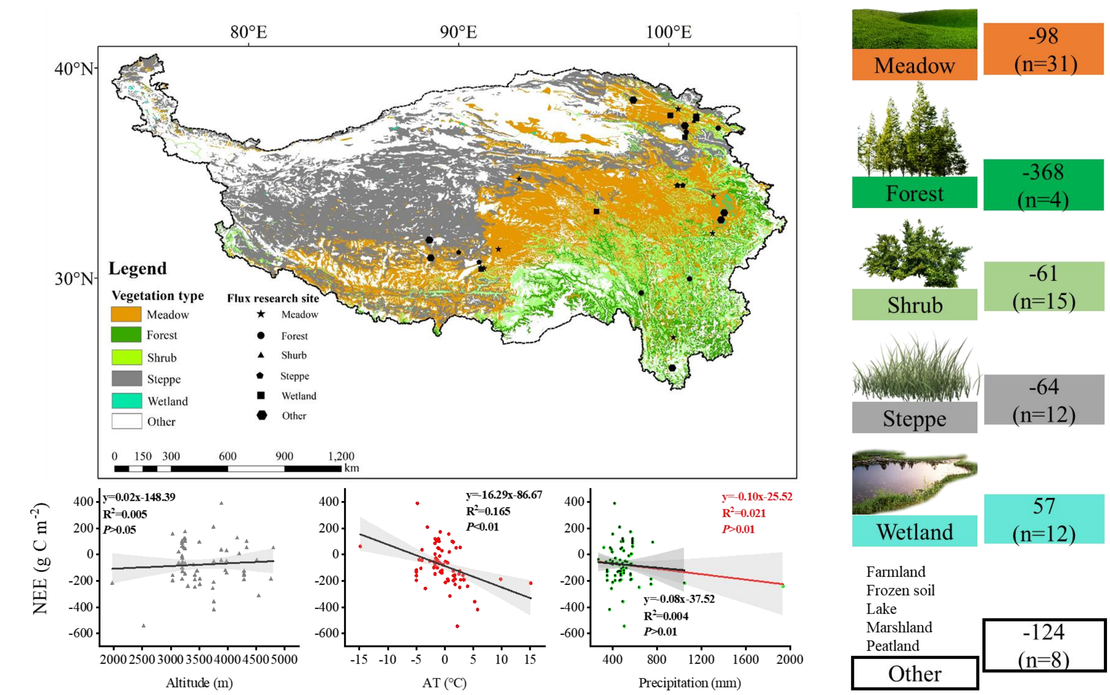


Figure 6. Change in total carbon flux and carbon use efficiency

3.6 The carbon sequestration potential of subalpine forests of QTP

To clarify the carbon sequestration contribution of the subalpine forests found in the QTP, we compared these research results (Figure 7). Found that ecosystems with high vegetation cover exhibited higher annual cumulative carbon sequestration. Among these ecosystems, the subalpine forests in the QTP showed the highest carbon sequestration potential, reaching an average of 368391.48 g C m^{-2} per year. The carbon sequestration potential of different ecosystems ranked as follows: forest > meadow > steppe > shrub. The average value for wetlands indicated that they are a significant source of CO_2, releasing 5756.93 g C m^{-2} into the atmosphere annually. We also analyzed the influence of altitude, mean annual air temperature, and precipitation on NEE at these sites in the QTP. It has been observed that these sites cover a wide range of altitudes, ranging from 1977 to 4800 m. According to existing results, an increase in elevation may lead to a reduction in carbon uptake, while the range of mean annual temperature varies between -14.8 to 15.1 °C, and higher mean annual temperatures significantly increase carbon uptake. Forests exhibit the highest mean annual precipitation, averaging 827 mm, with mean annual precipitation having a relatively weak impact on the NEE.It was found that increasing elevation had a negative impact on carbon uptake, while higher mean annual temperatures significantly increased carbon uptake. Mean annual precipitation had a weak influence on NEE. These findings highlight the important role of subalpine forests in carbon sequestration in the QTP and provide insights into the factors that affect carbon exchange in the QTP, such as altitude, temperature, and precipitation.



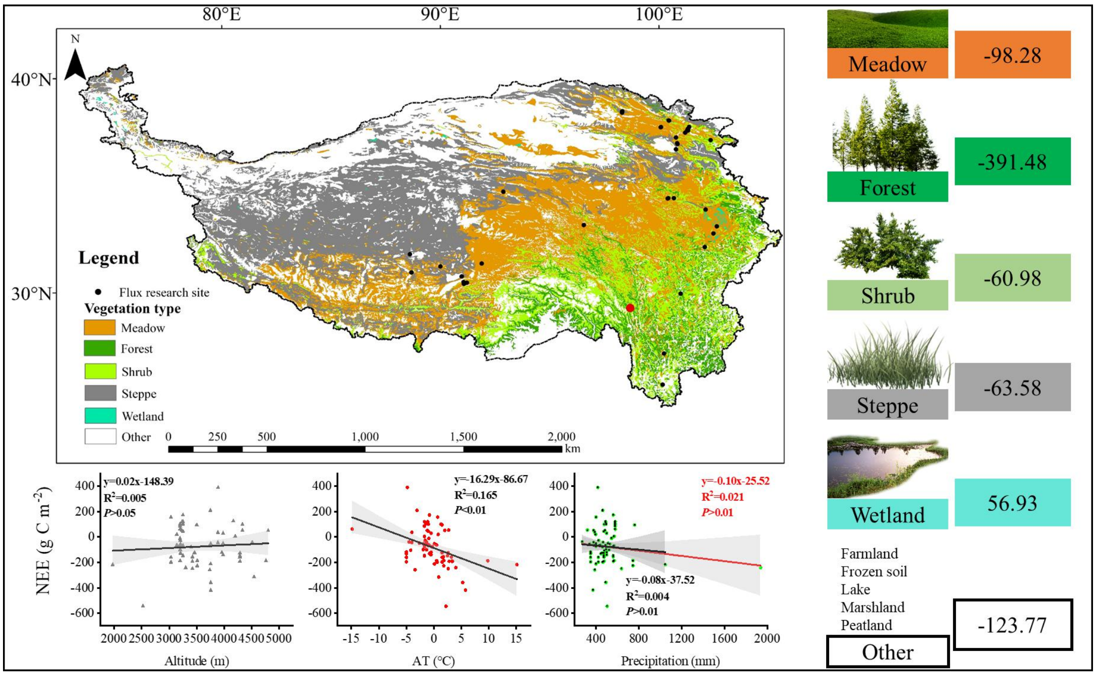


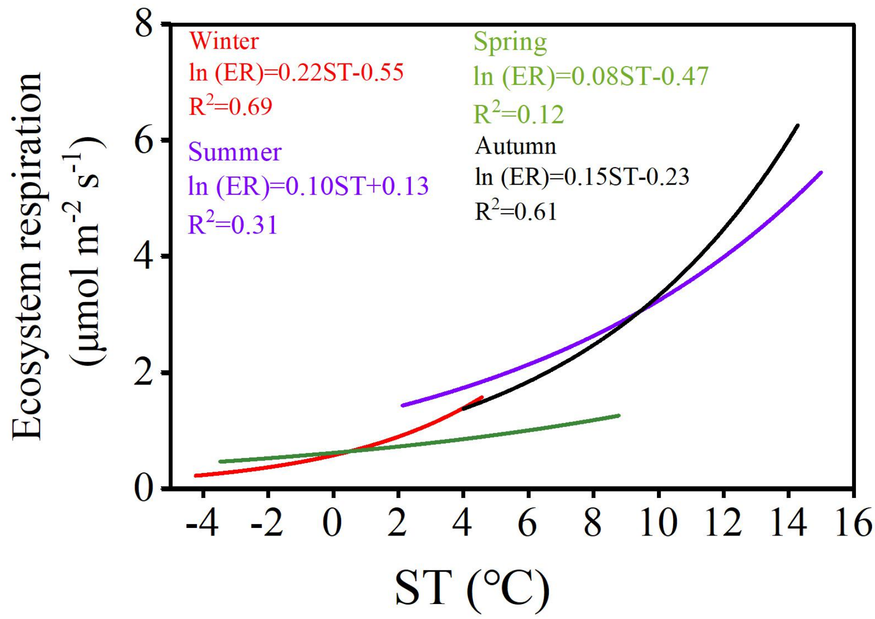
Figure 7. Carbon exchange potential of different ecosystems in the Qinghai-Tibet Plateau

4 Discussion

4.1 Main factors affecting the carbon sequestration function of subalpine forests

Climate change significantly affects the vegetation's carbon sequestration capacity, particularly at the seasonal scale due to phenological changes (Acosta-Hernández et al., 2020). In the short term, these factors (PAR, AT, RH, and VPD) play important roles in regulating vegetation photosynthesis and, consequently, carbon uptake. For instance, PAR representing the portion of solar energy that can be utilized by plants and is an essential component in chloroplast reactions. PAR drives a nonlinear response of GPP to Solar-induced fluorescence (SIF) across different seasons, resulting in a strong positive correlation between GPP and SIF (Wang et al., 2023b). VPD affects photosynthesis and transpiration of leaves, with stomata serving as tiny pores mediating carbon dioxide uptake. Research has demonstrated that excessive increases in VPD are detrimental to photosynthesis. For instance, a moderate increase in VPD significantly reduces photosynthetic efficiency under light fluctuations， due to changes in RH and/or AT often accompany fluctuations in light, studies also indicate that the impact of VPD on sunlight utilization efficiency is primarily determined by relative RH rather than AT (Liu et al., 2024)。In different seasons, the same influencing factors exhibit varying degrees of contribution to NEE. For example, during winter, when the climatic conditions are relatively harsh with low air temperature and humidity, the forest maintains a low level of carbon uptake.Climate change is the significant factor affecting the vegetation's carbon sequestration capacity, particularly at the seasonal scale due to phenological changes (Acosta-Hernández et al., 2020). Our study has demonstrated that, in the short term, NEE is primarily influenced by factors such as PAR, AT, RH, and VPD. These factors play a role in regulating vegetation photosynthesis and, consequently, carbon uptake. For instance, PAR represents the portion of solar energy that can be utilized by plants and is an essential component in chloroplast reactions. AT regulates the activity of enzymes involved in light and dark reactions, which may contribute to seasonal variations in NEE. RH and VPD impact the entire process of photosynthesis by influencing the concentration of CO_2 in the air and the stomatal conductance (the pathway for CO_2 exchange). In different seasons, the same influencing factors exhibit varying degrees of contribution to NEE. For example, during winter, when the climatic conditions are relatively harsh with low air temperature and humidity, the forest maintains a low level of carbon uptake. While the forest continues to absorb carbon dioxide, the uptake remains limited at a low level under such unfavorable conditions. On longer time scales, such as annual and decadal variations, the inherent changes in forest NEE may be attributed to disturbances and recovery (Hayek et al., 2018). In this study, significant differences in ecosystem respiration were observed during the summer and autumn in different years. Past research suggested that due to leaf aging or water stress, the photosynthetic light use efficiency of the ecosystem peaks after spring leaf expansion and gradually declines (Wehr et al., 2016). This implies a peak in carbon exchange during the summer, followed by higher productivity and ecosystem respiration in the following seasons. The variation in different years may be attributed to rainfall regulating the availability of natural resources such as water, biomass, litter, and soil nutrients (Schwinning and Sala, 2004). For instance, in temperate forests, when microbial biomass undergoes seasonal changes, microbial activity exhibits a seasonal lag in response to temperature variation, resulting in a seasonally delayed effect between litter heterotrophic respiration and temperature (Ataka et al., 2020). Whether such differences persist between different years on longer time scales remains to be demonstrated through more sustained and detailed research in the future. Ecosystem respirationResearch by Amiro (2001) has demonstrated that disturbances caused by fire and logging have been found to regulate the carbon balance of northern forests in Canada over several decades. Additionally, there are close relationships between subtle climate changes, stand dynamics, tree age, post-disturbance time, and forest carbon storage and cycling (Bradford et al., 2008). Compared to naturally regenerating forests, actively restored forests exhibit higher rates of carbon accumulation. Restoration efforts have been shown to increase aboveground carbon density recovery rates by more than 50% over a decade, from 2.9 to 4.4 megagrams per hectare per year (Philipson et al., 2020). The carbon dioxide generated by soil microbial activity is an essential component of forest ecosystem respiration. Soils contain the largest organic carbon reservoir on Earth, three times more than the carbon content in the atmosphere (Tifafi et al., 2018). With climate warming, soil microorganisms, and root systems will decompose soil organic carbon at a faster rate, releasing carbon dioxide into the atmosphere more rapidly. Temperature plays a more sensitive role in soil carbon turnover in cold climate regions compared to warmer conditions (Koven et al., 2017). Ecological respiration sensitivity to temperature is represented by the Q_{10} coefficient. In this study, seasonal variations influenced the magnitude of Q_{10} (as shown in Figure 8). The calculated Q_{10} for each season are as follows: 9.025, 2.22, 2.71, and 4.48. The winter season exhibited the highest sensitivity of forest ecosystem respiration to temperature, indicating that respiration rates in the winter are more responsive to changes in temperature compared to other seasons. The main reason for such differences is that ecosystem respiration consists of heterotrophic respiration and autotrophic respiration, which are typically governed by different factors (Edwards, 1975). For instance, the high activity of soil microbes contributes to heterotrophic respiration, a process dominated by soil temperature and moisture conditions, which are severely restricted during the cold and dry conditions of winter (Falge et al., 2002). Simultaneously, due to the changing relative roles of growth and maintenance respiration, the allocation of autotrophic respiration varies seasonally. In winter, soil CO_2 emissions constitute a significant portion of ecosystem CO_2 emissions, and in some boreal forests, the ratio between the two can reach 0.6 or even higher (Davidson et al., 2006), In winter, under the frequent coverage of snow, cold-adapted microorganisms thriving in a relatively narrow sub-zero temperature range engage in respiration and exhibit relatively high sensitivity to warming or cooling beyond this range (Monson et al., 2006). The seasonal patterns of the Q_{10} value are jointly determined by the variation in the ratio of soil respiration to ecosystem respiration, reflecting these seasonal changes.The winter season exhibited the highest sensitivity of forest ecosystem respiration to temperature, indicating that respiration rates in the winter are more responsive to changes in temperature compared to other seasons.

Our integrated analysis (as shown in Figure 7) reveals that despite the high elevation of the "Third Pole", the topographic factor of elevation does not have a significant impact on carbon uptake. Instead, NEE gradually increases with a steep rise in elevation. Research conducted by Wang et al. (2023c)WANG et al.(2023b), indicates that mean annual average temperature and precipitation are the main driving factors of interannual variations in NEE in alpine meadows and alpine steppes. Decreased precipitation resulting in a transition into carbon sources at some regions with high precipitation-dependent alpine grasslands. It is worth noting that, among all data collection sites, alpine wetlands show an average carbon source trend. Due to prolonged flooding and low temperatures, microbial activity in alpine wetlands is hindered, and the accumulation of organic carbon from plant litter decomposition is substantial. As a result, approximately 5756.93 g C m^{-2} is emitted into the atmosphere annually. Previous studies have indicated that NEE in alpine wetlands is increasing with global warming (Yasin et al., 2022).



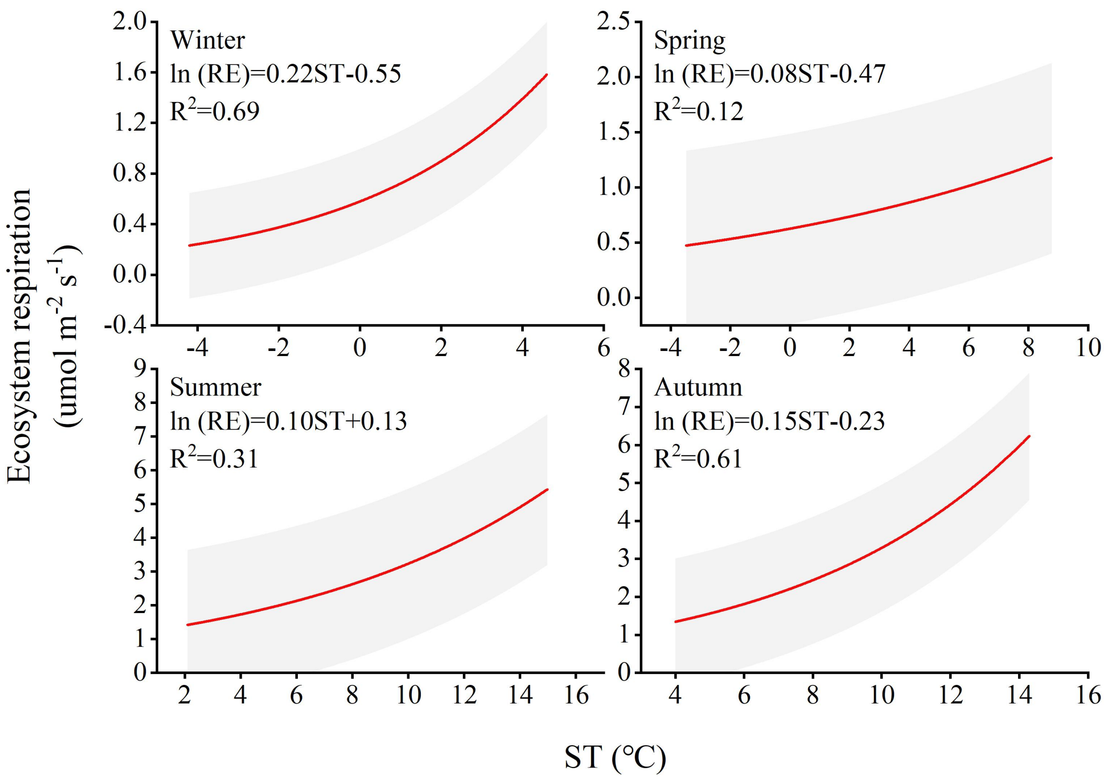


Figure 8. Relationship between NEEnight and soil temperature in different seasons

4.2 Sustained carbon sequestration of subalpine forests

Subalpine forests are integral components of global alpine ecosystems and play crucial roles in the global carbon cycle. Our study on subalpine forests demonstrates a continuous absorbing of carbon dioxide even during winter, which aligns well with measurements taken in the vicinity of Mount Fuji in Japan (Mizoguchi et al., 2012). The age of subalpine forests is a crucial factor influencing sustained carbon sequestration. Based on NPP simulations of natural subalpine forests in the Northern Rockies, Carey. (2001) found that aboveground net primary productivity reaches its maximum after approximately 250 years, followed by a decline, this challenges the previous view that forests older than 100 years are generally considered to be unimportant carbon sinks. Compared to the forest (mature forest) of Mount Gongga in the QTP (e.g., Zhang et al., 2018), the subalpine forest in this study exhibits a stronger carbon sequestration capacity. However, its carbon sequestration ability is slightly weaker than that of the Qilian Mountains high-mountain forests (approximately 60-70 years old) in the QTP (Zhang et al., 2018; Du et al., 2022b). Although existing flux monitoring results of high-altitude forests in the QTP indicate that these forest ecosystems act as carbon sinks, it is important to consider that globally there are still many cold regions with coniferous forests serve as carbon sources. For example, continuous CO_2 flux monitoring from native boreal forests in Sweden for over 10 years indicates that they are a net carbon source, which is attributed to the contribution of woody debris to RE due to disturbances such as extreme weather events, fires, insect infestations, and pathogen attacks (Hadden and Grelle, 2017). In the summer of 2018, Europe experienced a heatwave that affected the carbon cycling in forests. The mixed coniferous-deciduous forest in southern Estonian, under the influence of the heatwave, transitioned from a net carbon sink to a net carbon source in 2018 (Krasnova et al., 2022). Particular attention should be paid to the long-term monitoring in high-altitude environments of the impact of disturbances on forest carbon sequestration capacity. Our study has shown that forests in the QTP have the strongest carbon sink capacity, indicating that alpine forests will have an important sustained effect on carbon reduction in the QTP in the context of future climate change, but whether this sustained effect will be longer than other ecosystems is still unknown. However, a modeling experiment in a large semi-arid area of California predicted that grasslands are more resilient carbon sinks than forests in responding to climate change in the 21st century (Dass et al., 2018). In terms of carbon sequestration rate, forests in the QTP were significantly stronger than other ecosystems, followed by grasslands, while alpine deserts and alpine grasslands in the north-western and southern regions were the main carbon sources (Wu et al., 2022). Forests are mostly distributed in the south-eastern margin of the QTP and the mid-altitude area near 3000 m in the Sichuan-Tibet alpine gorge area, with an area of

19.3 × 10^4 km^2 (Yu et al., 2022)~~(Y et al., 2022)~~. Based on the average value of a few current carbon flux monitoring, the forest in the QTP will absorb about 71× 10^6 Mg C $year^{-1}$.

5 Conclusion

This study explores the carbon sequestration function, seasonal variations, and climate drivers of subalpine forests in the QTP. Over the observational period, We synchronously monitored ecosystem carbon exchange and primary environmental factors using an eddy covariance system. The research reveals that the subalpine forest is a carbon sink, with a total NEE, GPP, and RE of -332, 1121, and 788 g C m^{-2}, respectively, and -351, 1199, and 847 g C m^{-2} for two years, respectively.~~with a total NEE, GPP, and RE of -358.65, 1159.60, and 802.67 g C m^{-2}, respectively, and -419.41, 1265.96, and 846.55 g C m^{-2} for two years, respectively.~~ Photosynthetically active radiation was identified as the primary control of NEE. The NEE did not exhibit significant differences across seasons. Combining results from other eddy covariance sites on the QTP, this study highlights those forests have the highest carbon sequestration potential, reaching 368 g C m^{-2} annually, followed by meadows, steppes, and shrubs. Wetlands, however, were identified as a substantial carbon dioxide source. Despite the challenges posed by climate change, the subalpine forests in the QTP retain substantial carbon sequestration potential. Strengthening conservation and management efforts for subalpine forests is crucial to ensure their continued and significant carbon sequestration function in the future. Overall, this research underscores the vital role of subalpine forests in the QTP as essential carbon sink regions, playing a critical role in the context of global climate change.

Data availability. The data is available from the authors on request.

Authorship contributions. **Niu Zhu:** Conceptualization, study design, data analyses, visualization, writing-original draft. **JinNiu Wang:** study design, writing—review & editing, supervision, project administration, funding acquisition. **Dongliang Luo and Xufeng Wang:** writing-reviewing & editing. **Cheng Shen and Ning Wu:** resources, data curation, supervision. all authors approved the final manuscript.

Declaration of competing interest. The authors declare that they have no conflict of interest.

Acknowledgements. We thank Ms. Neha Bisht for her substantial comments and language revision on improving the manuscript. This study was funded by CAS "Light of West China" Program (2021XBZG-XBQNXZ-A-007); National Natural Science Foundation of China (31971436); State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy Sciences (SKLCS-OP-2021-06).

Reference

Acosta-Hernández, A. C., Padilla-Martínez, J. R., Hernández-Díaz, J. C., Prieto-Ruiz, J. A., Goche-Telles, J. R., Nájera-Luna, J. A., and Pompa-García, M.: Influence of Climate on Carbon Sequestration in Conifers Growing under Contrasting Hydro-Climatic Conditions, Forests, 11, 1134, 2020.

Ataka, M., Kominami, Y., Sato, K., and Yoshimura, K.: Microbial Biomass Drives Seasonal Hysteresis in Litter Heterotrophic Respiration in Relation to Temperature in a Warm-Temperate Forest, Journal of Geophysical Research: Biogeosciences, 125, e2020JG005729, https://doi.org/10.1029/2020JG005729, 2020.

Banbury Morgan, R., Herrmann, V., Kunert, N., Bond-Lamberty, B., Muller-Landau, H. C., and Anderson-Teixeira, K. J.: Global patterns of forest autotrophic carbon fluxes, Global Change Biology, 27, 2840-2855, https://doi.org/10.1111/gcb.15574, 2021.

Baumgartner, S., Barthel, M., Drake, T. W., Bauters, M., Makelele, I. A., Mugula, J. K., Summerauer, L., Gallarotti, N., Cizungu Ntaboba, L., Van Oost, K., Boeckx, P., Doetterl, S., Werner, R. A., and Six, J.: Seasonality, drivers, and isotopic composition of soil CO2 fluxes from tropical forests of the Congo Basin, Biogeosciences, 17, 6207-6218, 10.5194/bg-17-6207-2020, 2020.

Cai, W., He, N., Li, M., Xu, L., Wang, L., Zhu, J., Zeng, N., Yan, P., Si, G., and Zhang, X.: Carbon sequestration of Chinese forests from 2010 to 2060: Spatiotemporal dynamics and its regulatory strategies, Science Bulletin, 67, 836-843, 2022.

Cao, S., Cao, G., Chen, K., Han, G., Liu, Y., Yang, Y., and Li, X.: Characteristics of CO_2, water vapor, and energy exchanges at a headwater wetland ecosystem of the Qinghai Lake, Canadian Journal of Soil Science, 99, 227-243, 10.1139/cjss-2018-0104, 2019.

Carey, E. V., Sala, A., Keane, R., and Callaway, R. M.: Are old forests underestimated as global carbon sinks?, Global Change Biology, 7, 339-344, 10.1046/j.1365-2486.2001.00418.x, 2001.

Chen, H., Ju, P. J., Zhu, Q., Xu, X. L., Wu, N., Gao, Y. H., Feng, X. J., Tian, J. Q., Niu, S. L., Zhang, Y. J., Peng, C. H., and Wang, Y. F.: Carbon and nitrogen cycling on the Qinghai-Tibetan Plateau, NATURE REVIEWS EARTH & ENVIRONMENT, 3, 701-716, 10.1038/s43017-022-00344-2, 2022.

Cole, J. J., Caraco, N. F., Kling, G. W., and Kratz, T. K.: Carbon dioxide supersaturation in the surface waters of lakes, Science, 265, 1568-1570, 1994.

Dass, P., Houlton, B. Z., Wang, Y., and Warlind, D.: Grasslands may be more reliable carbon sinks than forests in California, Environmental Research Letters, 13, 074027, 10.1088/1748-9326/aacb39, 2018.

Davidson, E. A., Richardson, A. D., Savage, K. E., and Hollinger, D. Y.: A distinct seasonal pattern of the ratio of soil respiration to total ecosystem respiration in a spruce-dominated forest, Global Change Biology, 12, 230-239, https://doi.org/10.1111/j.1365-2486.2005.01062.x, 2006.

Du, C., Zhou, G., and Gao, Y.: Grazing exclusion alters carbon flux of alpine meadow in the Tibetan Plateau, Agricultural and Forest Meteorology, 314, 108774, 2022a.

Du, Y., Pei, W., Zhou, H., Li, J., Wang, Y., and Chen, K.: Net ecosystem exchange of carbon dioxide fluxes and its driving mechanism in the forests on the Tibetan Plateau, Biochemical Systematics and Ecology, 103, 10.1016/j.bse.2022.104451, 2022b.

Ebermayer, E.: Die gesammte Lehre der Waldstreu mit Rücksicht auf die chemische Statik des Waldbaues: unter Zugrundlegung der in den Königl. Staatsforsten Bayerns angestellten Untersuchungen, Springer1876.

Edwards, N. T.: Effects of Temperature and Moisture on Carbon Dioxide Evolution in a Mixed Deciduous Forest Floor, Soil Science Society of America Journal, 39, 361-365, https://doi.org/10.2136/sssaj1975.03615995003900020034x, 1975.

Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Burba, G., Clement, R., Davis, K. J., Elbers, J. A., Goldstein, A. H., Grelle, A., Granier, A., Guðmundsson, J., Hollinger, D., Kowalski, A. S., Katul, G., Law, B. E., Malhi, Y., Meyers, T., Monson, R. K., Munger, J. W., Oechel, W., Paw U, K. T., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Valentini, R., Wilson, K., and Wofsy, S.: Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements, Agricultural and Forest Meteorology, 113, 53-74, https://doi.org/10.1016/S0168-1923(02)00102-8, 2002.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, J., Moors, E., Munger, J. W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: Gap filling strategies for defensible annual sums of net ecosystem exchange, Agricultural and Forest Meteorology, 107, 43-69, https://doi.org/10.1016/S0168-1923(00)00225-2, 2001.

Foken, T., Göockede, M., Mauder, M., Mahrt, L., Amiro, B., and Munger, W.: Post-Field Data Quality Control, in: Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, edited by: Lee, X., Massman, W., and Law, B., Springer Netherlands, Dordrecht, 181-208, 10.1007/1-4020-2265-4_9, 2005.

Hadden, D. and Grelle, A.: Net CO2 emissions from a primary boreo-nemoral forest over a 10year period, Forest Ecology and Management, 398, 164-173, https://doi.org/10.1016/j.foreco.2017.05.008, 2017.

Hayek, M. N., Longo, M., Wu, J., Smith, M. N., Restrepo-Coupe, N., Tapajos, R., da Silva, R., Fitzjarrald, D. R., Camargo, P. B., Hutyra, L. R., Alves, L. F., Daube, B., Munger, J. W., Wiedemann, K. T., Saleska, S. R., and Wofsy, S. C.: Carbon exchange in an Amazon forest: from hours to years, Biogeosciences, 15, 4833-4848, 10.5194/bg-15-4833-2018, 2018.

Jia, X., Mu, Y., Zha, T., Wang, B., Qin, S., and Tian, Y.: Seasonal and interannual variations in ecosystem respiration in relation to temperature, moisture, and productivity in a temperate semi-arid shrubland, Science of The Total Environment, 709, 136210, https://doi.org/10.1016/j.scitotenv.2019.136210, 2020.

KATO, T., TANG, Y., GU, S., HIROTA, M., DU, M., LI, Y., and ZHAO, X.: Temperature and biomass influences on interannual changes in CO2 exchange in an alpine meadow on the Qinghai-Tibetan Plateau, Global Change Biology, 12, 1285-1298, https://doi.org/10.1111/j.1365-2486.2006.01153.x, 2006.

Kondo, M., Saitoh, T. M., Sato, H., and Ichii, K.: Comprehensive synthesis of spatial variability in carbon flux across monsoon Asian forests, Agricultural and Forest Meteorology, 232, 623-634, 2017.

Konopka, J., Heusinger, J., and Weber, S.: Extensive Urban Green Roof Shows Consistent Annual Net Uptake of Carbon as Documented by 5 Years of Eddy-Covariance Flux Measurements, Journal of

Geophysical Research: Biogeosciences, 126, e2020JG005879, 2021.

Krasnova, A., Mander, Ü., Noe, S. M., Uri, V., Krasnov, D., and Soosaar, K.: Hemiboreal forests' CO2 fluxes response to the European 2018 heatwave, Agricultural and Forest Meteorology, 323, 109042, https://doi.org/10.1016/j.agrformet.2022.109042, 2022.

Landsberg, J. and Waring, R.: A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning, Forest ecology and management, 95, 209-228, 1997.

Laurin, G. V., Chen, Q., Lindsell, J. A., Coomes, D. A., Del Frate, F., Guerriero, L., Pirotti, F., and Valentini, R.: Above ground biomass estimation in an African tropical forest with lidar and hyperspectral data, ISPRS Journal of Photogrammetry and Remote Sensing, 89, 49-58, 2014.

Leuning, R. and King, K. M.: Comparison of eddy-covariance measurements of CO2 fluxes by open- and closed-path CO2 analysers, Boundary-Layer Meteorology, 59, 297-311, 10.1007/BF00119818, 1992.

Li, L., Zhang, Y., Wu, J., Li, S., Zhang, B., Zu, J., Zhang, H., Ding, M., and Paudel, B.: Increasing sensitivity of alpine grasslands to climate variability along an elevational gradient on the Qinghai-Tibet Plateau, Science of the Total Environment, 678, 21-29, 2019.

Li, X. Y., Shi, F. Z., Ma, Y. J., Zhao, S. J., and Wei, J. Q.: Significant winter CO2 uptake by saline lakes on the Qinghai-Tibet Plateau, Global Change Biology, 28, 2041-2052, 2022.

Liu, C., Wu, Z., Hu, Z., Yin, N., Islam, A. T., and Wei, Z.: Characteristics and influencing factors of carbon fluxes in winter wheat fields under elevated CO2 concentration, Environmental Pollution, 307, 119480, 2022.

Liu, J., Zou, H.-X., Bachelot, B., Dong, T., Zhu, Z., Liao, Y., Plenković-Moraj, A., and Wu, Y.: Predicting the responses of subalpine forest landscape dynamics to climate change on the eastern Tibetan Plateau, Global Change Biology, 27, 4352-4366, https://doi.org/10.1111/gcb.15727, 2021.

Liu, N.-Y., Yang, Q.-Y., Wang, J.-H., Zhang, S.-B., Yang, Y.-J., and Huang, W.: Differential Effects of Increasing Vapor Pressure Deficit on Photosynthesis at Steady State and Fluctuating Light, Journal of Plant Growth Regulation, 10.1007/s00344-024-11268-0, 2024.

Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration, Functional Ecology, 8, 315-323, 1994.

Mamkin, V., Avilov, V., Ivanov, D., Varlagin, A., and Kurbatova, J.: Interannual variability in the ecosystem CO2 fluxes at a paludified spruce forest and ombrotrophic bog in the southern taiga, Atmospheric Chemistry and Physics, 23, 2273-2291, 10.5194/acp-23-2273-2023, 2023.

Mao, D., Luo, L., Wang, Z., Zhang, C., and Ren, C.: Variations in net primary productivity and its relationships with warming climate in the permafrost zone of the Tibetan Plateau, Journal of Geographical Sciences, 25, 967-977, 10.1007/s11442-015-1213-8, 2015.

Mauder, M. and Foken, T.: Documentation and Instruction Manual of the Eddy-Covariance Software Package TK3 (update),

Mizoguchi, Y., Ohtani, Y., Takanashi, S., Iwata, H., Yasuda, Y., and Nakai, Y.: Seasonal and interannual variation in net ecosystem production of an evergreen needleleaf forest in Japan, Journal of Forest Research, 17, 283-295, 10.1007/s10310-011-0307-0, 2012.

Moncrieff, J. B., Massheder, J. M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, H., and Verhoef, A.: A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide, Journal of Hydrology, 188-189, 589-611, https://doi.org/10.1016/S0022-1694(96)03194-0, 1997.

Monson, R. K., Lipson, D. L., Burns, S. P., Turnipseed, A. A., Delany, A. C., Williams, M. W., and Schmidt, S. K.: Winter forest soil respiration controlled by climate and microbial community composition, Nature, 439, 711-714, 10.1038/nature04555, 2006.

Monteith, J. L., Unsworth, M. H., and Webb, A.: Principles of environmental physics, Quarterly Journal of the Royal Meteorological Society, 120, 1699, 1994.

Mu, C., Mu, M., Wu, X., Jia, L., Fan, C., Peng, X., Ping, C. l., Wu, Q., Xiao, C., and Liu, J.: High carbon emissions from thermokarst lakes and their determinants in the Tibet Plateau, Global Change Biology, 2023.

Niu, Z., Jinniu, W., Xufeng, W., Dongliang, L., Cheng, S., and Aihong, G.: Net ecosystem co_2 exchange and its influencing factors in non-growing season at a sub-alpine forest in the core Three Parallel Rivers region, Acta Ecologica Sinica, 43, 5967-5979, 10.5846/stxb202204020841, 2023.

World Meteorological Organization.: 2019 concludes a decade of exceptional global heat and high-impactweather[EB/OL].https://public.wmo.intlen/media/press-release/2019-concludes-decade-of-exceptional-global-heat-and-high-impact-weather, 2019.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., and Canadell, J. G.: A large and persistent carbon sink in the world's forests, Science, 333, 988-993, 2011.

Pavelka, M., Acosta, M., Marek, M. V., Kutsch, W., and Janous, D.: Dependence of the Q10 values on the depth of the soil temperature measuring point, Plant and Soil, 292, 171-179, 10.1007/s11104-007-9213-9, 2007.

Qu, S., Xu, R., Yu, J., and Borjigidai, A.: Extensive atmospheric methane consumption by alpine forests on Tibetan Plateau, Agricultural and Forest Meteorology, 339, 109589, https://doi.org/10.1016/j.agrformet.2023.109589, 2023.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Global Change Biology, 11, 1424-1439, https://doi.org/10.1111/j.1365-2486.2005.001002.x, 2005.

Schotanus, P., Nieuwstadt, F. T. M., and De Bruin, H. A. R.: Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes, Boundary-Layer Meteorology, 26, 81-93, 10.1007/BF00164332, 1983.

Schweizer, V. J., Ebi, K. L., van Vuuren, D. P., Jacoby, H. D., Riahi, K., Strefler, J., Takahashi, K., van Ruijven, B. J., and Weyant, J. P.: Integrated Climate-Change Assessment Scenarios and Carbon Dioxide Removal, One Earth, 3, 166-172, 10.1016/j.oneear.2020.08.001, 2020.

Schwinning, S. and Sala, O. E.: Hierarchy of responses to resource pulses in arid and semi-arid ecosystems, Oecologia, 141, 211-220, 10.1007/s00442-004-1520-8, 2004.

Stein, T.: Carbon dioxide peaks near 420 parts per million at Mauna Loa observatory, NOAA Research, June, 7, 2021.

Tang, X., Xiao, J., Ma, M., Yang, H., Li, X., Ding, Z., Yu, P., Zhang, Y., Wu, C., Huang, J., and Thompson, J. R.: Satellite evidence for China's leading role in restoring vegetation productivity over global karst ecosystems, Forest Ecology and Management, 507, 120000, https://doi.org/10.1016/j.foreco.2021.120000, 2022.

Vote, C., Hall, A., and Charlton, P.: Carbon dioxide, water and energy fluxes of irrigated broad-acre crops in an Australian semi-arid climate zone, Environmental Earth Sciences, 73, 449-465, 2015.

Wang, C.-Y., Wang, J.-N., Wang, X.-F., Luo, D.-L., Wei, Y.-Q., Cui, X., Wu, N., and Bagaria, P.: Phenological Changes in Alpine Grasslands and Their Influencing Factors in Seasonally Frozen Ground Regions Across the Three Parallel Rivers Region, Qinghai-Tibet Plateau, Frontiers in Earth Science, 9, 10.3389/feart.2021.797928, 2022.

Wang, S., Grant, R., Verseghy, D., and Black, T.: Modelling plant carbon and nitrogen dynamics of a boreal aspen forest in CLASS—the Canadian Land Surface Scheme, Ecological Modelling, 142, 135-154, 2001.

Wang, Y., Yao, G., Zuo, Y., and Wu, Q.: Implications of global carbon governance for corporate carbon emissions reduction, Frontiers in Environmental Science, 11, 3, 2023a.

Wang, Y., Sun, Y., Chen, Y., Wu, C., Huang, C., Li, C., and Tang, X.: Non-linear correlations exist between solar-induced chlorophyll fluorescence and canopy photosynthesis in a subtropical evergreen forest in Southwest China, Ecological Indicators, 157, 111311, https://doi.org/10.1016/j.ecolind.2023.111311, 2023b.

Wang, Y., Xiao, J., Ma, Y., Ding, J., Chen, X., Ding, Z., and Luo, Y.: Persistent and enhanced carbon sequestration capacity of alpine grasslands on Earth’s Third Pole, Science Advances, 9, eade6875, doi:10.1126/sciadv.ade6875, 2023c.

Wang, Y., Xiao, J., Ma, Y., Luo, Y., Hu, Z., Li, F., Li, Y., Gu, L., Li, Z., and Yuan, L.: Carbon fluxes and environmental controls across different alpine grassland types on the Tibetan Plateau, Agricultural and Forest Meteorology, 311, 108694, 2021.

Wehr, R., Munger, J. W., McManus, J. B., Nelson, D. D., Zahniser, M. S., Davidson, E. A., Wofsy, S. C., and Saleska, S. R.: Seasonality of temperate forest photosynthesis and daytime respiration, Nature, 534, 680-683, 10.1038/nature17966, 2016.

Wu, T., Ma, W., Wu, X., Li, R., Qiao, Y., Li, X., Yue, G., Zhu, X., and Ni, J.: Weakening of carbon sink on the Qinghai–Tibet Plateau, Geoderma, 412, 115707, https://doi.org/10.1016/j.geoderma.2022.115707, 2022.

Y, W. Z., Y, L. Z., K, D. S., L, F. M., S, L. Y., M, L. S., N, W. S., H, M. C., X, M. T., and Y, C.:

Evolution of ecological patterns and its driving factors on Qinghai-Tibet Plateau over the past 40 years, Acta Ecologica Sinica, 42, 8941-8952, 2022.

Yasin, A., Niu, B., Chen, Z., Hu, Y., Yang, X., Li, Y., Zhang, G., Li, F., and Hou, W.: Effect of warming on the carbon flux of the alpine wetland on the Qinghai-Tibet Plateau, Frontiers in Earth Science, 10, 10.3389/feart.2022.935641, 2022.

YU, G. and SUN, X.: Principles of flux measurement in terrestrial ecosystem, Beijing: Higher Education Press, 2006.

Yu, Y.: Double-order system construction of China s climate change legislation under the dual carbon goals, China Population Resources and Environment, 32, 89-96, 2022.

Zemin, Z., Fenggui, L., Qiong, C., Xingsheng, X., and Qiang, Z.: Spatial Prediction of Potential Property Loss by Geological Hazards based on Random Forest—A Case Study of Chamdo, Tibet, Plateau Science Research, 7, 21-30, 10.16249/j.cnki.2096-4617.2023.02.003, 2023.

Zhang, J., Lin, H., Li, S., Yang, E., Ding, Y., Bai, Y., and Zhou, Y.: Accurate gas extraction (AGE) under the dual-carbon background: Green low-carbon development pathway and prospect, Journal of Cleaner Production, 134372, 2022.

Zhang, Y., Zhu, W., Sun, X., and Hu, Z.: Carbon dioxide flux characteristics in an Abies fabri mature forest on Gongga Mountain， Sichuan， China, Acta Ecologica Sinica, 38, 6125-6135, 2018.