

# Spatiotemporal Evolution and Driving Mechanism of NEP in Qilian Mountain National Park

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## ABSTRACT

Taking Qilian Mountain National Park as the study area, this research systematically analyzed the spatiotemporal evolution characteristics and driving mechanisms of carbon sources/sinks in the park based on the MOD17A3HGF net primary productivity (NPP) dataset and meteorological data including temperature, precipitation, humidity, and sunshine duration from 2000 to 2022. The methods applied included a net ecosystem productivity (NEP) estimation model, pixel-wise linear regression, and correlation analysis. The results showed that: From 2000 to 2022, the park's NEP exhibited a fluctuating upward trend with a slope of 1.89 gC m<sup>2</sup> a, reaching a peak of 181.6 gC m<sup>2</sup> a in 2019. The region was dominated by carbon sinks overall, with carbon source areas accounting for less than 0.5% and showing a decreasing trend. Spatially, NEP was higher in the southeast and lower in the northwest. High-value areas were concentrated in the Eastern Qilian Mountains spruce forest–alpine meadow and Hexi Corridor arid desert–oasis agricultural ecological subzones, while low-value areas were distributed in the Qaidam Basin desert, Western Qilian Mountains alpine desert steppe, and Qinghai Lake Wetland alpine meadow subzone. NEP showed an increasing trend across all five ecological subzones, with growth rates ranked as: Hexi Corridor (3.88) > Eastern Qilian Mountains (2.31) > Western Qilian Mountains (1.3) > Qaidam Basin (1.02) > Qinghai Lake Wetland (0.25). An increasing NEP trend occurred in 98.8% of the park area, among which 73.4% showed an extremely significant increase. NEP was positively correlated with meteorological factors; temperature was the primary driving factor, followed by precipitation and humidity, while sunshine duration had a relatively weak effect. This study can provide a scientific basis for ecological conservation, restoration, and carbon sink enhancement in Qilian Mountain National Park.

## KEYWORDS

Qilian Mountain National Park; Carbon Sink; Carbon Source; Spatiotemporal Variation; Net Ecosystem Productivity.

## 1. INTRODUCTION

Against the backdrop of increasingly severe global climate change, the carbon cycle not only reflects variations in atmospheric CO<sub>2</sub> concentration but also represents the comprehensive response of ecosystems to global change[1]. As components of natural ecosystems, forests, grasslands and wetlands possess strong carbon sink functions, and play vital roles in mitigating global warming. Forest ecosystems store approximately 45% of terrestrial carbon and maintain the global carbon balance as long-term carbon sinks. Their above-ground carbon (AGC) pools account for 30%–50% of the total forest carbon pool, serving as a key indicator for evaluating forest functions and productivity[2]. However, with intensified climate change and increasing anthropogenic disturbances, the global forest carbon sink is at risk of shifting to a carbon source.

As the world's largest developing country, China has explicitly proposed the goals of "carbon peaking and carbon neutrality", and incorporated the enhancement of ecosystem carbon sink functions into its national climate action framework. Guided by national strategies, various ecologically valuable regions have become focal points for carbon sink research and conservation. Among them, Qilian Mountain National Park, as one of China's first ten national park system pilots, is located on the northeastern margin of the Qinghai-Tibet Plateau. It acts as a robust ecological security barrier in western China and has been extensively investigated. This region encompasses diverse ecosystem types including forests, grasslands, wetlands and glaciers, exhibiting typical characteristics of alpine ecosystems and being highly sensitive to climate change[3]. Qilian Mountains is not only the source of inland rivers such as the Heihe, Shiyang and Shule Rivers, safeguarding water security for the Hexi Corridor oases, but also plays a crucial role in regional and even global carbon cycles through its prominent carbon sink functions[4]. The ecosystem of the Qilian Mountains features a strong carbon sink capacity, which exhibited a positive transition from 2016 to 2019[5]. The grassland carbon sink in the Qilian Mountains shows a spatial distribution pattern of high values in the northwest and low values in the southeast[6]. Using the biomass conversion factor method, Li et al. estimated carbon storage and found that *Picea crassifolia* had the largest carbon storage, followed by *Betula albosinensis*, *Betula platyphylla*, *Betula utilis*, *Juniperus przewalskii* and poplars[7].

Although existing studies have achieved certain findings on carbon sinks in Qilian Mountain National Park, the carbon sink processes remain highly uncertain under climate change impacts, and the research system is still incomplete. Therefore, long-term in-situ observations and in-depth investigations are urgently needed to maintain the stability of regional ecosystems. Accordingly, this study takes Qilian Mountain National Park as the research area, combines net primary productivity (NPP) and meteorological data (including temperature, precipitation, sunshine duration and humidity) from 2000 to 2022, systematically analyzes the spatiotemporal evolution characteristics of net ecosystem productivity (NEP), clarifies the dynamic patterns of carbon source/sink distribution, and reveals the driving mechanisms of meteorological factors on carbon sink functions. The conclusions can provide a scientific basis for ecological protection and restoration in the park.

## **2. STUDY AREA OVERVIEW AND DATA PROCESSING**

### **2.1. Study Area Overview**

Qilian Mountain National Park, with an average altitude of over 4,000 m and a total area of 5.02 km<sup>2</sup>, is a typical alpine region. The area is rich in grasslands, forests, wetlands, glaciers and biodiversity, and is known as the "Chinese Wet Island". It features a plateau continental climate characterized by strong solar radiation, large diurnal temperature variations, a long cold season, a short warm season, and synchronous rainfall and heat. To investigate the spatial patterns of carbon sources and sinks in different ecological zones of Qilian Mountain National Park, this study divided the park into five ecological subregions based on the Chinese Ecological Function Subregions published by the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. These are as follows: II-3-3 Arid Desert-Oasis Agricultural Ecological Subregion of the Hexi Corridor; III-1-1 Alpine Desert Steppe Ecological Subregion of the Western Qilian Mountains; III-1-2 Spruce Forest-Alpine Meadow Ecological Subregion of the Eastern Qilian Mountains; III-1-3 Qinghai Lake Wetland and Upstream Alpine Meadow Ecological Subregion; and III-2 Qaidam Basin Desert Ecological Region, as shown in Figure 1.

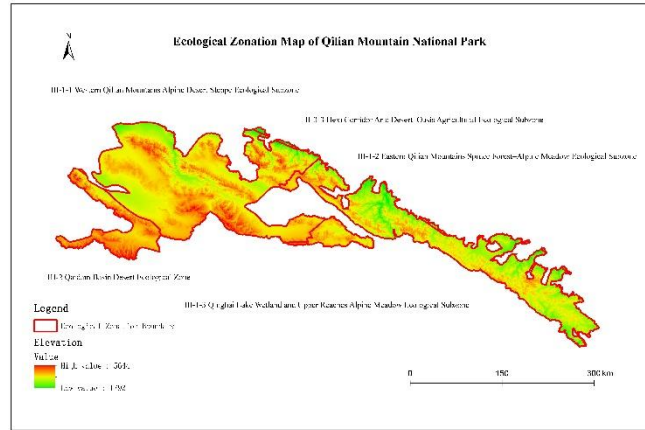


Fig 1. Ecological Zonation Map of Qilian Mountain National Park

## 2.2. Data Processing

### 2.2.1. Data Source

The net primary productivity (NPP) data used in this study were derived from the MOD17A3HGF dataset available on the official NASA website, covering a time series from 2000 to 2022 with a spatial resolution of 500 m. The NPP data for Qilian Mountain National Park were extracted by clipping to the park boundary. Annual mean temperature, precipitation, sunshine duration and humidity were obtained from the China Statistical Yearbook and local statistical yearbooks. The ecological function zoning data were obtained from the ecological subregion dataset released by the Ecosystem Assessment and Ecological Security Database of China. The DEM data were acquired from the Data Platform of the Resource and Environment Science and Data Center, Chinese Academy of Sciences.

### 2.2.2. Data Processing

#### ① NEP Estimation Model

Net ecosystem productivity (NEP) is defined as the difference between vegetation primary productivity and soil microbial respiration within the study area[8-10]. Therefore, NEP serves as a crucial indicator for assessing regional carbon sources and carbon sinks, and its calculation formula is as follows:

$$NEP = NPP - R_h \quad (1)$$

Where: NEP represents net ecosystem productivity of vegetation; NPP represents net primary productivity of vegetation;  $R_h$  represents soil microbial respiration. If  $NEP > 0$ , the carbon fixed by vegetation exceeds the carbon released via soil microbial respiration, indicating a carbon sink; otherwise, the ecosystem acts as a carbon source[11].

Soil microbial respiration ( $R_h$ ) was estimated using the model established by Pei et al.[12], and the calculation formula is as follows:

$$R_h = 0.22(Exp(0.913T) + \ln(0.3145R + 1)) \times 30 \times 46.5\% \quad (1)$$

Where:  $R_h$  is soil microbial respiration, in  $gC \cdot m^2 \cdot a$ ;  $T$  is the annual mean air temperature in the study area, in  $^{\circ}C$ ;  $R$  is the annual mean precipitation in the study area, in mm.

#### ② NEP Data Trend Analysis

To quantitatively describe the temporal variation and spatiotemporal evolution characteristics of NEP in the study area over the 23-year period, univariate linear regression analysis was performed pixel by pixel from 2000 to 2022 to reflect the interannual dynamics of vegetation NEP. The formula for the trend slope is given as follows[13-14]:

$$\text{Slope} = \frac{n \times \sum_{i=1}^n (i \times \text{NEP}_i) - \sum_{i=1}^n i \sum_{i=1}^n \text{NEP}_i}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (2)$$

Where: Slope represents the trend slope of each pixel over the 23-year period; n is the total number of research samples, where n = 23 in this study; NEP<sub>i</sub> denotes the NEP value in the i-th year. When Slope > 0, the pixel shows an increasing trend in the time series; otherwise, it shows a decreasing trend. The magnitude of Slope indicates the rate of increase or decrease.

### ③ Linear correlation analysis

To investigate the trends in carbon sink changes and the relationships between NEP and multiple influencing factors over the 23-year period, univariate linear regression and multiple linear regression models were employed in this study. The univariate linear regression model is expressed as follows:

$$y = \alpha + \beta x \quad (3)$$

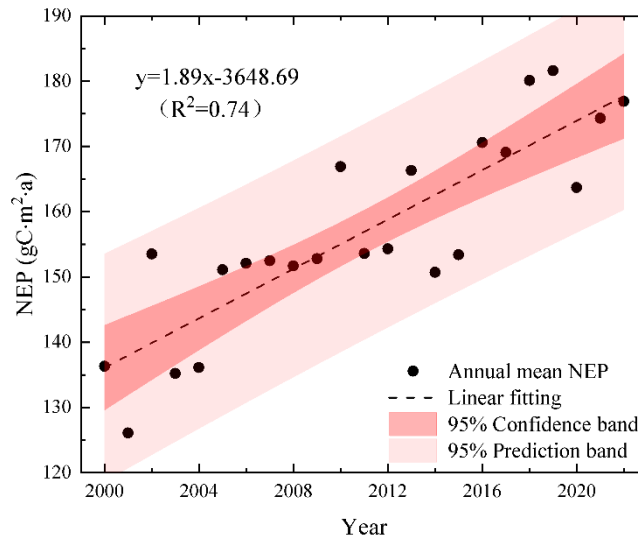
Where x represents the time series from 2000 to 2022, α is the intercept, and β is the slope. When β > 0, the model indicates an increasing trend; otherwise, it indicates a decreasing trend. The magnitude of β reflects the rate of the increasing or decreasing trend.

## 3. RESULTS AND DISCUSSION

### 3.1. Spatiotemporal Variation Analysis of NEP in Qilian Mountain National Park

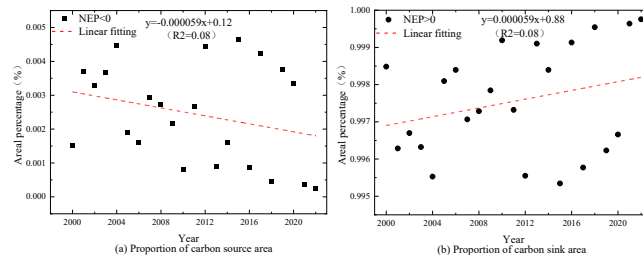
#### 3.1.1. Time Variation Analysis

To investigate the spatial variation of NEP in Qilian Mountain National Park, a linear fitting was conducted on the annual NEP values in this study, as shown in Figure 2. It can be seen that NEP in this region has exhibited a fluctuating upward trend since 2000, with a slope of 1.89. The maximum value of 181.6 gC·m<sup>-2</sup>·a occurred in 2019, and the minimum value of 126.1 gC·m<sup>-2</sup>·a appeared in 2001.



**Fig 2.** Linear fitting of NEP

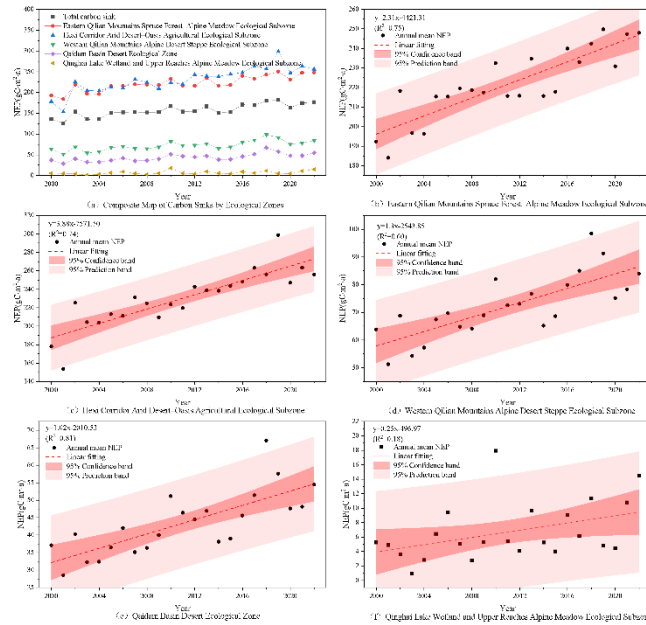
In terms of the proportion of carbon sources and sinks, the area is dominated by carbon sinks, with carbon sources accounting for less than 0.5%, as shown in Figure 3. From 2000 to 2022, the percentage of carbon source areas (NEP < 0) in the total area of Qilian Mountain National Park showed a fluctuating but overall decreasing trend.



**Fig 3.** Percentage of carbon source and carbon sink areas

Among them, the proportion of carbon source area reached its maximum of 0.4656% in 2015, and slight increases in carbon source areas occurred in 2012, 2015, 2017, 2019, and 2020. According to survey data, from 2000 to 2017, vegetation conditions in the Qilian Mountains exhibited a pattern of "overall improvement with local degradation". The main causes of degradation were intensive human activities, such as overgrazing, illegal logging, and irrational tourism development. In 2019, the annual precipitation in the Qinghai section was 530.2 mm, 10% higher than the average of the recent decade, while the sunshine duration was 2561.3 h, slightly 5.3% lower than the decadal average. In 2020, annual precipitation ranged from 277.4 to 504.5 mm, 20.1% to 28.8% lower than the recent decadal average, whereas snow-covered area during the snow season increased compared with the past decade. Under the combined effects of increases and decreases in annual precipitation and other factors during these two years, the area where soil microbial respiration exceeded net ecosystem productivity increased slightly. Over the past 23 years, the area of carbon sink regions (NEP > 0) in Qilian Mountain National Park has shown a fluctuating upward trend, followed by a steady upward trend after 2020. Since the release of policies such as the Three-Year Action Plan for Comprehensive Ecological Environment Management in the Muli Mining Area and the Qinghai Section of the Southern Qilian Mountains and the Qilian Mountains Ecological Green Book (2020) in 2020, a series of ecological projects have been implemented in this region, including mining pit backfilling, slag heap greening, slope treatment, and vegetation restoration. These measures have greatly improved the ecological quality of Qilian Mountain National Park, significantly enhanced ecosystem coverage and productivity, substantially increased carbon sequestration, and led to an obvious upward trend in net ecosystem productivity. Accordingly, the area of carbon source regions has decreased significantly and tended to be stable after 2020.

To further investigate the interannual variations in net ecosystem productivity across five distinct ecological subzones, this study calculated and analyzed the 22-year changes in NEP for each subzone separately, as shown in Figure 4. It can be clearly observed that NEP exhibits a fluctuating upward trend in all five ecological subzones of Qilian Mountain National Park, with considerable differences in growth rates.



**Fig 4.** Linear Fitting of Ecological Subzones

The East Qilian Mountains Spruce Forest–Alpine Meadow Ecological Subzone is located in the eastern part of the Qilian Mountains on the northeastern Qinghai-Tibet Plateau. This region boasts rich biodiversity, with a community structure consisting of arbor, shrub, and herb layers. The arbor layer is dominated by spruce forests, and studies have shown that spruce forests in the Qinghai region have the highest carbon sequestration capacity[15]. Meanwhile, the region is endowed with abundant water resources, including numerous rivers and lakes, and features a temperate to frigid climate, providing a favorable habitat for cold-tolerant and hygrophilous plants[16]. As shown in Figure 4(b), over the 23-year period, NEP fluctuated within the range of 184.03–249.8 gC·m<sup>2</sup>·a, displaying a fluctuating upward trend. The mean NEP was 221.61 gC·m<sup>2</sup>·a, the cumulative NEP reached 5097.12 gC·m<sup>2</sup>·a, and the annual change rate was 2.31, indicating rapid growth. The minimum NEP occurred in 2001, corresponding to poor hydrothermal conditions and low sunshine duration. The maximum NEP appeared in 2019 due to abundant rainfall. Judging from the cumulative and multi-year NEP values, the East Qilian Mountains Spruce Forest–Alpine Meadow Ecological Subzone serves as the most important carbon sink contribution area[17].

The Hexi Corridor Arid Desert–Oasis Agricultural Ecological Subzone is situated in the northern part of the study area, lying on the ecotone between the East Qilian Mountains Spruce Forest–Alpine Meadow Ecological Subzone and the Hexi Corridor Arid Desert–Oasis Agricultural Ecological Subzone. The climate transitions from arid to alpine, and vegetation types shift from agricultural oases to alpine meadows and spruce forests. Owing to the interaction between the two ecosystems, this region exhibits high biodiversity and ecological fragility, making it vulnerable to climate change and human activities. As shown in Figure 4(c), over the 23-year period, NEP fluctuated between 153.59 and 298.63 gC·m<sup>2</sup>·a, showing a fluctuating upward trend. The average NEP was 230.13 gC·m<sup>2</sup>·a, the cumulative NEP amounted to 5292.93 gC·m<sup>2</sup>·a, and the annual change rate was 3.88, representing rapid growth. The minimum NEP occurred in 2001 under poor hydrothermal conditions and insufficient sunshine duration, while the maximum was recorded in 2019. With high biodiversity, rich species composition, and favorable hydrothermal combination, this region constitutes an important carbon sink ecological zone.

The West Qilian Mountains Alpine Desert Steppe Ecological Subzone is located in the western part of the Qilian Mountains. Vegetation in this region is characterized by the alternating distribution of alpine steppe and alpine desert, with relatively low biodiversity and few vegetation types. Vegetation coverage varies with topography and climatic conditions, showing distinct vertical zonality and

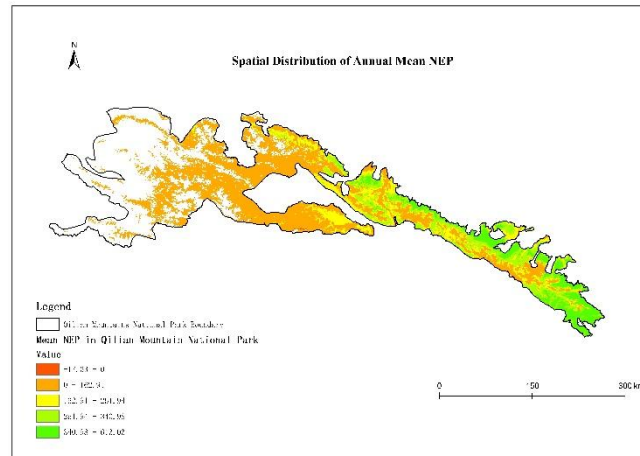
regional differentiation[18–19]. As shown in Figure 4(d), over the 23-year period, NEP fluctuated within the range of 51.23–91.22 gC·m<sup>2</sup>·a, displaying a fluctuating upward trend. The mean NEP was 72.16 gC·m<sup>2</sup>·a, the cumulative NEP reached 1659.63 gC·m<sup>2</sup>·a, and the annual change rate was 1.3, indicating steady growth. The minimum NEP occurred in 2001 due to poor hydrothermal conditions and short sunshine duration, while the maximum was observed in 2018 with abundant rainfall. Vegetation coverage in this area is dominated by steppe. With natural restoration and human intervention in recent years, the ecological environment has improved and biodiversity has increased, classifying this region as a significant carbon sink area.

The Qaidam Basin Desert Ecological Subzone features a typical plateau continental climate, characterized by cold and dry conditions, high annual total radiation, a fragile ecosystem, harsh ecological environment, limited ecosystem service functions, infertile soils, and low vegetation coverage. The dominant vegetation types are desert shrubs, small shrubs, and subshrubs, placing this region in a desert-steppe transition zone[20]. As shown in Figure 4(e), over the 23-year period, NEP fluctuated between 28.51 and 67.06 gC·m<sup>2</sup>·a, showing a fluctuating upward trend. The mean NEP was 43.39 gC·m<sup>2</sup>·a, cumulative NEP was 998 gC·m<sup>2</sup>·a, and the annual change rate was 1.02, indicating steady growth. The minimum NEP occurred in 2001 under poor hydrothermal conditions and low sunshine duration, whereas the maximum appeared in 2018 with abundant precipitation. Despite artificial ecological restoration measures, strengthened management and further biodiversity enhancement are still required. With NEP values all below 100 gC·m<sup>2</sup>·a, this region remains a weak carbon sink area.

The Qinghai Lake Wetland and Upper Reaches Alpine Meadow Ecological Subzone is located in the ecotone shared by the West Qilian Mountains Alpine Desert Steppe Ecological Subzone and the East Qilian Mountains Spruce Forest–Alpine Meadow Ecological Subzone. The ecosystem in this transition zone is highly fragile, and its climate is mainly influenced by the West Qilian Mountains alpine desert steppe subzone. The alpine climate and insufficient soil moisture reduce the metabolic rates of plants and microorganisms, thereby limiting the carbon uptake efficiency of vegetation, resulting in relatively low carbon sequestration in this region. As shown in Figure 4(f), over the 23-year period, NEP fluctuated between 0.94 and 17.94 gC·m<sup>2</sup>·a, showing a fluctuating upward trend. The mean NEP was 6.69 gC·m<sup>2</sup>·a, the cumulative NEP was 153.9 gC·m<sup>2</sup>·a, and the annual change rate was 0.25, indicating a slow upward trend. The minimum NEP occurred in 2001 under poor hydrothermal conditions and insufficient sunshine duration, while the maximum was reached in 2010 with abundant sunshine. Although NEP values remain at a low level, this region can still be defined as a weak carbon sink area.

### 3.1.2. Spatial Change Analysis

The spatial pattern of NEP in Qilian Mountain National Park from 2000 to 2022 shows significant spatial heterogeneity, as shown in Figure 5, with a gradual decreasing trend from southeast to northwest. The multi-year mean NEP of Qilian Mountain National Park is 156.9 gC·m<sup>2</sup>·a, and the cumulative multi-year average NEP is 3608.9 gC·m<sup>2</sup>·a. The area of carbon sink regions (NEP > 0) is approximately 50,077.01 km<sup>2</sup>, accounting for 99.755% of the total area. The area of carbon source regions (NEP < 0) is about 122.99 km<sup>2</sup>, accounting for 0.245% of the total area. Therefore, Qilian Mountain National Park is identified as a prominent carbon sink region.



**Fig 5.** Spatial Distribution of Annual Mean NEP

High NEP values in carbon sink regions are mainly distributed in the southeastern part of Qilian Mountain National Park, including the East Qilian Mountains Spruce Forest–Alpine Meadow Ecological Subzone and the Hexi Corridor Arid Desert–Oasis Agricultural Ecological Subzone. The arbor layer in this region is dominated by *Picea crassifolia* (Qinghai spruce) with absolute dominance, and large areas of *Juniperus przewalskii* (Qilian juniper) are distributed on near-sunny mountain slopes. In addition, shrubs are an important plant group in the eastern Qilian Mountains, occurring from low mountains to alpine zones [21]. Previous studies have confirmed that these vegetation species possess high carbon sequestration capacity. Low NEP values in carbon sink regions are mainly concentrated in the central and northwestern parts of the park, including the Qinghai Lake Wetland and Upper Reaches Alpine Meadow Ecological Subzone, the West Qilian Mountains Alpine Desert Steppe Ecological Subzone, and the Qaidam Basin Desert Ecological Subzone. Vegetation in these areas is dominated by cold-tolerant herbaceous plants, as well as subalpine shrubs and alpine subnival sparse vegetation transitioning to higher elevations. Such vegetation generally exhibits low carbon sequestration. Moreover, the cold and arid conditions in these regions are unfavorable for plant growth.

### 3.1.3. Trend Variation of NEP in Qilian Mountain National Park

In this study, the results of trend analysis were classified into six change categories according to significance level and slope value: extremely significant increase, significant increase, non-significant increase, non-significant decrease, significant decrease, and extremely significant decrease, as shown in Table 1.

**Table 1** Slope grading and classification statistics

Slope value	P value	Classification level	Proportion
Slope<0	P<0.01	Extremely significant decrease	0.3%
Slope<0	0.01<P<0.05	Significant decrease	0.1%
Slope<0	0.05<P	Nonsignificant decrease	0.8%
Slope>0	P<0.01	Extremely significant increase	73.4%
Slope>0	0.01<P<0.05	Significant increase	13.1%
Slope>0	0.05<P	Nonsignificant increase	12.3%

According to the spatial distribution of the 23-year NEP trend in Qilian Mountain National Park (Figure 6), NEP shows an increasing trend across most areas of the park. Regions with an increasing trend account for 98.8% of the total area, among which extremely significant increase accounts for 73.4%, significant increase for 13.1%, and nonsignificant increase for 12.3%. Driven by natural restoration capacity and artificial ecological restoration measures, along with increased precipitation, the carbon sequestration capacity of vegetation in these regions has improved significantly. Areas with decreasing NEP are sparse and scattered, accounting for only 1.2% of the total area. Among them, extremely significant decrease accounts for 0.3%, significant decrease for 0.1%, and

nonsignificant decrease for 0.8%. Spatially, these areas exhibit a patchy distribution at high elevations, where conditions are unfavorable for vegetation growth and also limit the effectiveness of human ecological restoration.

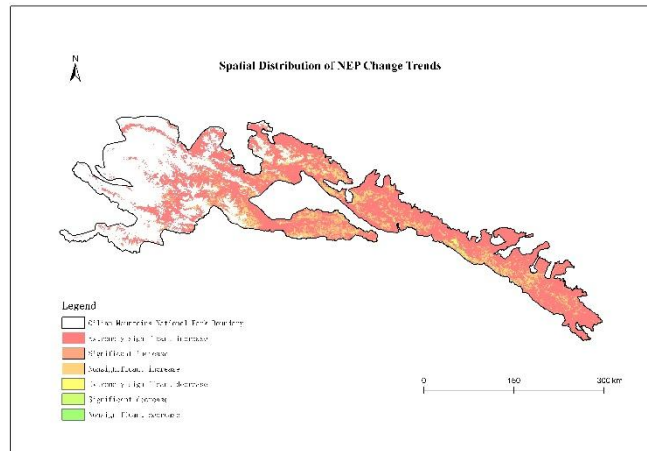


Fig 6. Spatial Distribution of NEP Change Trends

### 3.2. Analysis of the Relationship Between NEP and Climatic Factors

The carbon sequestration process during plant growth is complex and is jointly influenced by multiple factors; a single factor cannot adequately explain or analyze this process. Therefore, this study employs the Spearman correlation analysis to examine the effects of temperature, precipitation, relative humidity, and sunshine duration on carbon sink dynamics, as shown in Figure 7 and Table 2.

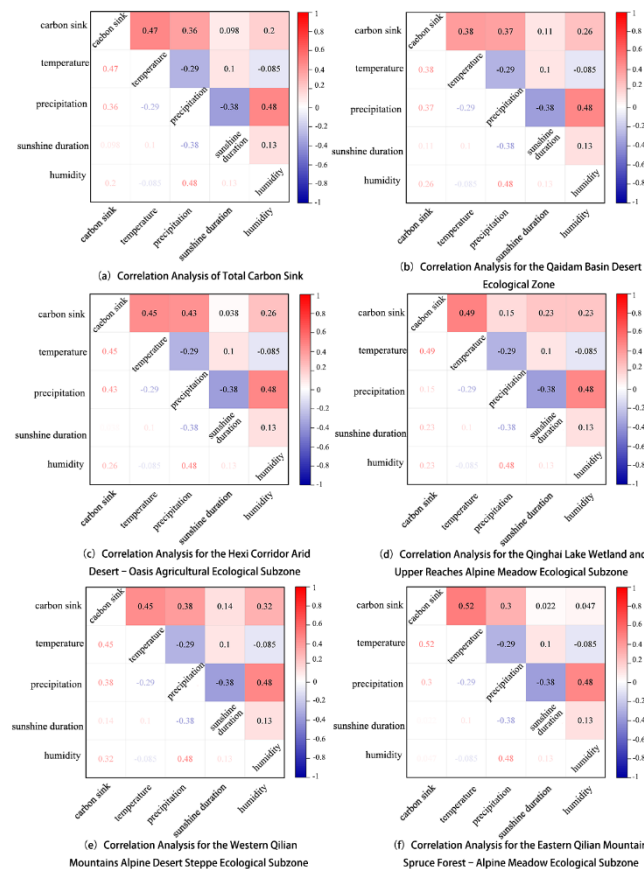


Fig 7. Spearman correlation analysis

**Table 2** Ranking of Correlation Factors

Region	Ranking of Correlation Factors
Whole Region	Temperature (0.47) > Precipitation (0.36) > Humidity (0.20) > Sunshine Duration (0.098)
Qaidam Basin Desert Ecological Zone	Temperature (0.38) > Precipitation (0.37) > Humidity (0.26) > Sunshine Duration (0.11)
Hexi Corridor Arid Desert–Oasis Agricultural Ecological Subzone	Temperature (0.45) > Precipitation (0.43) > Humidity (0.26) > Sunshine Duration (0.038)
Qinghai Lake Wetland and Upper Reaches Alpine Meadow Ecological Subzone	Temperature (0.49) > Humidity (0.23) = Sunshine Duration (0.23) > Precipitation (0.15)
Western Qilian Mountains Alpine Desert Steppe Ecological Subzone	Temperature (0.45) > Precipitation (0.38) > Humidity (0.32) > Sunshine Duration (0.14)
Eastern Qilian Mountains Spruce Forest–Alpine Meadow Ecological Subzone	Temperature (0.52) > Precipitation (0.30) > Humidity (0.047) > Sunshine Duration (0.022)

The results indicate that carbon sinks in Qilian Mountain National Park are mainly influenced by temperature, precipitation, and humidity, all showing a positive correlation trend. Increasing temperature generally accelerates plant metabolism, including photosynthetic rate. Within an appropriate range, higher temperature promotes vegetation to absorb more carbon dioxide for photosynthesis, thereby fixing more carbon. In addition, a warmer climate prolongs the growing season by advancing spring onset and delaying autumn senescence, which allows plants more time for photosynthesis and carbon fixation. Increased precipitation improves soil water availability, facilitating better water and nutrient uptake by plant roots, promoting vegetation growth and biomass accumulation, and thus enhancing carbon sequestration capacity. Higher humidity indicates increased moisture content in the atmosphere. Appropriate humidity reduces transpiration water loss from plants and maintains favorable water balance, helping sustain high photosynthetic efficiency over extended periods and further promoting carbon fixation efficiency.

Carbon sink dynamics in the Qinghai Lake Wetland and Upper Reaches Alpine Meadow Ecological Subzone are mainly influenced by temperature, sunshine duration, and humidity, which are determined by the vegetation characteristics and ecosystem structure of this subzone. In alpine regions, appropriate warming can prolong the growing season, accelerate photosynthetic rates, and enhance plant CO<sub>2</sub> uptake capacity, thereby affecting carbon sink intensity. Sunshine duration directly regulates photosynthesis and further influences vegetation carbon sequestration capacity. In this subzone, longer sunshine duration provides sufficient light energy for alpine meadow plants, promoting vegetation growth and reproduction and thus increasing carbon fixation rates. Alpine meadow and wetland ecosystems are highly sensitive to water conditions; maintaining suitable humidity favors plant growth and facilitates carbon dioxide fixation.

In recent years, numerous observations and studies have confirmed that Northwest China is becoming increasingly warm and humid. Such warm, humid hydrothermal conditions provide favorable environments for vegetation growth, thereby enhancing the carbon sequestration capacity of the Qilian Mountain National Park region [22–24].

#### 4. CONCLUSION

Using long-term remote sensing data, this study analyzed the spatiotemporal variation characteristics of NEP in Qilian Mountain National Park from 2000 to 2022 (a 23-year period) and discussed the potential relationships between NEP and climatic factors including temperature, precipitation, humidity, and sunshine duration in the study area. The main conclusions are as follows:

(1) From 2000 to 2022, the net ecosystem productivity (NEP) of Qilian Mountain National Park showed an overall fluctuating upward trend, dominated by carbon sinks, with carbon sources

accounting for less than 0.5%, indicating that the ecosystem is currently a significant net carbon sink. Spatially, NEP exhibited a distinct pattern of **“high in the southeast and low in the northwest”**. High-value areas were mainly concentrated in the Eastern Qilian Mountains spruce forest–alpine meadow and Hexi Corridor oasis agricultural ecological subzones with favorable hydrothermal conditions, while low-value areas were distributed in the harsh climate zones of the Qaidam Basin desert and the Western Qilian Mountains alpine desert steppe.

(2) During the study period, NEP in the park showed an overall increasing trend, with 98.8% of the region exhibiting rising NEP, including 73.4% with extremely significant increase and 13.1% with significant increase. The proportion of carbon source areas fluctuated downward. After 2020, the implementation of ecological restoration projects continuously improved carbon sequestration capacity, and areas with decreasing NEP accounted for only 1.2%, scattered sporadically in high-altitude zones.

(3) NEP in Qilian Mountain National Park was positively correlated with temperature, precipitation, humidity, and sunshine duration. Temperature was the primary driving factor, followed by precipitation and humidity, while sunshine duration had a relatively weak influence. The dominant climatic factors varied slightly among different ecological subzones. The warming and humidification of the regional climate prolonged the vegetation growing season and enhanced photosynthetic and carbon sequestration efficiency, which are the key natural reasons for the strengthened carbon sink function.

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