Postprint: Simulation and Dynamic Change Analysis of Carbon Source/Sink in Typical Grassland Communities in the Three-River-Source Region, 2001–2017

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Abstract

Carbon source/sink is an important indicator for interpreting the Earth' s atmospheric carbon cycle process, and investigating the carbon source/sink characteristics of the Sanjiangyuan region is of great significance for understanding the response of vegetation in this area to global climate change. Sanjiangyuan is dominated by fragile grassland ecosystems and is highly sensitive to global climate change. The ecological environment of this region is extremely fragile, and harsh conditions in most areas lead to scarce measured data, making it difficult to conduct a complete analysis of the spatiotemporal patterns of carbon source/sink in this region. Therefore, by taking five typical grassland communities in Sanjiangyuan (Potentilla fruticosa, Stipa purpurea, Saussurea, Kobresia pygmaea, and Carex moorcroftii communities) as research subjects, based on the BIOME-BGC model, and utilizing geographic data, meteorological data, and vegetation physiological parameters, we obtained simulated values of net primary productivity (NPP) and net ecosystem productivity (NEP) for grassland communities in Sanjiangyuan from 2001 to 2017, and conducted a comprehensive analysis of the changing characteristics of NPP and NEP in grassland communities, their correlation with temperature and precipitation, and changes in carbon use efficiency. The results show that: NPP and NEP in the Sanjiangyuan region exhibit a gradually decreasing trend from southeast to northwest in terms of spatial pattern; the multi-year NPP of the five typical grassland communities all show an increasing trend year by year, with an average value of 196.06 g C · m -2 · a -1. Among them, the Potentilla fruticosa community has the highest average NPP at 342.00 g C · m -2 · a -1, while the Carex moorcroftii community has the lowest average NPP at 55.93 g C · m -2 · a -1; the multi-year average NEP of the five grassland communities is 49.02 g C · m -2 · a -1, with NEP values of Potentilla fruticosa, Stipa purpurea, and

Carex moorcroftii showing a slow upward trend, while Saussurea and Kobresia pygmaea communities show a slow downward trend. The study found that the grassland ecosystem in Sanjiangyuan has a significant carbon sink effect, and different communities show varying degrees of response in NPP and NEP to temperature and precipitation. NPP of all five communities is significantly positively correlated with temperature, but the correlation between NPP, NEP and precipitation is relatively low; all five communities have strong carbon sequestration potential, and except for Potentilla fruticosa, the carbon use efficiency of the other vegetation communities is above 0.625.

Full Text

Simulation and Dynamic Change Analysis of Carbon Source/Sink in Typical Grassland Communities in the Three River Source Area from 2001 to 2017

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Abstract

Carbon source/sink is a crucial indicator for understanding atmospheric carbon cycling processes. Investigating the carbon source/sink characteristics of the Three River Source Area is essential for comprehending how vegetation in this region responds to global climate change. Dominated by fragile grassland ecosystems that are highly sensitive to global climate change, the Three River Source Area features an extremely vulnerable ecological environment. Harsh conditions across most of the region result in scarce measured data, making comprehensive analysis of the carbon source/sink spatiotemporal patterns challenging. This study selected five typical grassland communities—*Potentilla fruticosa*, *Stipa purpurea*, *Saussurea japonica*, *Kobresia pygmaea*, and *Carex moorcroftii*—as research objects in the Three River Source Area. Using the BIOME-BGC model with geographic data, meteorological data, and vegetation physiological parameters, we simulated net primary productivity (NPP) and net ecosystem productivity (NEP) of grassland communities from 2001 to 2017. We comprehensively analyzed the temporal variation characteristics of NPP and NEP, their correlations with temperature and precipitation, and changes in carbon use efficiency (CUE).

Results showed that the spatial pattern of NPP and NEP in the Three River Source Area gradually decreased from southeast to northwest. The multi-year average NPP across the five typical grassland communities was 196.06 g $C \cdot m^{-2} \cdot yr^{-1}$, showing a stable increasing trend annually. Among them, *Potentilla fruticosa* exhibited the highest average NPP at 342.00 g $C \cdot m^{-2} \cdot yr^{-1}$, while *Carex moorcroftii* showed the lowest at 55.93 g $C \cdot m^{-2} \cdot yr^{-1}$. The annual mean NEP across the five grassland communities was 49.02 g $C \cdot m^{-2} \cdot yr^{-1}$. The NEP values of *Potentilla fruticosa*, *Stipa purpurea*, and *Carex moorcroftii* increased slowly, whereas those of *Saussurea japonica* and *Kobresia pygmaea* showed a gradual decline. The grassland ecosystem in the Three River Source Area demonstrates significant carbon sink function. NPP exhibited a significant positive correlation with temperature across all communities, while correlations between NPP, NEP, and precipitation were weak. All five communities possess strong carbon sequestration potential. Except for *Potentilla fruticosa*, the carbon utilization efficiency of other vegetation communities exceeded 0.625.

Keywords: carbon source/sink; NPP; NEP; BIOME-BGC model; climate factor; Three River Source Area

Introduction

Grasslands are an indispensable component of natural ecosystems, providing ecological functions such as windbreak and sand fixation, biodiversity support, and water conservation. They not only promote material and energy cycling in the biosphere but also possess carbon sequestration capacity that regulates global carbon balance and maintains climate stability. Net Primary Productivity (NPP), also known as net primary production, represents the energy accumulated by plants through photosynthesis after subtracting autotrophic respiration. NPP reflects plant growth status, regional ecosystem health, and serves as a critical indicator of global terrestrial carbon balance and cycling. Net Ecosystem Productivity (NEP), calculated as NPP minus heterotrophic respiration, reflects ecosystem material cycling and energy flow. Its magnitude directly indicates the strength of carbon source/sink and represents a key metric for characterizing carbon source/sink dynamics.

With rapid global socioeconomic development, the consumption of natural resources such as petroleum and coal has accelerated, causing continuous increases in atmospheric CO_2 concentration. Current CO_2 levels have exceeded the pre-industrial concentration of 5.04×10^{-3}, marking the beginning of a "new era" of global warming. Since industrialization, global average temperature has risen by approximately 1°C, with the greenhouse effect becoming increasingly severe. These issues have attracted widespread attention from scholars worldwide.

Since the implementation of the International Biological Program in the 1960s, experts have conducted extensive research on key indicators in the global carbon cycle and factors influencing ecosystem carbon cycling. Methods for estimating vegetation biomass primarily include model simulation and traditional field measurement. Field measurement was widely used in early research, estimating grassland biomass based on measured data from study areas. While simple and accurate, this method is destructive and only applicable to small areas, making it difficult to implement in harsh, inaccessible regions. Consequently, model-based estimation of NPP and NEP has become an important and widely applied approach. Model simulation methods have evolved rapidly, initially employing statistical models before developing into light use efficiency models and ecological process models that integrate remote sensing data, such as BIOME-BGC, CASA, and MIAMI models.

Overall, research on carbon cycling processes continues to expand, with methodologies and techniques constantly improving—from traditional field measurements to multi-technology applications, from single-source data to multi-source data fusion, and from local small-scale regions to global scales. Historical data from China over the past millennium indicate that climate change on the Tibetan Plateau occurs earlier than in eastern China, making it a climate change initiation zone with significantly greater amplitude of change than other regions. Consequently, it represents a sensitive area for global climate change.

The Three River Source Area, located in the hinterland of the Tibetan Plateau, features a cold and arid habitat with vegetation in early developmental stages, simple system structure, and grassland-dominated ecosystems. The ecological environment is extremely fragile and difficult to restore once damaged. However, theoretical and practical knowledge about the ecological environment of the Three River Source Area remains limited. Increasing human activity in the region will inevitably bring a series of ecological problems. Therefore, this study selected five typical grassland communities in the Three River Source Area, simulated NPP and NEP values using the BIOME-BGC model, analyzed the dynamic changes of carbon source/sink and vegetation carbon use efficiency, evaluated the impact of climate change on grassland carbon source/sink, revealed the response mechanism of carbon sequestration potential of grassland communities to climate change, and provided references for objectively assessing the carbon source/sink function of the Three River Source ecosystem and conducting practical activities.

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1. Study Area, Data, and Methods

1.1 Study Area

The Three River Source Area is located in southern Qinghai Province, in the hinterland of the Qinghai-Tibet Plateau, with geographical coordinates of 31°39′-36°12′N and 89°45′-102°23′E. This region is the source of the Yangtze River, Yellow River, and Lancang River. The main landform type is mountainous, with an average elevation of 800 m and total land area of 30.25$×10^{4}$ km^2. Grassland accounts for 65.37% of the total area. Significant dry-wet differences exist across regions, with elevation gradually increasing and water-heat combinations decreasing from southeast to northwest. The region features a unique alpine ecosystem. According to vegetation distribution in the Three River Source Area [Figure 1: see original paper], this study selected five sites corresponding to typical grassland vegetation types: *Potentilla fruticosa* community (Banma County), *Kobresia pygmaea* community (Dari County, Henan County), *Saussurea japonica* community (Zaduo County), *Stipa purpurea* community (Qumalai County, Wudaoliang), and *Carex moorcroftii* community (Tuotuo River).

1.2 Data Sources

Vegetation data were obtained from 1:100,000 vegetation classification data, including vegetation types, groups, formations, and categories, ultimately identifying five grassland vegetation types as research objects. Site data were derived from national meteorological station data. Based on grassland distribution in the study area, four benchmark stations (Dari, Xinghai, Nangqian, Golmud) within and surrounding the study area were selected, primarily extracting their elevation and coordinate information. Meteorological data were obtained from the China Meteorological Data Service Center (http://cdc.cma.gov.cn), including daily maximum temperature, minimum temperature, mean temperature, and total precipitation from 2001 to 2017. The Mountain Climate Simulator (MTCLIM) was used to simulate saturated vapor pressure deficit, surface solar radiation, and sunshine duration at each station as input parameters for the BIOME-BGC model. Vegetation physiological parameter data were obtained from literature review, with Table 1 showing the main parameter settings used in this study.

1.3 BIOME-BGC Model

The BIOME-BGC model is a biogeochemical model developed through continuous improvement of the Biome-FOREST-BGC model. Based on meteorological data (temperature, precipitation, CO_2 concentration), basic geographic data, and vegetation physiological parameters, the model simulates daily vegetation growth by modeling photosynthesis, autotrophic respiration, heterotrophic respiration, and soil litter decomposition processes. The model operates on a daily time step, simulating the cycling of three key factors—carbon, water, and nitrogen—to estimate vegetation growth status. The model outputs include initialization files (.ini), daily meteorological data (metdata), and results files (.ann). Key formulas in the model include:

1) **Stomatal conductance (gs) calculation:**

$$gs = SF \times g_{max} \times f(VPD) \times f(T_{min})$$

where g_{max} is maximum stomatal conductance, SF is the limiting stress function, VPD is vapor pressure deficit, T_{min} is minimum temperature, and ψ is soil water potential.

2) **Photosynthesis rate (A) calculation:**

$$A = \min(W_c, W_j)$$

where A_v is the photosynthetic rate when RuBP (a five-carbon sugar crucial in photosynthesis) is saturated, established by Farquhar and Von

Caemmerer:

$$A_v = V_{cmax} \frac{C_i - \Gamma_j}{C_i + K_c(1 + p_{O_2}/k_o)}$$

where V_{cmax} is the maximum carboxylation capacity of Rubisco enzyme (a carboxylase crucial in photosynthesis), C_i is intercellular CO_2 concentration, Γ_j is the light compensation point, K_c is the Michaelis constant for CO_2, p_{O_2} is intercellular O_2 partial pressure, R_d is leaf respiration rate in light, and k_o is the competitive inhibition constant for O_2.

Maximum carboxylation capacity (Vcmax) calculation:

$$V_{cmax} = N_{leaf} \times act \times flnr/(fnr \times sla)$$

where act is Rubisco enzyme activity, $flnr$ and fnr are the proportions of leaf nitrogen and leaf Rubisco enzyme molecules, respectively, sla is specific leaf area, and C/N_{leaf} is the carbon-to-nitrogen ratio in leaves.

3) **Radiation-limited photosynthesis rate (Aj):**

$$A_j = J \frac{C_i - \Gamma_j}{C_i + 2\Gamma_j}$$

where J is the electron transport rate.

4) **Autotrophic respiration rate (R) calculation:**

$$R = M_{rpern} \times leaf_n$$

where M_{rpern} is plant nitrogen content, $leaf_n$ is leaf nitrogen concentration, and R_c is vegetation respiration rate at 20°C.

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2. Results

2.1 Model Validation

Comparisons between simulated and measured NPP data revealed that some simulated sites did not exactly coincide with measured points, and harsh conditions near some simulated sites resulted in missing measured values. Table 2 shows that the simulated NPP value near the Dari station was significantly lower than the measured value because this site is located in the Bayan Har Mountains at higher elevation than the nearest measurement point. The simulated value at the Wudaoliang station was also lower than the measured point due to the large distance between them. Other groups showed relatively small differences.

Comparisons between simulated NEP data and BEPS model simulation values (Table 3) for the validation period (July-August) showed small differences at the Dari station, while the other four stations showed slightly higher values than the validation data. These results indicate that the simulated values are relatively close to actual values with high simulation accuracy, demonstrating that the model can reliably simulate carbon source/sink dynamics in the Three River Source Area.

2.2 Temporal Variation of NPP and NEP

2.2.1 Daily Variation Trends The daily variation characteristics of NPP and NEP for grassland vegetation in the Three River Source Area (represented by *Potentilla fruticosa*) showed that the active growing period gradually shortened from southeast to northwest [Figure 2: see original paper], decreasing from 250 days to 130 days. Daily NPP peaks, sorted from high to low, were: *Potentilla fruticosa* (2.15 g $C \cdot m^{-2} \cdot d^{-1}$), *Stipa purpurea* (1.85 g $C \cdot m^{-2} \cdot d^{-1}$), *Saussurea japonica* (1.61 g $C \cdot m^{-2} \cdot d^{-1}$), *Kobresia pygmaea* (1.19 g $C \cdot m^{-2} \cdot d^{-1}$), and *Carex moorcroftii* (0.8 g $C \cdot m^{-2} \cdot d^{-1}$). NEP values were negative in winter and spring because vegetation respiratory consumption exceeded photosynthetic production during these periods. After spring onset, rising temperatures and increased water-heat availability triggered vegetation growth, causing NEP to increase dramatically. In autumn, leaf senescence and dormancy led to sharp NEP declines.

2.2.2 Interannual Variation Trends Analysis of annual NPP mean values for the five grassland communities from 2001 to 2017 [Figure 3: see original paper] revealed stable increasing trends for all communities, with annual growth rates of 5.63% for *Potentilla fruticosa*, 5.21% for *Stipa purpurea*, 4.84% for *Saussurea japonica*, 4.55% for *Kobresia pygmaea*, and 1.12% for *Carex moorcroftii*. Growth rates were lower in colder regions and higher in areas with better climate conditions. The NPP of *Carex moorcroftii* increased slowly, averaging 68 g $C \cdot m^{-2} \cdot yr^{-1}$, because this community is located in the Kunlun Mountains where cold temperatures limit vegetation growth more than precipitation. Temperature is the limiting factor for vegetation growth in this region.

Annual NEP values [Figure 3: see original paper] showed that *Potentilla fruticosa*, *Stipa purpurea*, and *Carex moorcroftii* increased slowly, while *Saussurea japonica* and *Kobresia pygmaea* showed gradual declining trends. Both NPP and NEP exhibited an inverted "U" shape: stable in spring, increasing dramatically in summer, decreasing sharply in autumn, and stable again in winter. All grassland communities had NEP values greater than 0, indicating that the Three River Source Area functions as a significant carbon sink, with carbon sink capacity gradually weakening from southeast to northwest. The ranking of carbon sink function from strong to weak was: *Potentilla fruticosa* > *Stipa purpurea* > *Saussurea japonica* > *Kobresia pygmaea* > *Carex moorcroftii*.

2.3 Correlation Analysis

2.3.1 Correlation with Precipitation Statistical analysis of annual precipitation at the five vegetation sites showed that *Potentilla fruticosa* had the largest average annual precipitation increase, though not exceeding a certain threshold annually. All five vegetation types showed R^2 values greater than 0.5, indicating significant correlations between grassland communities and precipitation. However, correlation analysis between NPP, NEP and precipitation [Figure 4: see original paper] revealed weak relationships, with all R^2 values below 0.2. NEP-precipitation correlation coefficients were: *Saussurea japonica* ($R^2 = 0.1239$), *Kobresia pygmaea* ($R^2 = 0.0006$), *Stipa purpurea* ($R^2 = 0.00003$), *Potentilla fruticosa* ($R^2 = 0.04$), and *Carex moorcroftii* ($R^2 = 0.0003$). These results indicate that NPP and NEP are not significantly affected by precipitation, consistent with findings from Zhao et al. and Pei et al.

2.3.2 Correlation with Temperature Similarly, statistical analysis of annual temperature [Figure 5: see original paper] showed an overall fluctuating upward trend, with *Carex moorcroftii* showing the fastest temperature increase at approximately 0.08°C per year. Correlation analysis revealed significant positive relationships between NPP and temperature for all communities, with R^2 values of *Stipa purpurea* ($R^2 = 0.6968$), *Carex moorcroftii* ($R^2 = 0.525$), *Kobresia pygmaea* ($R^2 = 0.6235$), *Saussurea japonica* ($R^2 = 0.3775$), and *Potentilla fruticosa* ($R^2 = 0.2163$). All R^2 values exceeded 0.2, indicating significant correlations. In contrast, NEP showed weaker correlations with temperature. The overall correlation between NPP and temperature showed an opposite trend to the spatial distribution of temperature because severe cold limits vegetation growth, and when this limiting factor improves, it strongly promotes vegetation growth.

2.4 Carbon Use Efficiency (CUE) Analysis

Carbon Use Efficiency (CUE) is the ratio of NPP to Gross Primary Productivity (GPP), reflecting vegetation' s ability to absorb and fix carbon. The multi-year average CUE of the five grassland communities was 0.49, decreasing from southeast to northwest. Daily CUE values showed an obvious convex pattern [Figure 6: see original paper], with no significant peaks or troughs. Spatially, CUE values gradually decreased from (0.49–0.52) in the southeast to (0.42–0.45) in the northwest, indicating declining carbon sequestration potential per unit area annually.

Annual CUE trends [Figure 6: see original paper] showed that *Carex moorcroftii* exhibited relatively obvious fluctuating increases, while *Stipa purpurea* showed large fluctuations but an overall stable trend. *Kobresia pygmaea*, *Saussurea japonica*, and *Potentilla fruticosa* showed significant declining trends. Spatially, from southeast to northwest, the trend shifted from slow decline to slow increase. Studies indicate that CUE is negatively correlated with temperature overall. With precipitation trends remaining relatively stable while temperatures show significant increases, vegetation growth in alpine regions remains limited even under modest warming, resulting in unclear CUE change trends. Degraded areas show lower CUE values, and the spatial pattern of CUE changes in the five southeastern grassland communities aligns with existing research.

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3. Conclusions

1) Typical grassland communities in the Three River Source Area function as carbon sinks, with carbon sink capacity strengthening during 2001–2017. The active growing period for grassland vegetation occurs during days 120–240 of the year. All communities showed increasing NPP trends, with *Carex moorcroftii* having the lowest NPP value (68 g $C \cdot m^{-2} \cdot yr^{-1}$), less than one-tenth of *Potentilla fruticosa* (342.00 g $C \cdot m^{-2} \cdot yr^{-1}$). The average annual NEP across the study area exceeded 20 g $C \cdot m^{-2} \cdot yr^{-1}$, with a mean value of 55.93 g $C \cdot m^{-2} \cdot yr^{-1}$, indicating significant carbon sink function.

2) All communities exhibited high CUE values. *Kobresia pygmaea*, *Stipa purpurea*, *Saussurea japonica*, and *Carex moorcroftii* had CUE values above 0.625, demonstrating strong carbon sequestration potential. Spatially, vegetation carbon sequestration potential gradually decreased in the southeastern region and increased in the northwestern region.

3) NPP showed significant positive correlation with temperature. The R^2 values for *Stipa purpurea* ($R^2 = 0.6968$), *Carex moorcroftii* ($R^2 = 0.525$), and *Kobresia pygmaea* ($R^2 = 0.6235$) all exceeded 0.5, indicating significant correlations. Many datasets in this study demonstrate unique spatial distribution patterns. From southeast to northwest across the Three River Source Area, elevation increases while water-heat combinations decrease, causing vegetation to transition from tall, dense shrubs and trees to sparse, low-growing cold- and drought-resistant alpine plants, with NPP and NEP values gradually decreasing while carbon sequestration potential increases.

4) Further research is needed on parameter optimization settings for the BIOME-BGC model.

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