frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 23 January 2023
DOI 10.3389/fenvs.2022.922968

Check for updates

OPEN ACCESS

EDITED BY
Russell Doughty,
University of Oklahoma, United States

REVIEWED BY
Zheng Gang Guo,
Lanzhou University, China
Xiaojing Qin,
Henan Polytechnic University, China

*CORRESPONDENCE
Meiling Zhang,
zhangml@gsau.edu.cn

†These authors have contributed equally to this work and share first authorship

SPECIALTY SECTION
This article was submitted to Environmental Informatics and Remote Sensing, a section of the journal Frontiers in Environmental Science

RECEIVED 18 April 2022
ACCEPTED 30 November 2022
PUBLISHED 23 January 2023

CITATION
Wang X, Zhang M, Nazieh S and Nkrumah T (2023), Temporal and spatial distribution of the alpine meadow carbon budget in Gannan, China from 1969 to 2018.
Front. Environ. Sci. 10:922968.
doi: 10.3389/fenvs.2022.922968

Temporal and spatial distribution of the alpine meadow carbon budget in Gannan, China from 1969 to 2018

Xingyu Wang†, Meiling Zhang*†, Stephen Nazieh and Teddy Nkrumah

College of Science, Gansu Agricultural University, Lanzhou, China

In recent years, carbon balance has been a hot research topic both at home and abroad. The grasslands are rich in carbon storage and are also sensitive to climate change, and the Gannan alpine meadow, a distinct type of grassland in Gansu Province, is used as the study area in this paper. The consequences of climate change have a huge impact on human development and can even cause major human disasters. Effective management of climate change is, therefore, a major problem that currently needs to be solved, and grasslands play an indispensable role in the process of carbon deposition in terrestrial ecosystems. The CENTURY model has been used to study the spatial distribution and changes in the carbon budget in the Gannan alpine meadow of Gansu Province over the last 50 years, which is of great significance for climate change management. The results show that 1) the carbon budget has different distribution characteristics in different regions. 2) The spatial distribution of the carbon budget changes over time, as evidenced by the different spatial distribution of the carbon budget in each study stage and quarter. The spatial distribution differs as well. Some areas in the northern part of southern Gansu are carbon sources in spring and carbon sinks in summer, autumn, and winter. The spatial distribution of the carbon budget changes over time and is different at each stage, but it is a carbon sink overall. 3) The Gannan alpine meadow as a whole demonstrated a carbon sink phenomenon from 1969 to 2018, and the carbon balance is a carbon sink. 4) Every year, the carbon sink initially increases and then shows a decreasing trend, with the carbon sink reaching a maximum in August. 5) Temperature and precipitation are positively correlated with net ecosystem productivity (NEP). 6) In the last 50 years, the Gannan alpine meadow has sequestered 43,580.9 gC of carbon. The annual and monthly average NEP values are approximately 871.62 gC/m^2 and 72.635 gC/m^2, respectively.

KEYWORDS

carbon budget, temporal and spatial distribution, alpine meadow, CENTURY model, NEP

10.3389/fenvs.2022.922968

Introduction

Human activities such as burning fossil fuels (Heede et al., 2016) and poor land management have led to a continuous increase in greenhouse gases in the atmosphere (Tian et al., 2016), which has accelerated climate change, particularly in the northern alpine regions (IPCC 2020). Climate change has become one of the most popular research topics because it is a problem that must be addressed for human survival and social and economic development (Zhou et al., 2013). Climate change and human activities clearly have different impacts on different types of grasslands (Berkelhammer et al., 2014). Climate change research studies are extremely beneficial to grassland restoration (Brienen et al., 2020). Human activities such as intensive grazing (Kang, et al., 2013), land cultivation (Zhang, et al., 2019), and afforestation both accelerate and cause grassland degradation (Li et al., 2020). Carbon sequestration by vegetation (Scheiter et al., 2020) is an important way to reduce atmospheric carbon dioxide concentrations and effectively control climate change (Yan et al., 2015). Mitigating global warfare in Min County is the responsibility of the whole nation (Jiang et al., 2019). However, the role of grasslands in carbon sequestration is very crucial (Li et al., 2020).

In recent years, carbon balance has been a hot research topic both at home and abroad. The grasslands are rich in carbon storage and sensitive to climate change, and the Gannan alpine meadow, a distinct type of grassland in Gansu Province, is used as the area of study in this paper. Grassland covers approximately 40% of the world's land area (Zhang et al., 2017) and is one of the most widely distributed types of vegetation. At the same time, grassland ecosystems store approximately 20% of the vegetation and soil carbon (Nagy et al., 2006), so they play an important role in the carbon cycle of the terrestrial ecosystem (Li et al., 2013). China has vast grasslands and abundant natural resources. China's current natural grassland area is $2.80 \times 1{,}063.93 \times 106\ km^2$. Some of the recoverable reserves are large and play an irreplaceable role as forest carbon sinks (Yang et al., 2017). Wang et al. (2016) discovered that the grassland carbon storage in China is 41.67 Pg C, indicating a large carbon sink potential.

Gansu Province is the study area for this paper, and alpine meadows are a typical type of grassland in Gansu, covering a relatively large area and being representative enough to study climate change and carbon balance. Therefore, the focus of this paper is to study the carbon budget of alpine meadows in Gannan. In this paper, NEP is used as a measure of the carbon budget, and it is briefly explained that NEP >0 indicates a carbon sink, and NEP <0 indicates a carbon source.

The carbon sink function (Zhang et al., 2019) of alpine meadows plays an important role in climate regulation. Zhang et al. (2019) investigated the effects of different management models on the carbon storage of alpine meadows in Gannan and discovered that PG, FE, and TG management models could effectively improve the status of degraded grasslands and increase the carbon storage of degraded grassland ecosystems. Li et al. (2020) investigated the changes in vegetation and microorganisms in different degraded grasslands in the Gannan grassland.

Changes in soil C stocks over time can be difficult to measure (Wall et al., 2020), especially when the time scale is short (e.g., annually). Carbon cycling and the greenhouse effect of terrestrial ecosystems (Tobi et al., 2020) can be used to quantitatively evaluate the carbon budget of the ecosystem through carbon source/sink indicators (Trevor et al., 2013) and then to measure the status of climate change. When measuring carbon budgets (NEP), NPP (Zhou et al., 2012), GPP (Li et al., 2013; Hao et al., 2021), and Rh (Zhang et al., 2014) are frequently mentioned. Methods such as the CASA model, CENTURY model, VPM model, and combination of remote sensing (Yin et al., 2020) and GIS are often used to estimate NEP. Using the CASA model, Li et al. (2020) estimated the vegetation carbon budget of the Hexi Corridor (Gansu Corridor) and its response to climate change and discovered that the Hexi Corridor was a carbon source from 2001 to 2016. Precipitation was found to be significantly and positively related to changes in C stock during the growing season (Zhang et al., 2019). The increasing temperature was found to be negatively correlated with the C stock, especially for soil carbon. Using an ecological process model to estimate global and regional C budgets is a widely accepted approach (Zhou et al., 2013). Their research has effectively promoted carbon budget research studies while also providing a reference basis and methods for carbon budget research studies.

The CENTURY model was jointly developed by Colorado State University and the United States Department of Agriculture (Parton et al., 1996). It is now a widely used model for simulating the biogeochemical cycle of terrestrial ecosystems. It can be used to assess the impact of human activities and climate change on terrestrial ecosystems in depth (Yang et al., 2017). The CENTURY model is well suited for studying grassland carbon budgets. Guo et al. (2020) studied the applicability of the CENTURY model in Tianshan, Xinjiang. Their findings indicate that the CENTURY model can be used to investigate the impact of climate change on grasslands. Yang et al. (2017) studied the applicability of the CENTURY model in terrestrial ecosystems and concluded that it performed well in China's terrestrial ecosystems. He proposed that combining the CENTURY model with other remote sensing technologies could become a new trend in carbon budget research studies in the future.

This study used the CENTURY model to estimate the NEP of the Gannan alpine meadow in China from 1969 to 2018, to investigate the temporal and spatial changes of the carbon budget of alpine meadows in Gannan, and to examine the relationship between the carbon stock of the Gannan alpine meadow and climate factors.

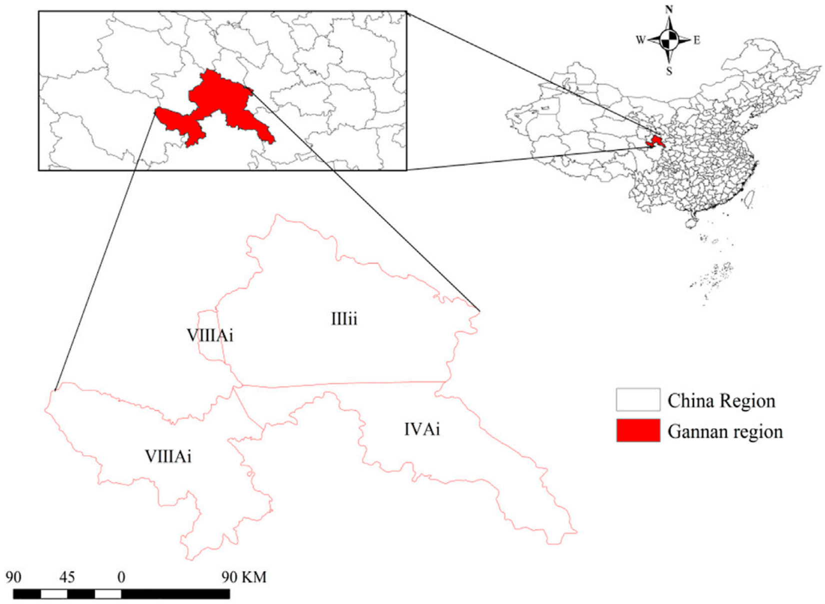

FIGURE 1
Spatial distribution of the meteorological observation station in Gansu, China.

Materials and methods

Study area

The alpine meadow in Gannan, Gansu Province of China (100°46′–104°44′E, 33°06′–36°10′N) was the site of this study. The area has a mean average altitude of 3,050 m above the sea level and average annual temperatures between 1 and 13°C. Annual rainfall ranges from 400 to 800 mm with average annual sunshine hours of 2,200–2,400 h.

Data preparation and sources

Meteorological data such as monthly average maximum and minimum temperatures and monthly average precipitation were obtained from the national meteorological database of China (http://data.cma.cn/wa/). These weather data were preprocessed and converted into WTH files in accordance with the CENTURY model requirements.

Soil data, including soil texture, C, N, S, and P contents in the soil, and soil pH, were downloaded from China's soil data collection and were freely accessible at http://www.ncdc.ac.cn/.

Statistical software used in this paper includes ArcGIS 10.6 (Figures 1, 2), Python 3.7 (Figures 5, 6), and Excel 2010 (Figures 3, 4).

Note: Figure 1 and the rest of the maps in the text were created using the mapping software ArcGIS 10.6, specialized software for creating various maps. VIIAi indicates alpine scrub and meadowland; IVAi indicates north subtropical evergreen forest and deciduous forest; IIIii indicates warm temperate southern deciduous oak forest.

The CENTURY model

The CENTURY model is a process-based biogeochemical cycle model of terrestrial ecosystems (Parton et al., 1996). It is mainly used to simulate the long-term dynamics of carbon, nitrogen, phosphorus, and sulfur in various soil-vegetation systems. The CENTURY model divides the total organic carbon pool based on the rate of soil organic matter decomposition. This can help us estimate the carbon content of grasslands more effectively and accurately. It can simulate the dynamic changes in carbon, nitrogen, phosphorus, and sulfur. At the same time, grass/crop, forest, or grassland systems can be selected as producer sub-models. This study used the CENTURY 4.0 version. To reduce errors, parameters were localized as much as possible based on the data from the studied area. The system's default values were used for the unknown data.

Carbon sources and carbon sinks (NEP) are the main components of the carbon cycle in grassland ecosystems (Campbell et al., 2019). Grasses absorb carbon dioxide (CO_2) from the atmosphere through photosynthesis and convert it into organic compounds, which are then stored in plants. Many factors, such as temperature, precipitation, solar radiation, climate change, and soil moisture, influence grassland carbon sources and sinks. Through correlation analysis, the correlation

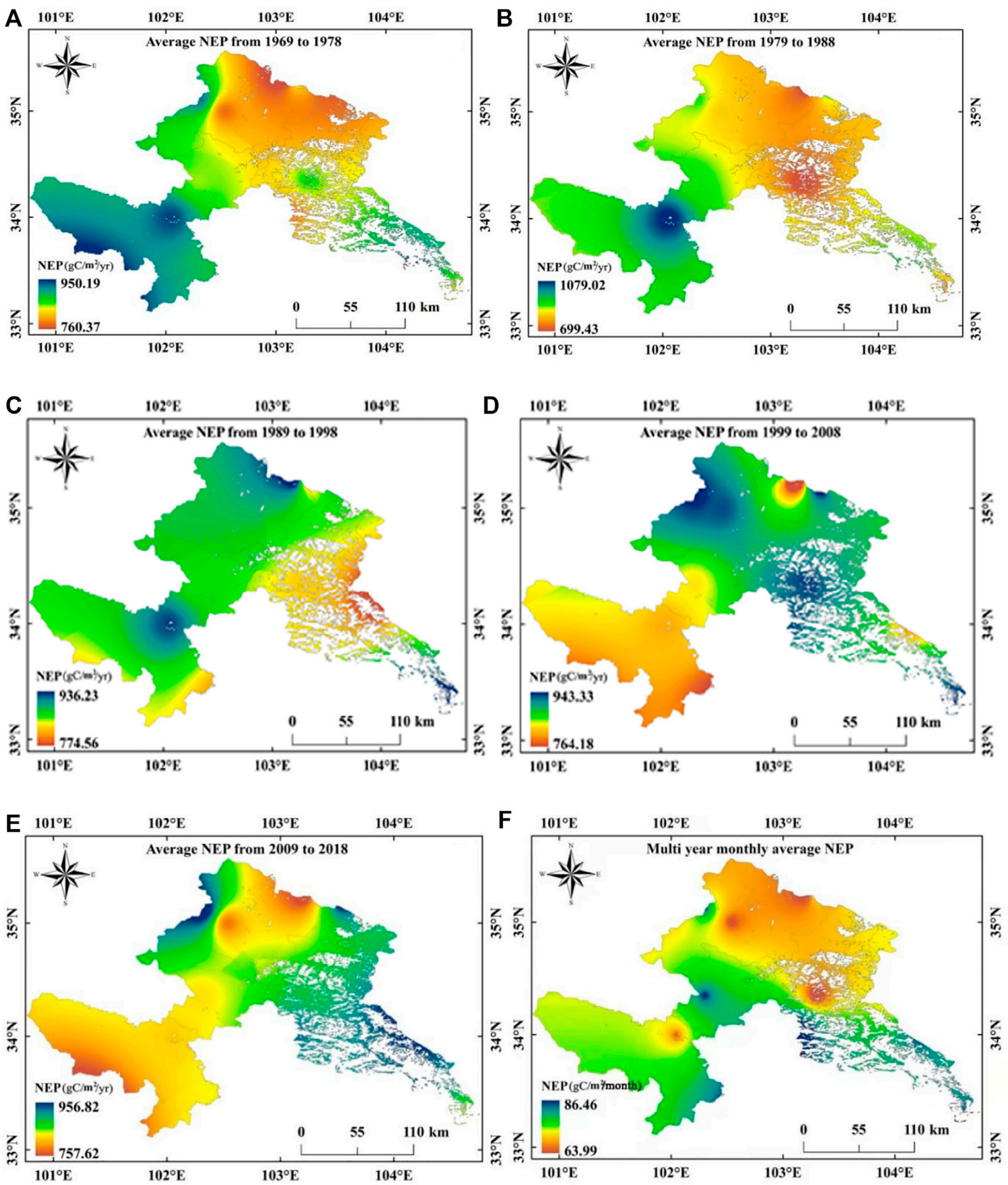

FIGURE 2
Spatial distribution of NEP of alpine meadows in Gannan, China, for the past 50 years. **(A)** From 1969 to 1978, **(B)** from 1979 to 1988, **(C)** from 1989 to 1998, **(D)** from 1999 to 2008, **(E)** from 2009 to 2018, and **(F)** monthly NEP from 1969 to 2018.

between each factor and the estimated NEP values can be obtained. NEP values can be used to assess the role of grassland in the carbon budget of terrestrial ecosystems (Andrew et al., 2015), study grassland ecosystem responses to global changes, rationally manage and use grassland, and develop appropriate usage policies. Net ecosystem productivity (NEP) can be estimated as follows:

$$NEP = NPP - R_H, \tag{1}$$

where NPP denotes net primary productivity, and Rh denotes heterotrophic respiration. The NPP values were estimated using the CENTURY model, which was then verified. Soil and atmosphere exchange carbon through respiration (Caquet et al., 2012). This is of great importance for the study of

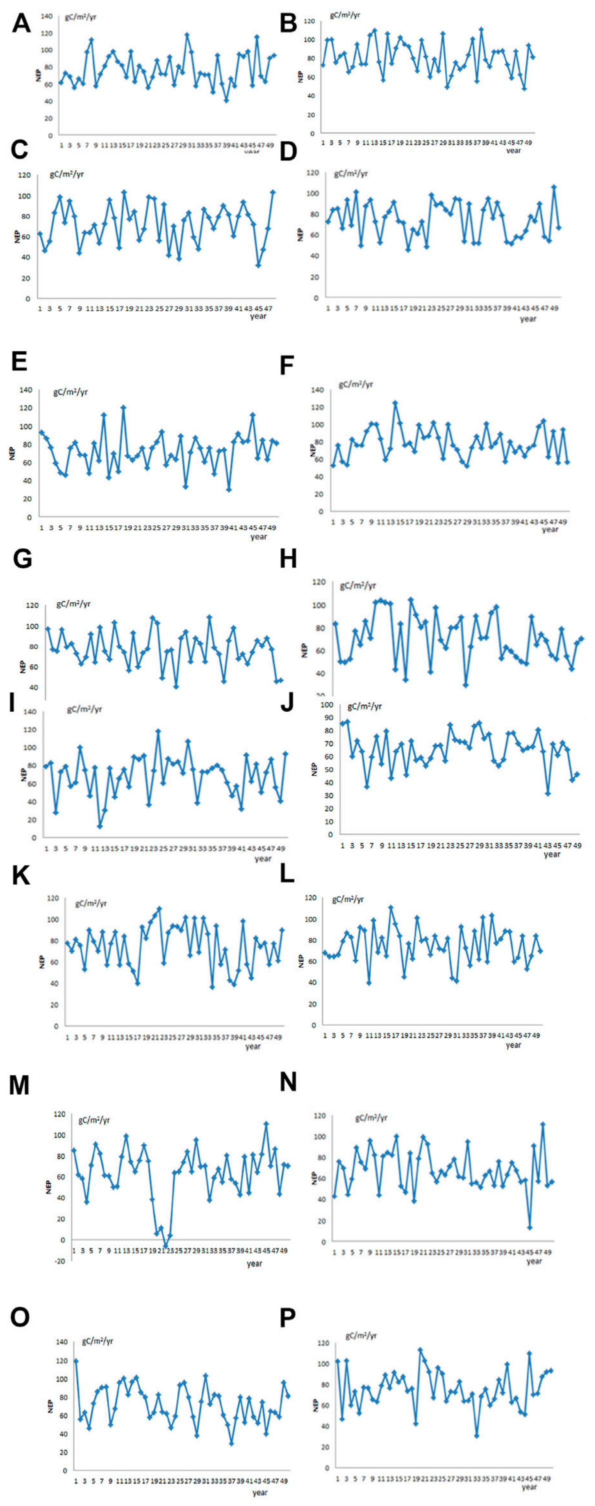

FIGURE 3
Trend of the monthly average carbon budget in various regions of the Gannan alpine meadow in China from 1969 to 2018. Figures **(A–P)** represent, respectively, the average monthly NEP of Xiahe, Luqu, Lintan, Diebu, Maqu, Hezuo, Min County, Lintao, Wudu, Yongjing, Dongxiang, Guanghe, Kangle, Zhouqu, Tanchang, and Wen County in the past 50 years.

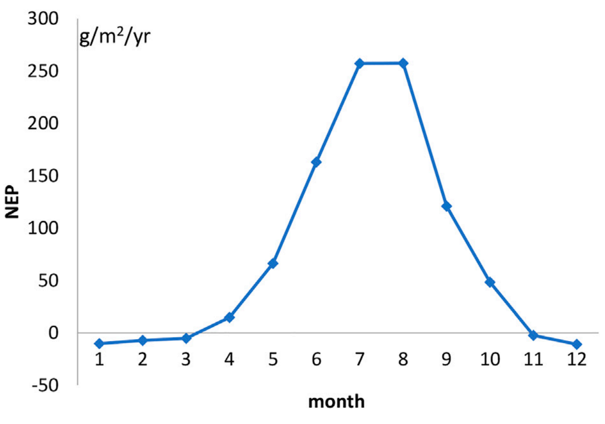

FIGURE 4
Monthly average NEP.

global climate change. It is a complex ecological process restricted and influenced by many factors, such as vegetation type, litter cover, soil microbial activity, temperature, humidity, soil physical and chemical properties, and other environmental factors and changes in these factors will affect the rate of soil respiration. Soil respiration was measured by both indirect and direct methods. The direct method interferes with soil respiration in Min County by measuring the CO_2 released from the soil surface. The indirect method uses other indicators, such as changes in the weight of the soil humus layer, the content of adenosine triphosphate in the soil, *etc.*, to calculate the soil respiration values. The formula is

$$RH = 0.22 \times EXP(0.0913T) + Ln((0.314|5R + 1)) \times 30 \times 46.5\%, \quad (2)$$

where T is the temperature and R is precipitation.

Results

Spatial distribution of the NEP of the alpine meadow in Gannan

The Gannan alpine meadow has proven to be a carbon sink over the past 50 years (Figures 2A–F). Also, it continues to be a carbon sink, as evidenced by the monthly average (Figure 2F). From 1969 to 1978, the annual average NEP was greater than 600 gC/m²/yr. (Figure 2A), indicating that it was a carbon sink. During this period, the minimum annual average NEP value was 648 gC/m²/yr, and the maximum annual average value was 997 gC/m²/yr. Among all 16 study sites, Zhuoni and Kangle counties recorded slightly lower NEP values. The carbon budget has generally increased in the southwest over the last decade while decreasing in the northeast.

10.3389/fenvs.2022.922968

TABLE 1 Carbon budget of each district in the Gannan Alpine Meadow, China.

Site	Min(gc/m^2/yr)	Year	Max (gc/m^2/yr)	Year	Carbon budget
Xiahe	40.75	1989	117.70	2002	Carbon sink
Luqu	47.70	2016	111.05	2007	Carbon sink
Lintan	32.43	2015	103.22	2018	Carbon sink
Diebu	45.71	1987	105.78	2018	Carbon sink
Maqu	30.15	2010	120.13	1987	Carbon sink
Hezuo	52.52	1999	124.31	1983	Carbon sink
Min County	40.20	1997	108.45	2005	Carbon sink
Lintao	29.69	1985	104.47	1997	Carbon sink
Wudu	12.69	1981	118.07	1993	Carbon sink
Yongjing	31.49	2013	86.66	1970	Carbon sink
Dongxiang	36.69	2003	109.76	1991	Carbon sink
Guanghe	39.55	1980	110.37	1985	Carbon sink
Kangle	-6.00	1991	110.29	2014	Carbon sink
Zhouqu	3.40	2013	111.56	2018	Carbon sink
Tanchang	28.99	2006	118.95	1969	Carbon sink
Wen County	30.74	2002	112.74	1989	Carbon sink

The Gannan alpine meadow appeared to be a carbon sink from 1979 to 1988. The minimum annual average NEP was 506 gC/m^2/yr. The maximum exceeded 1,000 gC/m^2/yr. Compared with other study areas and counties, Guanghe's NEP was relatively small. The carbon budget of alpine meadows in Gannan has remained constant over the last 10 years, with an increasing trend in the southwest and a decreasing trend in the northeast (Figure 2B).

From 1989 to 1998, the annual average NEP values were very high, making the study area a strong carbon sink. The minimum annual average NEP in this decade exceeded 700 gC/m^2/yr. The maximum annual average NEP has increased significantly over the previous 2 decades, approaching 950 gC/m^2/yr. Despite having relatively low NEP values, Zhuoni County, Min County, and Guanghe County were still carbon sinks. In contrast to the last 2 decades, the carbon budget is higher in the northwest and lower in the southeast (Figure 2C).

As shown in Figure 2D, the study area was still a carbon sink during the 10 years from 1999 to 2008, as it had been for the previous 3 decades. The Gannan alpine meadow had average annual Min County NEP greater than 700 gC/m^2/yr, reaching 723 gC/m^2/yr, and the maximum annual average NEP was close to 950 gC/m^2/yr. During this decade, the NEP value of the study area increased in the east while decreased in the west.

Similarly, the region was a clear carbon sink between 2009 and 2018. The NEP value was far greater than zero in general, and the annual average minimum value exceeded 700 gC/m^2/yr. Among all sixteen counties, the NEP values in Jiuzhi, Hezheng, Zhuoni, and Guanghe counties were relatively small but still greater than zero, indicating an obvious carbon sink. This decade is slightly different from the previous decades, increasing from west to east (Figure 2E).

Gannan alpine meadow's monthly average NEP value has ranged between 63.99 gC/m^2/month and 84.46 gC/m^2/month over the last 50 years. The Gannan alpine meadow has been a clear carbon sink over the last 50 years, based on monthly averages.

In general, the annual average spatial distribution of NEP (Figures 2A–E) of Gannan alpine meadow carbon has demonstrated that it has been a significant carbon sink over the last 50 years. The monthly average spatial distribution revealed the same characteristic (Figure 2F).

Temporal distribution of the NEP of the alpine meadow in Gannan

The average monthly carbon stocks of these 16 observation sites were calculated for the past 50 years in this study. NEP was used as an indicator to measure the carbon budget, and a line chart was created, as shown in Figure 3.

Except for Kangle County in 1991, the entire study area has been a carbon sink over the last 50 years. However, it does switch to a carbon source at times.

TABLE 2 CENTURY model verification.

Item	Field data (gc/m^2/yr)	Simulation data (gC/m^2/yr)	Above ground biomass (g/m^2)	RMSE (gc/m^2/yr)
Maqu	312.46	246.78	84.67	32.83
Luqu	302.65	264.15	84.92	19.25
Xiahe	237.22	368.76	66.55	65.77
Hezuo	234.05	302.80	65.67	34.37
Zhuoni	204.04	213.88	57.25	4.92
Lintan	197.94	325.32	55.54	63.69

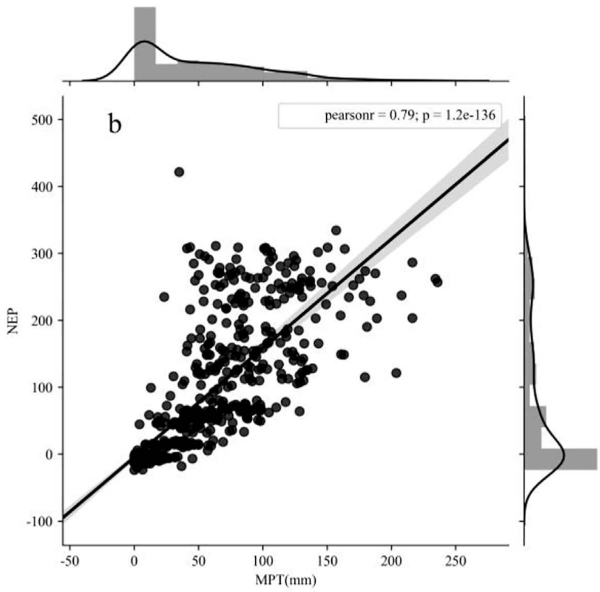

FIGURE 5
Scatter plot between the temperature and NEP. Note: Figures 5, 6 are both drawn using Python, which is relatively easy to use software.

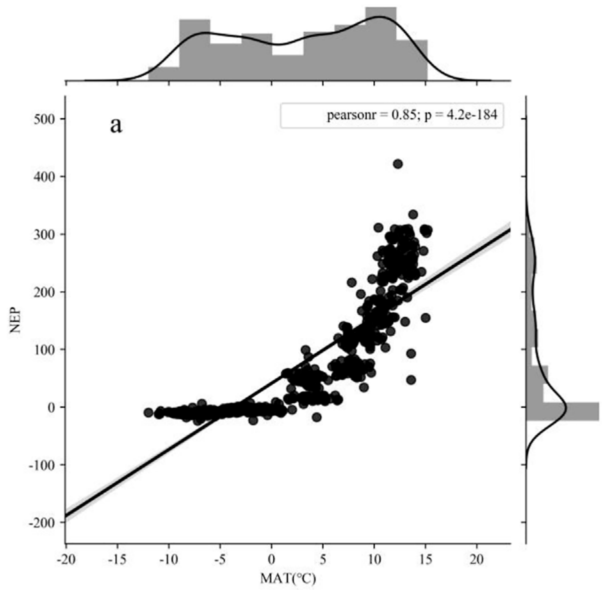

FIGURE 6
Scatter plot between precipitation and NEP.

The NEP values of all 16 sites have changed over the last 50 years. Carbon sinks in Xiahe, Lintan, Diebu, and Wudu were gradually increasing. Hezuo, Lintao, Dongxiang, Guanghe, Zhouqu, and Wen counties were the carbon sinks that increased and then decreased. Maqu and Kangle, whose carbon sinks decrease before increasing. Carbon sinks in Yongjing and Tanchang were declining (Figures 3A–P).

The monthly average Min County NEP of each year was above 50 gC. However, Hezuo, Xiahe, Luqu, Diebu, and Min counties had monthly average Min County NEP within the range of 40 gC and 50 gC, whereas Dongxiang, Guanghe Wen , Lintan, Maqu, and Yongjing counties had monthly average Min County NEP in the range of 30 gC and 40 gC. At the same time, only the Min County monthly average NEP of Kangle was less than 0 gC/m^2/yr in the previous 50 years. Except for Yongjing County, the monthly average maximum NEP was greater than 100 gC/m^2/month, and the monthly average maximum NEP of Yongjing was only 86.66 gC/m^2/month.

Table 1 shows the carbon budget of Gannan alpine meadows in China and the minimum and maximum values of NEP, as well as the corresponding years for over the last 50 years. According to this study, Gannan alpine meadows in China have generally been carbon sinks over the last 50 years. Furthermore, except for Kangle, the NEP values of all the sites have always been greater than 0 gC/m^2/yr, indicating that Kangle County was a carbon source in 1991 (Table 1).

The NEP value in the first season was less than 0 gC/m^2/yr, and the NEP values in March and November were close to the carbon sink threshold. The monthly NEP values in December alternate between less and greater than 0 gC/m^2/yr. It is well

TABLE 3 Statistical analysis of temperature, precipitation, and NEP.

Item	Coef	T-value
c	31.973***	4.922
Temp	8.122***	8.499
Prep	0.737***	3.962

*Significant at the 0.1 level, **significant at the 0.05 level, and ***significant at the 0.01 level.

known that when the NEP is less than 0 gC/m^2/yr, it is presented as a carbon source, and when the NEP is greater than 0 gC/m^2/yr, it is presented as a carbon sink. Our results showed that in January, February, and December, Gannan alpine meadows were carbon sources. However, March and November are balanced. For the rest of the year, it acts as a carbon sink. This could be attributed to lower temperatures from December to February and even lower at other times. As a result, low temperatures appear to prevent carbon loss from the soil. As can be seen in Figure 4, August has the highest NEP value and corresponds with the highest precipitation value. As a result, precipitation appears to have a positive effect on NEP. In general, low temperatures inhibit carbon sinks, while precipitation has a positive effect on NEP. This is consistent with the findings of other researchers and further supports our conclusion. In addition, it can be seen from Figure 4 that from January to August, the average NEP of each study site showed a clear upward trend, increasing from a negative NEP value in January to a maximum of about 250 gC/m^2/yr in August. From August to December, the NEP values showed a downward trend, and by December, they had fallen to less than 0 gC/m^2/yr.

The previous study attempted to simulate the annual changes in the carbon budget of alpine meadows in various counties of Gannan alpine meadows in China. However, the time step is too long to observe the changes in the monthly data in detail. To better understand the NEP, we monitored the changes in the carbon budget of the Gannan alpine meadow on a monthly basis.

Model validation

To test the CENTURY model, first update the model parameters according to the FILE.100 program, then adjust the model to a balanced state, and finally display the measured value of the CENTURY model to achieve the testing goal. The linear regression analysis method and the square root of error method are used in this paper to verify the simulated and measured values of the CENTURY model.

$$y = \text{a} + \text{bx}. \tag{3}$$

In Formula 3, y represents the estimated value of the model, x represents the corresponding measured value, a represents the regression constant, b represents the regression coefficient, and the values of a and b are estimated using the least square method.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - x_i\right)^2}, \tag{4}$$

where y_i represents the model output value, x_i represents the corresponding measured value, and i (i = 1,2,...,n) represents the month for each year from 1969 to 2018. The root mean square error (RMSE) can reflect the difference between the model output value and the measured data, which can indirectly validate the reliability of the CENTURY model.

In this study, we used RMSE (Root Mean Square Error) to validate the CENTURY model output. The measured data used is that of a local area in Gannan, and the results are shown in Table 2. It demonstrates that the CENTURY model performed better in estimating the productivity of Gannan alpine meadow vegetation.

The relationship between climatic factors and NEP

Relationship between temperature and NEP

The scatter plot between temperature and NEP shows that when the temperature is less than 0°, the NEP value fluctuates around 0 gC/m^2/yr, with basically no deviation. However, a slight increase in temperature leads to a significant increase in NEP above 0 gC/m^2/yr (Figure 5). It is clear that there is a correlation between the air temperature and carbon stock. According to the results of the correlation analysis, the correlation coefficient between the carbon stock and air temperature in China's Gannan alpine meadows is 0.722 (p = 0.01). When the temperature is below 0°, the NEP is less than 0 gC/m^2/yr. Therefore, it can be inferred that low temperatures prevent carbon loss from the soil.

Relationship between precipitation and NEP

The scatter plot of precipitation and NEP shows that when precipitation is slightly greater than zero, the NEP value fluctuates around 0 gC/m^2/yr, but as precipitation increases, the NEP value significantly increases (Figure 6). It is clear that there is a link between precipitation and the carbon budget. Correlation analysis showed a correlation coefficient of 0.671 (p = 0.01) between the carbon budget and precipitation. This demonstrates a positive relationship between precipitation and the carbon budget.

NEP rises as precipitation increases. In this study, the partial correlation coefficient between precipitation and NEP was calculated to be 0.671 (p = 0.01).

Relationship among temperature, precipitation, and NEP

We used regression analysis to study the effect of temperature and precipitation interactions on NEP (Table 3).

Eq. 5 shows how the interaction between temperature and precipitation affects NEP significantly.

$$NEP = 0.737*prep + 8.122*temp + 6.382. \quad (5)$$

The linear relationship between temperature or precipitation and NEP was established in this study, and multiple regression models of temperature and precipitation and NEP were established as well.

The model is significant, and the effects of temperature and precipitation on NEP are both significantly positive (p = 0.01; Table 3). Temperature and precipitation were found to be the main factors influencing the carbon source and sink.

Discussion

The climate of the Gannan alpine meadow changed significantly over the last several decades, influencing plant growth and, ultimately, the carbon budget of the alpine vegetation (Piao et al., 2012). Our findings show that the NEP of the Gannan alpine meadow increased significantly between 1969 and 2018 in response to significant changes in climate, which is consistent with previous research studies at both the site (Zhang et al., 2019) and regional levels. Furthermore, our findings revealed that the spatial distribution of NEP varies greatly over time. During the spring and the last 2 months of winter, the study region was a carbon source. However, it was completely the carbon sink during the second and the third seasons, indicating that the role of the Gannan alpine meadow in the terrestrial carbon cycle varied with time and space.

Many previous studies attempted to investigate vegetation productivity (e.g., GPP and NPP) in a short period of time, and most of the time, singular factors were taken into account (e.g., NDVI). Therefore, the comprehensive interaction of multiple factors was overlooked (Gao et al., 2013). Wang et al. (2010) used the MODIS vegetation index to investigate the temporal and spatial changes in the Gannan grassland net primary productivity. Their results showed that the annual NPP values of the Gannan grassland from 2006 to 2008 were 637.04, 599.98, and 566.5 gC/m^2/yr, respectively. The distribution shows a gradually decreasing trend from northwest to northeast, with the NPP value reaching their maximum in July or August.

In this study, a regression model was used to systematically describe the effects of two different climatic factors (temperature and precipitation) on the carbon budget of Gannan alpine meadow vegetation, as well as the spatial distribution (Figure 2) and temporal variation (Figure 3) over the last 50 years. Our findings show that temperature and precipitation have significant positive effects on NEP (p = 0.01). Except for Kangle County in 1991, the entire region of the Gannan alpine meadow has essentially been a carbon sink over the last 50 years. Also, the spatial distribution of the carbon stock in the Gannan alpine meadows changes over time.

According to the results of a 2018 study in Gansu Province, China, the Gannan grassland NEP gradually decreases from northwest to southwest. The grassland's NEP showed that the Gannan grassland exhibits a carbon sink characteristic. Their research, on the other hand, revealed that the carbon stock is decreasing year by year. During the spring, summer, autumn, and winter seasons, the region acts as a carbon sink. The study area is a carbon source in January and March of each year but a carbon sink the rest of the time. This is slightly different from the results of this study. The study found that the Gannan alpine meadows were carbon sources from January to March and then again in December. For the rest of the year, the area acts as a carbon sink. Similar to the results of this study, their study showed that the monthly average temperature and precipitation were positively correlated with NEP. In this study, the correlation coefficients between the monthly average temperature and NEP and between monthly average precipitation were 0.722(p = 0.01) and 0.671 (p = 0.01), respectively. As a result, the monthly average temperature and precipitation have a significant positive impact on NEP.

China is rich in grassland types, and the study area of this paper is the Gannan alpine meadow. They studied the carbon budget of northern China's temperate grasslands. Zhang et al. (2013) studied the area consisting of alpine meadows and their NEP values reached 200–300 gC/m^{2}yr during the growing season from May to September. In this article, the NEP value of the Gannan alpine meadow reached 280–330 gC/m^{2}yr during the growing season, which further verified the reliability of the research results.

Using remote sensing techniques, Chen et al. (2016) studied the NEP of the Gannan grassland terrestrial ecosystem and estimated the temporal and spatial distribution of NEP and their influencing factors from 2005 to 2014. According to their findings, the average NEP in the Gannan grassland from 2005 to 2014 was 1.47×10^{13} gC/m^{2}yr. Over the 10 years, the NEP of the Gannan grassland decreased while the area of carbon sources increased gradually. The NPP peak appeared in July. However, in this study, the NEP increased in the early part of the year, peaking in July and August, and then declining in the latter part of the year. The average annual carbon stock of the Gannan alpine meadow over the last 50 years was 871.62 gC/m^2/yr. The first, second, third, fourth, and fifth decades had average annual carbon stocks of 859.58 gC/m^2/yr, 853.37 gC/m^2/yr, 878.12 g C/m^2/yr, 893.31 gC/m^2/yr, and 873.71 gC/m^2/yr, respectively.

To summarize, the alpine meadows in the Gannan region of China are in good condition and serve as significant carbon sinks. The value of NEP rises in the early part of the year and then falls toward the end. The highest value usually reached in July. To some extent, low temperatures inhibit carbon sinks. Temperature and precipitation are the main factors affecting the carbon budget, and they have a significant positive impact on NEP. Changes in climate will continue to raise the temperature. Although the high temperature is beneficial to carbon sinks, they have negative effects on humans, such as rising sea levels and ozone layer depletion. Therefore, addressing climate change is everyone's responsibility and requires the collective efforts of the entire world. Other factors influencing NEP include light duration and humidity, but light duration affects temperature as well, and humidity is primarily due to precipitation and possibly soil texture. Soil texture tests are still being conducted and cannot be analyzed at this time, but we expect to be able to do so in the future (Zhang and Cui, 2019a).

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

XW: methodology, formal analysis, investigation, and writing—review and editing. MZ: conceptualization, supervision, funding, review, and editing. SN: formal analysis, review, and editing. TN: review and editing.

Funding

This work was supported by the National Natural Science Foundation of China (32260353), the Key Research and Development Program of Gansu Province, China (21YF5WA096), the Ministry of Science and Technology of China High-End Foreign Expert Introduction Program (G2022042009L), and the Natural Science Foundation of Gansu Province, China (1606RJZA077 and 1308RJZA262).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Andrew, H. M., Kirsten, Z., Reto, K., and Matthews, H. D. (2015). Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO2 forcings. *Environ. Res. Lett.* 10 (12), 125003. doi:10.1088/1748-9326/10/12/125003

Bård, L. (2020). Changing climate change: The carbon budget and the modifying-work of the IPCC. *Soclal Stud. Sci.*, 0306312720941933.

Berkelhammer, M., Asaf, D., Still, C., Montzka, S., Noone, D., Gupta, M., et al. (2014). Constraining surface carbon fluxes using *in situ* measurements of carbonyl sulfide and carbon dioxide. *Glob. Biogeochem. Cycles* 28 (2), 161–179. doi:10.1002/2013gb004644

Brienen, R. J. W., Caldwell, L., Duchesne, L., Voelker, S., Barichivich, J., Baliva, M., et al. (2020). Forest carbon sink neutralized by pervasive growth-lifespan trade-offs. *Nat. Commun.* 11 (1), 4241. doi:10.1038/s41467-020-17966-z

Campbell, D. L., Mudge, P. L., Rutledge, S., and Schipper, l. A. (2019). Carbon budget of an intensively grazed temperate grassland with large quantities of imported supplemental feed. *Agric. Ecosyst. Environ.* 281, 1–15. doi:10.1016/j.agee.2019.04.019

Caquet, B., Grandcourt, A. D., and Thongo, A. M. (2012). Soil carbon budget in a tropical grassland: Estimation of soil respiration and its partitioning using a semi-empirical model. *Agric. For. Meteorol.* 158–159, 71–79.

Chen, Y. Z., Mu, S. J., Sun, Z. G., Gang, C., Li, J., Padarian, J., et al. (2016). Grassland carbon sequestration ability in China: A new perspective from terrestrial aridity zones. *Rangel. Ecol. Manag.* 69 (1), 84–94. doi:10.1016/j.rama.2015.09.003

Gao, Y., Zhou, X., Wang, Q., Wang, C., Zhan, Z., Chen, L., et al. (2013). Vegetation net primary productivity and its response to climate change during 2001–2008 in the Tibetan Plateau. *Sci. Total Environ.* 444, 356–362. doi:10.1016/j.scitotenv.2012.12.014

Guo, Y. Y., Liu, Y., Li, Q. Y., Chen, C., and Wang, S. (2020). Applicability analysis of CENTURY model in xinjiang tianshan mountains. *Acta Grassl.* 28 (01), 252–258.

Hao, Z., Xu, Y., and Lei, Y. D. (2021). Responses of grass primary productivity to diffuse radiation at global FLUXNET sites. *Atmos. Environ.* 244. ((in Chinese with English abstract)).

Heede, R., and Oreskes, N. (2016). Potential emissions of CO2 and methane from proved reserves of fossil fuels: An alternative analysis. *Glob. Environ. Change* 36, 12–20. doi:10.1016/j.gloenvcha.2015.10.005

Jiang, Y. L., Wang, R. H., Peng, Q., Li, Y., Li, C., and Guo, J. (2019). Research on the evolution of landscape pattern and carbon budget in arid areas: A case study from the tarim basin. *J. Ecol. Rural Environ.* 35 (07), 875–884. ((in Chinese with English abstract)).

Kang, X. M., Hao, Y. B., Cui, X. Y., Chen, H., Li, C., Rui, Y., et al. (2013). Effects of grazing on CO2 balance in a semiarid steppe: Field observations and modeling. *J. Soils Sediments* 13 (6), 1012–1023. doi:10.1007/s11368-013-0675-5

Kim, D., Lim, C. H., Song, C., Lee, W. K., Piao, D., Heo, S., et al. (2016). Estimation of future carbon budget with climate change and reforestation scenario in North Korea. *Adv. Space Res.* 58 (6), 1002–1016. doi:10.1016/j.asr.2016.05.049

Li, X. L., Liang, S. L., Yu, G. R., Yuan, W., Cheng, X., Xia, J., et al. (2013). Estimation of gross primary production over the terrestrial ecosystems in China. *Ecol. Modell.* 261–262, 80–92. doi:10.1016/j.ecolmodel.2013.03.024

Li, X. P., Li, J. H., Liu, Y. G., Fan, Y. X., Zhao, S. D., and Li, M. Q. (2020). Vegetation and soil microbial characteristics of different degraded grasslands in Gannan grassland. *Acta Grassl.* 28 (05), 1252–1259. ((in Chinese with English abstract)).

Li, Y. C., Hou, M. J., GeFeng, J, Q. S., and Liang, T. G. (2020). Research on NDVI changes and driving factors of grassland vegetation in southern Gansu and northwestern Sichuan. *J. Grassl.* ((in Chinese with English abstract)).

Matsuura, S., Miyata, A., Mano, M., Hojito, M., Mori, A., Kano, S., et al. (2014). Seasonal carbon dynamics and the effects of manure application on carbon budget of a managed grassland in a temperate, humid region in Japan. *Grassl. Sci.* 60 (2), 76–91. doi:10.1111/grs.12042

Nagy, Z., Pintér, K., Czóbel, S., Balogh, J., Horvath, L., Foti, S., et al. (2006). The carbon budget of semi-arid grassland in a wet and a dry year in Hungary. *Agric. Ecosyst. Environ.* 121 (1), 21–29. doi:10.1016/j.agee.2006.12.003

Parton, W. (1996). *The CENTURY model in evaluation of soil organic matter models*. Berlin/Heidelberg, Germany: Springer, 283–291.

Piao, S., Tan, K., Nan, H., Ciais, P., Fang, J., Wang, T., et al. (2012). Impacts of climate and CO2 changes on the vegetation growth and carbon balance of Qinghai–Tibetan grasslands over the past five decades. *Glob. Planet. Change* 99 (6), 73–80. doi:10.1016/j.gloplacha.2012.08.009

Scheiter, S., Kumar, D., Corlett, R. T., Gaillard, C., Langan, L., Lapuz, R. S., et al. (2020). Climate change promotes transitions to tall evergreen vegetation in tropical Asia. *Glob. Chang. Biol.* 26 (9), 5106–5124. doi:10.1111/gcb.15217

Tian, H. Q., Lu, C. Q., Ciais, P., Michalak, A. M., Canadell, J. G., Saikawa, E., et al. (2016). The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature* 531 (7593), 225–228. doi:10.1038/nature16946

Tobi, A. O., and Heather, A. H. (2020). Plant community dynamics and carbon sequestration in *Sphagnum* -dominated peatlands in the era of global change. *Glob. Ecol. Biogeogr.* 29 (10), 1610–1620. doi:10.1111/geb.13152

Trevor, J. F., and Brian, D. A. (2013). Initial carbon dynamics of perennial grassland conversion for annual cropping in Manitoba. *Can. J. Soil Sci.* 93 (3), 379–391. doi:10.4141/cjss2012-109

Wall, A. M., Campbell, D. I., Mudge, P. L., and Schipper, L. (2020). Temperate grazed grassland carbon balances for two adjacent paddocks determined separately from one eddy covariance system. *Agric. For. Meteorol.* 287, 107942. doi:10.1016/j.agrformet.2020.107942

Wang, Y., Xia, W. T., Liang, T. G., and Wang, C. (2010). Study on the temporal and spatial changes of Gannan grassland net primary productivity based on MODIS vegetation index. *Acta Prataculturae Sin.* 19 (1), 201–210. ((in Chinese with English abstract)).

Wang, Z. Q., Yang, Y., and Li, J. L. (2016). Perisphaerinae brunner von Wattenwyl and hyposphaeria lucas are valid names concealed by the unavailable names perisphaeriinae and perisphaeria burmeister (blattodea, blaberidae). *Zookeys* 2, 75–80. doi:10.3897/zookeys.574.7063

Yan, l., Zhou, G. Y., Hu, T., and Sui, X. (2015). The spatial and temporal dynamics of carbon budget in the alpine grasslands on the Qinghai-Tibetan Plateau using the Terrestrial Ecosystem Model. *J. Clean. Prod.* 107, 195–201. doi:10.1016/j.jclepro.2015.04.140

Yang, D. X., Zhang, H. F., Liu, Y., Chen, B., and Cai, Z. (2017). Monitoring carbon dioxide from space: Retrieval algorithm and flux inversion based on GOSAT data and using CarbonTracker-China. *Adv. Atmos. Sci.* 34 (8), 965–976. doi:10.1007/s00376-017-6221-4

Yin, J. P. (2020). *Research on remote sensing estimation of grass layer height of alpine grassland in Gannan area*. Lanzhou University Lanzhou, China. ((in Chinese with English abstract)).

Zhang, H. F., and Cui, G. S. (2019a). The impact of land use/cover changes on the carbon budget of terrestrial ecosystems. *China Resour. Compr. Util.* 37 (1), 176–179.

Zhang, H. F., and Cui, G. S. (2019b). The impact of land use/cover changes on the carbon budget of terrestrial ecosystems. *China Resour. Compr. Util.* 37 (01), 176–179. ((in Chinese with English abstract)).

Zhang, L. Y., Sun, Y. K., Song, T. Y., and Xu, J. (2019). Harvested wood products as a carbon sink in China, 1900–2016. *Int. J. Environ. Res. Public Health* 16 (3), 445. doi:10.3390/ijerph16030445

Zhang, L., Zhou, G. S., Ji, Y. H., and Bai, Y. (2017). Grassland carbon budget and its driving factors of the subtropical and tropical monsoon region in China during 1961 to 2013. *Sci. Rep*. 7 (1), 14717–14753. doi:10.1038/s41598-017-15296-7

Zhang, Q., Wang, Z. C., Pu, Q. S., Hou, Q. Q., Cai, Z. Y., Yang, J., et al. (2020). The influence of different management modes on the carbon storage of Gannan alpine meadow. *J. Grassl.* 28 (02), 529–537. ((in Chinese with English abstract)).

Zhang, X. S., Ritvik, S., Manowitz, D. H., Zhao, K., Leduc, S. D., Xu, M., et al. (2014). Multi-scale geospatial agroecosystem modeling: A case study on the influence of soil data resolution on carbon budget estimates. *Sci. Total Environ.* 479 (480), 138–150. doi:10.1016/j.scitotenv.2014.01.099

Zhang, Z. H., Wang, B., Yang, B., Zhu, C., Shi, J., liu, M., et al. (2019). Stabilization of carbon sequestration in a Chinese desert steppe benefits from increased temperatures and from precipitation outside the growing season. *Sci. Total Environ.* 691, 263–277. doi:10.1016/j.scitotenv.2019.06.481

Zhou, T., Shi, p., Jia, G., and Luo, Y. (2013). Nonsteady state carbon sequestration in forest ecosystems of China estimated by data assimilation. *J. Geophys. Res. Biogeosci.* 118, 1369–1384. doi:10.1002/jgrg.20114

Zhou, X., Zhou, T., and Luo, Y. (2012). Uncertainties in carbon residence time and NPP-driven carbon uptake in terrestrial ecosystems of the conterminous USA: A bayesian approach. *Tellus B Chem. Phys. Meteorology* 64, 17223. doi:10.3402/tellusb.v64i0.17223