The Net Influence of Drought on Grassland Productivity over the Past 50 Years

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Abstract: The focus of this paper is on the grassland productivity response to drought under the background of climate change. There is an established lag impact on the response of grassland ecosystems to drought events, which may have additional effects on subsequent drought events. Meanwhile, due to climate change interference, the influence of drought on grassland productivity over the past 50 years is not simply equal to the algebraic sum of all the historical drought events. In the Inner Mongolia grassland, precipitation deficit plays a leading role in causing drought. Therefore, taking into consideration the impacts of drought lag effect and climate change, in this paper, we focus on the net influence of drought on grassland productivity over the past 50 years on the basis of long-term precipitation deficit, we identify the interference effect from different climate factors (precipitation and temperature) by using different scenario simulation tests, and therefore, further clarify the net influence on the grassland productivity of Inner Mongolia over the past 50 years.

Keywords: drought; standardized precipitation index (SPI); Biome-BGC; grassland productivity; net influence

1. Introduction

Since the industrial revolution, human activities have affected the ecological environment at an unprecedented speed and scale. The phenomena of global warming, rising CO2 concentration, ozone layer destruction, and frequent extreme climate events are becoming more and more obvious [1,2]. Drought is an important adverse climate disturbance that has been occurring globally, and it is expected to intensify this century. Droughts affect the terrestrial carbon and water cycles by reducing the carbon sequestration ability and aggravating the evaporation rate of ecosystems [3,4]. Grassland composes approximately 40.5% of the Earth's continents and sequesters approximately 34% of the total carbon of the terrestrial ecosystem [5,6]. Grassland ecosystems are affected by a variety of biological and abiotic factors with climate change [7,8]. At a global scale, climate change has a significant impact on crucial ecological processes and functions of ecosystems [9–11]. Meanwhile, extreme events such as droughts, which are characterized by higher frequency, longer duration, and greater intensity in many regions, have a more serious impact on ecosystems [12]. Under the background of global climate change, driving factors including
precipitation pattern changes and global climate warming have continuous, accumulated, and moderate external influences on grassland ecosystems; the effects of extreme climate events on an ecosystem can be intermittent, impulsive, and violent driving responses [13]. These environmental factors can interfere with the influence of drought on grassland net primary production (NPP) to some extent [14].

Global changes have increased the uncertainty of drought impact on grassland ecosystems. At present, most studies have mainly focused on the impact of climate change on grassland ecosystems, specifically, the impact of climate change on grassland vegetation, soil, microorganisms, and the entire grassland ecosystem [15]. In terms of research content, studies have mainly involved grassland biological enzyme activity; species composition, structure, and function; biodiversity; grassland productivity and phenology; and carbon cycle dynamics [16–21]. In terms of the scope of research, studies have covered the main types of grassland in the world (Morgan et al., 2011; Parton et al., 1995) [22]. Global climate changes such as decreased rainfall in semi-arid regions have caused changes in biodiversity and ultimately affected ecosystem functioning [23,24]. Traditionally, drought properties have been investigated using univariate frequency analysis [25–28]. In general, current interference patterns and global changes have had a series of influences on available ecosystem resources, and have affected the response of an ecosystem to a single factor [29]. For example, temperature variations and land-use changes increase or decrease the drought impact on the NPP of different vegetation types [30]. Wood and Silver’s pilot drought experiment in tropical forests in Puerto Rico demonstrated that drought reduced greenhouse gas (CO₂) emissions from tropical soil, and the effects were critical when drought was considered alone. However, the actual emissions depended on the combined effects of changes in precipitation and temperature, as well as long-term changes in atmospheric CO₂ content and nutrient deposition, which, unfortunately, were not controlled in the author’s experiment [31]. At the same time, their study showed that under the joint influence of climate change and CO₂, the decrease in grassland productivity was significantly reduced. Nevertheless, the evaluation of drought impact did not eliminate the influence of other factors. Thus, the effects of interaction between drought and other factors should be a consideration, because other environmental factors can increase or decrease the the effect of drought on ecosystem productivity [32]. Therefore, it is necessary to further explore the net impact of drought as a single factor on an ecosystem under global change [33]. The purpose of this paper is to analyze the net impact of drought on a grassland ecosystem and reasonably evaluate the net contribution of drought to ecosystem productivity.

The Inner Mongolia grassland is the main body of temperate grassland in China, but there are few studies on the impact of drought on grassland productivity, especially the impact of different levels of drought. Research on the carbon cycle process of temperate grassland in China has mainly focuses on the response of grassland primary productivity, biomass dynamics, and soil organic carbon dynamics to climate change. For the Inner Mongolia grassland, the grassland ecosystem has been mainly affected by climate change, and the impact of other global change factors has been weak. Tian found that the nitrogen deposition level of grassland in Inner Mongolia was relatively low (about 1–2 GN m⁻²) (Tian et al., 2011), and the response level of grassland carbon sequestration to nitrogen deposition in China was less than 10 gc/m²/yr [34]. Based on the ecological process model, Sui et al. designed sensitivity tests of different factors to study the sensitivity of the carbon budget of temperate grasslands in China to climate and CO₂ concentration changes. Their study found that the fertilization effect of CO₂ contributed 1.4% to an increase in grassland carbon storage, which could not offset the serious negative effect of climate change on carbon storage (−15.3%) (Sui and Zhou, 2013). Ren et al. also reported that the interannual fluctuation of grassland carbon flux in China was mainly affected by climate change. Based on domestic and foreign literature and previous research, precipitation has been the main influence factor on the NPP change in Inner Mongolia. Thus, we pay attention to the net effect of drought caused by precipitation deficit on the productivity of the Inner Mongolia grassland over the past 50 years. Based on an analysis of the impacts
of drought events on grassland productivity, due to the lag impact from drought and the interference of climate change factors, we could not obtain the total impact of drought events on grassland productivity from historical information. Therefore, we investigated the total impact of drought on grassland productivity using the Biome-BGC model as a tool based on different scenario sensitivity simulation experiments and attempted to separate the interaction influence between drought and climate change factors, to clarify the net influence caused by precipitation deficit (drought) on grassland ecosystem productivity over the past 50 years.

2. Materials and Methods
2.1. Study Area and Data

The Inner Mongolia grassland is the main area of temperate grassland in China, in the region of 97°12′–126°04′ E and 37°24′–53°23′ N. The plateau is the primary topography in the research area, constituted by the Hulun buir plateau, Xilingol plateau, and Ordos plateau. The temperature decreases from southwest to northeast, and precipitation increases from southwest to northeast, as a typical temperate continental monsoon climate [35]. The average annual temperature is from −5 to 9 °C, while the annual precipitation is from 150 to 500 mm [36]. From the east to the west, three grassland types, namely meadow grassland, typical grassland, and desert grassland appropriating the soil types as Chernozem, chestnut soil, and brown soil, are distributed in the study area (Figure 1) [37]. The meadow steppe is concentrated in the subhumid area at the base of the Greater Hinggan mountains, dominated by perennial xerophytes and mesophytes, such as *Stipa baicalensis*, *Filifolium sibiricum*, and *Leymus*; the typical steppe is mainly composed of xerophytic perennial herbaceous plants, with the dominant types being *Leymus* and *S. bungeana*; the desert steppe is mainly composed of xerophytic perennial dwarf herbaceous plants with the dominant types being *S. klemenzii*, *S. glareosa*, and *S. breviflora*.

![Figure 1](image-url). The distribution of the Inner Mongolia temperate grassland.

The China Meteorological Data Sharing Network provides meteorological data for the past 50 years (1961–2009) from six stations in the study area (http://cdc.cma.gov.cn, accessed on 29 April 2022). At the same time, the grid daily data from 1961 to 2012 was used to build a Biome-BGC model, and the monthly data from 1961 to 2012 were used to build the SPI drought monitoring index. Daily maximum temperature, daily minimum temperature, daily average temperature, daily total rainfall, and daytime length data were included. The MTCLI model was used to simulate the average water vapor pressure and the average short wave radiation flux density. Monthly rainfall data were used in the calculation of SPI. In the study area, the distribution of vegetation types, at a scale of 1:1,000,000, was obtained from the China Vegetation Type Map Editorial Committee.
Soil data including sand, silt, and clay content and depth data were obtained from the International Soil Reference and Information Center (ISRIC, http://www.isric.org, accessed on 29 April 2022). Nitrogen deposition data and CO₂ data were obtained from the UK Air Pollution Information System (APIS: http://www.apis.ac.uk, accessed on 29 April 2022) and Pro Oxygen from the Mauna Loa Observatory/NASA, Hawaii (http://www.co2now.org, accessed on 29 April 2022), respectively [38].

2.2. Experimental Design and Assessment Methods

The sensitivity between land ecosystem carbon flux and single environment factors (such as historical CO₂ concentration, precipitation, temperature, and land use) have been analyzed to describe the net influence of drought as a single factor on grassland productivity [30,39,40]. Currently, the multifactor sensitivity simulation test has become an important method for studying the effect of a single factor and multiple factors. To eliminate the influence of historical CO₂ concentration changes on carbon flux, according to the CO₂ concentration data released by NASA from 1959 to 2012, this study took the CO₂ concentration level of 317.419 PPM in 1961, the starting year of the model operation, and the nitrogen deposition adopted the regional level of the 1980s which was 0.000411 kgN/m²/yr [41].

Using the Biome-BGC model as a tool and the NPP as an evaluation index of carbon balance, and based on multiple scenario simulation experiments, we quantified the effects of single climate factors on grassland productivity by analyzing the effects of temperature and precipitation changes on grassland carbon fluxes, identified the quantitative effects of drought on grassland productivity patterns in Inner Mongolia over the past 50 years, and revealed the differences in the responses of different grassland types to drought.

Through designing different factors to simulate drought conditions, the datum such as different climate factors (precipitation and temperature); the historical levels, at a specific time, of CO₂ concentration and nitrogen deposition; precipitation change (using the average of all the other factors); and temperature change (using the average of all the other factors) in different situations were inputted to the Biome-BGC model for simulating the NPP change in the Inner Mongolia grassland over the past 50 years and evaluating the carbon balance changes on the Inner Mongolia grassland under different situations. The experimental design is shown in Table 1. Under the CLM test mode, the different climate factors (precipitation and temperature) and the historical level, at a certain time, of CO₂ concentration and nitrogen deposition are executed using control test groups, to simulate the NPP change from 1961 to 2012 in every grid cell at a regional scale. In the precipitation change test group (using the average of all the other factors), the grassland NPP change respond to precipitation during 1964–2012 is analyzed while only the precipitation changed. In terms of the temperature change test group (using the average of all the other factors), the grassland NPP change respond to precipitation during 1964–2012 is analyzed, while only the temperature changed. The net effect of drought, over the past 50 years, on grassland productivity features the following: The net effect of drought on the NPP analysis equals the whole climate factor and the historical average CO₂ concentration and nitrogen deposition scene simulation minus the influences of the temperature and precipitation change scene simulations, to obtain the interaction influences, coupled with the precipitation change scene simulation of the NPP [42]. Since drought effects could be induced both by precipitation and temperature changes, we added the interactive effects between precipitation and temperature scenarios to the drought effects from precipitation change to reflect drought effects induced by both precipitation and temperature changes. This implies that the drought effect is the sum of the PREC and interactive effect. The main processes were as follows:

(a) To simulate the grassland NPP change from 1961 to 2012, under the test of CLM, PREC, and REMP situations,
(b) The interactive effect of precipitation and temperature on productivity equals CLM–PREC–TEMP, indicating that the interactive effect produced by precipitation and temperature change simultaneously.

c) The net influence on the productivity of drought equals the sum of the interactive effect and PREC, indicating that the influence of drought may be from precipitation and temperature change.

Table 1. Experimental design considering the sensibility of different factors.

| Test Designing                                      | Test Content                                                                 |
|----------------------------------------------------|-----------------------------------------------------------------------------|
| CO₂, N deposition, climate change (CLM)            | The real value of CO₂ concentration and N deposition in 1961 levels + the real historical value of the climate factor |
| Only change the precipitation (PREC)               | The real value of CO₂ concentration and N deposition in 1961 levels + the average of other climate elements (temperature, vapor pressure deficit, solar radiation) + the real historical value of precipitation |
| Only change the temperature (TEMP)                 | The real value of CO₂ concentration and N deposition in 1961 levels + the average of other climate elements (precipitation, vapor pressure deficit, solar radiation) + the real historical value of temperature |
| The other variables                                | Longitude and latitude, elevation, available depth of soil, the composition of soil particles, vegetation type |

Different physiological and ecological parameters were used to distinguish different grassland types, and different factors were used to simulate the experimental input to the Biome-BGC model to dissect the trends of drought on the NPP of different grassland types and its differences, to identify the quantitative effects of drought on the carbon balance of different grassland types in Inner Mongolia over the past 50 years, and to further reveal the differences in the response of different grassland types to drought. Based on the study of quantitative impacts of drought on carbon source sinks of different grassland types, the quantitative impacts of drought on the total carbon balance of temperate grasslands in Inner Mongolia were carved out using the changes in the NPP over the past 50 years as the evaluation criteria.

2.3. Biome-BGC Model

With climate, soil, and vegetation types as input data, the Biome-BGC model can simulate any scale from 1 m² to a regional, or even world, space and can simulate the daily value data of ecosystem variables to the annual value data of the NPP and other parameters in time, which has been widely used in the world. The Biome-BGC model is developed from the forest dynamic model, based on photosynthetic reaction and soil water balance, calculating the photosynthetic intensity and primary productivity. Based on the principle of energy and substance conservation, the Biome-BGC mode mainly simulates the substance fluxion and circulation process in the ecological system, such as energy, carbon, nitrogen, and water. The energy and substance, which are subtracted from the import and export of the energy and substance in the ecosystem, are allocated to different pools through the vegetation’s physiological and ecological processes, and interrelate each pool by fluxes at the same time. Solar shortwave radiation is a driving power source of the whole process of ecology, using the albedo and the bill law to calculate the absorbed radiation of the canopy. Precipitation in the form of rain and snow, are saved in snowdrifts, soil, and the canopy when they fall into the ecosystem, and they leave the ecosystem by evaporation, evapotranspiration, runoff, and seepage. The evaporation and evapotranspiration can be estimated using the Penman–Monteith equation. Carbon and nitrogen are involved in plant photosynthesis, growth, and decomposition processes. The canopy is divided into the sun part and lunar part, simulating photosynthesis by Farquhar, the carbon is used firstly for autotrophic breathing and allocated to each part of vegetation using the differences in growth rate, as shown in Figure 2.
The simulated step length is one day, while the ecosystem is separated into four carbon pools. The emphasis on the water cycle and water availability for the control function of the absorption and storage of carbon, with consideration of the effects on organic matter decomposition of soil temperature, water content, and lignin content of branches and leaves, the model mechanism is perfectly suited for studying the effect of drought on the carbon cycle. It is suitable for carbon cycle simulation on a regional scale because of the diversified analog scale and flexible output form. Mu et al. evaluated the influence of climate change and increased atmospheric CO$_2$ concentration on the Chinese terrestrial ecosystem carbon cycle based on the Biome-BGC process [42]. Therefore, in this study, we chose the Biome-BGC model to depict the grassland productivity response to drought.

The Biome-BGC model simulates energy and substance circulation processes under different ecological systems based on different vegetation function types, with the ability to simulate woody or nonwoody (C3/C4 grasses), evergreen or deciduous, coniferous or broad-leaved vegetation. In this study, the simulation mechanism of the model is closely related to the content of this research. Generally, the operation of the Biome-BGC model requires three input files: initialization file, meteorological data file, and physiological ecology parameters file. These files should be organized in a strict specific format. The input and output parameters of the Biome-BGC model are shown in Table 2.

| Input Data                      | Content                                                                 | Spatial Resolution                              | Temporal Resolution    | Output Data                                             |
|--------------------------------|------------------------------------------------------------------------|-------------------------------------------------|------------------------|---------------------------------------------------------|
| Meteorological data            | Daily maximum, minimum, and average temperature; precipitation; vapor pressure deficit; shortwave radiation, and day length | From the site scale to the regional global scale | Day-month-year         | Max LAI, annual evaporation, annual runoff, annual net primary productivity, annual net biomes productivity |
| Site initialization            | Latitude and longitude, altitude, available depth of soil, quality of material, atmospheric CO$_2$ concentration, vegetation types, and the setting of the input and output files | From the site scale to the regional global scale | Day-month-year         | Max LAI, annual evaporation, annual runoff, annual net primary productivity, annual net biomes productivity |
| Physiological ecology parameters | Including 44 parameters, such as leaf CN, radicula CN, stomatal conductance, canopy extinction coefficient, canopy leaf area, and the percentage of nitrogen in leaf tissue carboxylase | From the site scale to the regional global scale | Day-month-year         | Max LAI, annual evaporation, annual runoff, annual net primary productivity, annual net biomes productivity |
2.4. Model Applicability Evaluation

Based on the model parameterization and sensitivity analysis, it is necessary to further evaluate the model’s ability to be applied regionally. The validation of model applicability is mainly to evaluate the degree of agreement between simulated and observed values until there is no statistically significant difference between simulated and observed values. In this study, linear regression analysis, root mean square error (RMSE), and significance level ($p < 0.001$) were used as evaluation indicators to validate the accuracy of model simulations, and the calculations using Equations (1) and (2) for each indicator were as follows:

$$y = bx + a$$  \hspace{1cm} (1)

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (C_{si} - C_{oi})^2}$$  \hspace{1cm} (2)

where $y$ is the simulated value, $x$ is the observed value, $b$ is the slope, and $a$ is the intercept; the most ideal result of the model simulation should be $a = 0$ and $b = 1$. Therefore, the closeness of $b$ to 1 in the linear regression equation directly reflects the effect of model simulation. $N$ denotes the number of samples, $C_{si}$ denotes the simulated result value, and $C_{oi}$ denotes the measured result value.

In this paper, the Biome-BGC model was calibrated according to different carbon and water fluxes using different grassland-type flux sites and literature data in Inner Mongolia. The data details are shown in Table 3. According to the aim of the study, the key carbon and water flux parameters such as GPP, Re, NEP, and ET were mainly calibrated and optimized. According to the data characteristics of different stations, the NPP data of corresponding periods were extracted for comparative analysis to evaluate the accuracy and applicability of the Biome-BGC model simulation.

Table 3. The details of fluxes and experimental sites.

| Grassland Type     | Site Name          | Site Location       | Elevation (m) | Time Scale    | Data Source                        | Application                  |
|--------------------|--------------------|---------------------|---------------|---------------|------------------------------------|------------------------------|
| Meadow steppe      | Tongyu flux station| 44.42 N, 122.87 E   | 184           | 2004–2007     | COIRAS                             | Calibration models           |
|                    | Xing’an League     | 46.10 N, 123.00 E   | 191           | 1981–1990     | ORNL (Oak Ridge National Laboratory) | Validation of drought assessment results |
|                    | experimental site  |                     |               |               | Literature biomass                  | Calibration models           |
|                    | Hailar pilot site  | 49.22 N, 119.75 E   | 610.2         | 1989–2005     | Literature biomass                  | Calibration models           |
| Typical steppe     | Xilinhot flux station | 43.55 N, 116.67 E   | 1125          | 2003–2007     | ChinaFLUX and Literature biomass   | Calibration models           |
|                    |                    |                     |               |               | (Hao et al., 2010; Wu et al., 2008) |                              |
| Desert steppe      | Xilingole flux station | 43.63 N, 116.70 E   | 1100          | 2004–2005     | Literature biomass                  | Validation of drought assessment results |
|                    | Xilinhot experimental Station | 43.72 N, 116.63 E | 1200 | 1980–1989     | ORNL (Oak Ridge National Laboratory) | Validation of drought assessment results |
|                    | Xilinhot pilot site | 43.95 N, 116.12 E   | 1063          | 1982–2006     | Literature biomass                  | Calibration models           |
|                    | Sunit Zuqi flux station | 44.08 N, 113.57 E   | 970           | 2008–2009     | Literature biomass                  | Calibration models           |
|                    | Inner Mongolia     | 42.09 N, 110.61 E   | 1210          | 1983–1994     | China Grassland Resource Information System (GRIS) | Verification of drought assessment results |
|                    | Ummeng Damao Banner pilot site | 41.56 N, 08.52 E | 1288 | 1980–2006     | Literature biomass                  | Calibration models           |
|                    | Pilot site in Ulaat Central Banner | 41.56 N, 08.52 E | 1288 | 1980–2006     | Literature biomass                  |                              |

The meadow grassland carbon and water fluxes were verified mainly using the data from 2003–2007 at the Tongyu flux station, as shown in Table 3. The GPP of the Tongyu flux station is the synthetic data for 8 days from 2004 to 2006; the NEP and ET are the daily values from 2003 to 2007. According to the conversion relationship of aboveground and belowground biomass (belowground biomass = 5.26 × aboveground biomass) and the NPP and biomass conversion relationship (carbon $\text{g C} \cdot \text{m}^{-2} = \text{biomass} \times 0.45 \text{ g} \cdot \text{m}^{-2}$) for temperate meadow grasslands, the Ewenke Banner grazing NPP data were calculated from 1989–2005 at the weather station. From Figure 3, it can be seen that, generally, the model simulated values are in good agreement with the flux observations, and all the
carbon and water fluxes passed the test of significance level 0.001, in which the slopes of GPP, NEP, ET, and NPP are 0.80, 0.60, 0.65, and 0.78, respectively, and the simulated values are all relatively close to the 1:1 line and evenly distributed on both sides. The GPP, NEP, ET, and NPP root mean square error values were 5.36 gC/m$^2$/8 d, 0.89 gC/m$^2$/d, 0.62 mm/d, and 36 gC/m$^2$/yr, respectively, which were within a reasonable range of the simulation errors. The coefficients of determination of GPP, NEP, ET, and NPP were 0.59, 0.30, 0.46, and 0.79, respectively, and the regression effects were significant, indicating that the Biome-BGC model could better simulate meadow grassland carbon and water fluxes with high simulation accuracy, and had strong simulation performance and adaptability.

Figure 3. Different carbon and water flux validations of meadow steppe in Inner Mongolia: (a) GPP; (b) NEP; (c) ET; (d) NPP.

The typical grassland carbon and water flux validation mainly used the data of the Xilinhot station from 2003–2007, as shown in Table 3. The GPP and Re of the Xilinhot flux station are the daily value data from 2006–2007, and the NEP and ET are the daily value data from 2003–2007. Based on the conversion relationship between aboveground and belowground biomass (belowground biomass = 4.25 × aboveground biomass) and the conversion relationship between NPP and biomass (carbon gC·m$^{-2}$ = biomass × 0.45 g·m$^{-2}$) for typical grasslands in temperate zones, the NPP was calculated for the Xilinhot grazing weather station from 1980 to 2006 data. As can be seen from Figure 4, all carbon and water fluxes passed the test of significance level 0.001, where the slopes of GPP, Re, NEP, ET, and NPP were 0.79, 1.11, 0.73, 0.96, and 0.77, respectively, and the simulated values were all relatively close to the 1:1 line and evenly distributed on both sides. The GPP, Re, NEP, ET, and NPP root mean square error values were 0.69, 0.67, 0.53 gC/m$^2$/d, 0.61 mm/d, and 45.6 gC/m$^2$/yr, respectively, and the simulation errors were within a reasonable range. The coefficients of determination of GPP, Re, NEP, ET, and NPP were 0.70, 0.81, 0.55, 0.64, and 0.71, with significant regression effects, indicating that the Biome-BGC model could better simulate typical grassland carbon and water fluxes with high simulation accuracy, and had strong simulation performance and adaptability.
The verification of the carbon and water fluxes in the desert grassland mainly used the data of the Sunit Zuqi station from 2008–2009, as shown in Table 3. The NEP and ET of the Sunit Zuqi flux station are the daily value data from 2008–2009. Based on the conversion relationship of aboveground and belowground biomass of temperate desert grassland (belowground biomass = 7.89 × aboveground biomass) and the NPP and biomass conversion relationship (carbon gC·m⁻² = biomass × 0.45 g·m⁻²), the 1982–2006 NPP data were calculated for the pastoral Ulaatzhongqi meteorological station NPP data. As can be seen from Figure 5, all carbon and water fluxes passed the test of significance level 0.001, where the slopes of NEP, ET, and NPP were 0.75, 0.87, and 1.0, respectively, and the simulated values were all relatively close to the 1:1 line and evenly distributed on both sides. The NEP, ET, and NPP root mean square error values were 0.66 gC/m²/d, 0.54 mm/d, and 21.7 gC/m²/yr, respectively, which were within a reasonable range. The coefficients of determination of NEP, ET, and NPP were 0.77, 0.56, and 0.83, respectively, with significant regression effects, indicating that the Biome-BGC model could better simulate the typical grassland carbon and water fluxes with high simulation accuracy, and had strong simulation performance and adaptability.
566 gC/m²/yr. The flux observatory is able to make long-term continuous observations of different carbon and water fluxes, and obtains a large amount of flux data that can provide reliable mainstream technical support for studying the effects of drought on the productivity of grassland ecosystems. The effective integration of flux observation data with ecological process models can greatly expand the spatial and temporal scales of the study and provide a guarantee for further in-depth exploration of the differences in the effects of drought on grassland productivity. In this study, the Biome-BGC model was accurately calibrated and optimized using flux observation data of different grassland types, which reduced the uncertainty of model application and laid the foundation for the depth and reliability of the study.

3. Results and Discussion

3.1. The Spatial and Temporal Characteristics of Precipitation and Temperature Changes over the Past 50 Years

It is necessary to analyze the trend of precipitation and temperature changes to further investigate the net influence of drought on NPP because the influence of drought in this study is mainly affected by precipitation and temperature changes. As shown in Figure 6a, there has been no significant change in precipitation ($p > 0.05$) in Inner Mongolia over the past 50 years, with a slight decrease of 2.2 mm/10a, while the temperature raised significantly with a value of $0.358\, ^\circ\text{C}/10\text{a}$ (Figure 6b). Some researchers have also indicated that precipitation changed indistinctively, while the temperature rose significantly in the arid and semi-arid regions of North China, with an increased value of $0.04\, ^\circ\text{C}/10\text{a}$ [43]. However, Figure 7 shows that the annual average of precipitation in eastern regions is higher than in western regions, and it decreased from southeast regions to northwest regions. The precipitation increased in the meadows and desert grassland regions over the past 50 years, while it decreased in the northeast, southeast, and middle small areas of typical grassland regions. The are significant variations in the range of precipitation changes, with about 37.8% of the region with an increase, and 62.2% of the region with a decrease, which is similar to the trend of drought over the past 50 years. The precipitation of the Inner Mongolia grassland in recent decades has shown a change trend, in which the west has more precipitation and the east has less precipitation, divided by middle Inner Mongolia, with asymmetrical spatial distribution. In particular, desert grassland precipitation increased obviously in the autumn, the number of rainy days were reduced, single rainfalls increased, and the rainfall seasons changed significantly.

Figure 6. The trends of annual mean precipitation and temperature in Inner Mongolia over the past 50 years: (a) Precipitation; (b) temperature.
Figure 7. Annual mean precipitation, temperature, and their changing trends in Inner Mongolia over the past 50 years: (a) Average annual precipitation; (b) change rate of annual precipitation; (c) annual mean temperature; (d) change rate of annual mean temperature.

The annual average temperature in Inner Mongolia showed that the temperature in the western regions is highest, followed by the southeast regions and north regions. There is a change trend of increased temperature in the whole region, especially the north and middle-west regions with significant increases. However, the temperature change has relatively small variations, with about 45.8% of the region with 0.2 °C increments, and 53.9% of the region with 0.1–0.2 °C increments. The regions with increased temperature are mainly distributed in the north, west, and middle areas of typical grassland, and the north of the meadow steppe, which may be beneficial for grass growth in meadow steppes in cold regions and harmful to grass growth in typical grassland.

3.2. The Interaction of Precipitation and Temperature on Grassland Productivity

Through different scenario simulation tests, we researched the average trend of productivity change in the Inner Mongolia grassland regions over the past five decades, as shown in Figure 8. There was no significant trend in the average NPP in the Inner Mongolia grassland regions over the past 50 years (p > 0.05). Over the past 50 years, the regional average NPP did not present significant change (R² < 0.05). Under the current pattern of climate change, the regional average NPP was 211.33 gC/m²/yr in 1961, and it increased to 366.93 gC/m²/yr in 2012, with the change value of −4.73 gC/m²/10a, shown in Figure 5b. It demonstrated that the pattern of climate change had a slightly negative influence on grass-
land productivity in Inner Mongolia. In the scenario of PREC (only precipitation change), the regional average NPP also did not present a significant change trend ($R^2 < 0.05$). The regional average NPP was 278.88 gC/m$^2$/yr in 1961, and it increased to 343.83 gC/m$^2$/yr in 2012, with the change value of $−6.17$ gC/m$^2$/10a, as shown in Figure 8c. It was found that the pattern of precipitation changes also had a slightly negative influence on grassland productivity in Inner Mongolia. However, in the scenario of TEMP (only temperature change), the regional average NPP increased significantly ($R^2 < 0.05$). The regional average NPP average value was 228.48 gC/m$^2$/yr in 1961, and it increased to 235.12 gC/m$^2$/yr in 2012, with the change value of 0.59 gC/m$^2$/10a, as shown in the Figure 8d. This showed that the pattern of temperature change had a positive influence on grassland productivity in Inner Mongolia. Grassland productivity over the past 50 years decreased slightly under the current climate change, indicating that the influence of precipitation change was greater than that of temperature change on the NPP. Therefore, the current pattern of climate change harmed Inner Mongolia grassland productivity, which may have exacerbated the effect of drought on the grassland ecosystem to some degree.

Figure 8. Interannual variations in NPP under the changing climate (CLM), precipitation only (PREC), and temperature only (TEMP) experiments. (a) Aggregate graph of results; (b) Interannual variations in NPP under the changing climate (CLM); (c) Interannual variations in NPP under the precipitation only (PREC), and (d) Interannual variations in NPP under the temperature only (TEMP) experiments.

However, the role of current climate change in altering the response of grassland NPP to drought cannot be ignored, as shown in Figures 9 and 10. Precipitation and temperature changes had a significant interactive effect on grassland NPP ($p < 0.05$), and the regional NPP mean for grassland productivity in Inner Mongolia over the past 50 years ranged from $−207.51$ in 1961 to $−212.02$ gC/m$^2$/yr in 2012, with a trend of $−1.96/10a$. Therefore, when assessing the net effect of drought on grassland ecosystems, it is important to consider the current disturbances from climate change (precipitation and temperature changes). At the same time, from the above, there is a significant decrease ($p < 0.05$) in the effect of
drought on grassland NPP over the past 50 years, but the effect of drought on regional NPP is decreasing significantly ($p < 0.05$) with a trend of $-7.44/10a$ from 71.37 gC/m$^2$/yr in 1961 to 41.81 gC/m$^2$/yr in 2012. This suggests that the negative effect of drought on grassland productivity has been diminishing and the promoting effect has been increasing in the past 50 years. In most cases, the climatic patterns of the 20th century have contributed to the growth of forest ecosystem productivity [44]. Some scholars in the Midwestern grasslands of the United States have also found a positive trend of climate change effects on the annual NPP of grasslands [45]. In the southern United States, Chen also found that temperature changes could enhance or diminish the effects of drought on the NPP in different types of ecosystems, with the interaction of precipitation and temperature changes enhancing the effects of drought on forest productivity and leading to increased productivity declines, but at the same time diminishing the effects of drought on productivity in agricultural and wetland ecosystems. The reduction in the magnitude of drought-induced changes in grassland productivity is supported by the significant increase in grassland NPP as drought severity decreased in grassland ecosystems between 1895 and 2007 [30]. Under the current climate change model, the negative effect of drought on grassland productivity in Inner Mongolia has been reduced in the past 50 years.

Figure 9. The impacts on grassland productivity caused by precipitation and temperature change over the past 50 years.

Figure 10. The net impacts on grassland productivity caused by droughts over the past 50 years.
As shown in Figures 8 and 9, although temperature changes had significant effects on the regional NPP ($p < 0.05$), the annual variation of the regional NPP average was mainly determined by the fluctuations in precipitation. The maximum NPP appeared in the wettest year and the minimum NPP appeared in the driest year. Figure 11 shows that, in the CLM test mode, the NPP average value under the extreme drought year (2005) was 247.21 gC/m²/yr, with a decreased value of 41.51 gC/m²/yr (the normal year, 2007) and a larger decreased value of 127.05 gC/m²/yr (the wet year, 1964). In the PREC test mode, the NPP average value (2005) was 223.26 gC/m²/yr, with a decreased value of 55.84 gC/m²/yr (2007), and a larger decreased value of 105.52 gC/m²/yr (1964). In the TEMP test mode, the NPP average value (2005) was 228.92 gC/m²/yr, with decreased values of 0.62 gC/m²/yr (2007) and $-0.35$ gC/m²/yr (1964). We statistically analyzed the average state of the three years, based on a variation analysis of the regional NPP average values in the typical drought year, normal year, and wet year. As shown in Figure 12, based on the regional SPI_12 data, we classified the 50 years into three types, a drought year, normal year, and wet year. In the CLM test mode, the NPP average value (the extreme drought year) was 266.49 gC/m²/yr, with a decreased value of 28.38 gC/m²/yr (the normal year, 294.87 gC/m²/yr), and a larger decreased value of 66.89 gC/m²/yr (the wet year, 333.38 gC/m²/yr). In the PREC test mode, the NPP average value (drought year) was 250.38 gC/m²/yr, with a decreased value of 31.73 gC/m²/yr (normal year, 226.71 gC/m²/yr) and a larger decreased value of 68.6 gC/m²/yr (wet year, 318.98 gC/m²/yr). In the TEMP test mode, the NPP average value (drought year) was 226.17 gC/m²/yr, with decreased values of 0.54 gC/m²/yr (normal year, 226.71 gC/m²/yr) and 0.50 gC/m²/yr (wet year, 226.67 gC/m²/yr). Therefore, in Inner Mongolia, the influence of drought on grassland productivity was mainly controlled by the precipitation deficit, but there were significant interferences in the effects of temperature and precipitation on drought. Some researchers have found that precipitation variation was the main impact factor that led to the reduction of temperate grassland productivity in North China through the global change factor sensitivity simulation test [43].

Figure 11. NPP under CLM experiment for the extremely dry, extremely wet, and normal years based on drought intensity data.
3.3. The Net Influence on Regional Grassland Productivity of Drought over the Past Five Decades

From the analysis of the overall level of loss over the past 50 years, the total NPP losses in Inner Mongolia caused by drought ranged from 1140.30 to 15,003.30 gC/m²/yr, especially the NPP of typical steppe loss was most seriously. Overall, for 72.9% of the regions in Inner Mongolia grassland, there were large NPP losses caused by drought, which was almost distributed over the east and southeast meadow grassland, middle and northeast typical grassland, and eastern desert grassland. There was only 27.1% of the regions where the NPP increased, which were mainly distributed over the western desert grassland. Figure 8 shows that the influence on grassland productivity of drought had spatial heterogeneity. This spatial difference may result from the sensitivity of dynamic interannual variations of grassland on climate and biomass, and a lack of understanding of the response of the climate and atmospheric composition change in the regional grassland ecosystem process [46–48].

Climate change interferes, to some extent, with the influence of drought on a grassland ecosystem, which makes the influence of drought on a grassland ecosystem more complicated. Figure 13 indicates that, over the past 50 years, the regional average net impact of drought on the NPP in the meadow, typical, and desert steppes were 7005.73, 8466.10, and 4753.25 gC/m²/yr, respectively. As compared with the mixed impact of drought on grassland under the global climate change, the typical grassland NPP losses were the most serious, the meadow steppe losses were less than typical grassland, and the desert grassland had the least NPP losses. The net impact of drought on grassland productivity changed along the gradient of meadow steppe, typical steppe, and desert grassland, presenting the “two head low, middle high” phenomenon. Other scholars have also found that climate change significantly changed the pattern of drought on grassland productivity [43]. Therefore, to investigate the net impact of drought on grassland productivity, the interference of climate change factors on drought influence needs to be eliminated.

Figure 12. Mean annual NPP under CLM experiment for the dry, wet, and normal years based on drought intensity data (* indicates that the 0.05 significance level test has been passed, and () indicates the standard).

Figure 13. Total NPP losses for different grassland types caused by droughts over the past 50 years.
It is shown in Figure 14 that there was a large difference in the net response to drought on the NPP of different grassland types. For the meadow steppe, the areas where the NPP had large losses (NPP change greater than zero) accounted for about 95.4%, which were mainly distributed in the north, middle, and west of the meadow steppe. The areas where the NPP increased in the northeast and southeast areas accounted for only 4.6% (NPP change less than zero). Regarding the distribution of drought frequency, intensity, and duration, it was severe in the northern, middle, and western parts of the meadow steppe, while in the northeast and southeast areas, it was relatively slight. For the typical steppe, the area where the NPP had large losses accounted for about 91.6%, and it was mainly distributed over the middle and south of the typical steppe. The area where the NPP increased in the northwest, southwest, and northeast areas accounted for only 8.4%. The frequency, intensity, and duration of drought were also relatively severe in the central, southern, and northeastern areas, and relatively mild in the southeast area. For the desert steppe, the area where the NPP had large losses accounted for about 36.8%, and it was mainly distributed over the northeast and southeast of the desert steppe. The area where the NPP increased in the western area accounted for 63.2% There was a severe drought that occurred in the northeastern and southeastern desert steppe, while in the western area, drought was slight. The desert steppe can resist the interference of severe drought, without resulting in serious degradation of the desert steppe ecosystem or ecosystem collapse. Based on the analysis of the influence on the desert steppe of different degraded droughts, severe and moderate droughts had less influence on the desert steppe NPP, while the water-use efficiency of vegetation increased, and therefore did not cause a serious influence on the desert grassland NPP [49–51]. Due to the increased precipitation in the western desert steppe, we know that the interference of appropriate drought in the west region had promoted the NPP increased instead. It was shown that the interference of drought, to a certain extent, had promoted increased grassland ecosystem water-use efficiency, and even increased productivity.

Figure 14. Total NPP changes for different grassland types caused by droughts over the past 50 years: (a) Inner Mongolia grassland; (b) meadow steppe; (c) typical steppe; (d) desert steppe. A positive value indicates that NPP decreases, and a negative value indicates that NPP increases.
Climate change intensifies the uncertainty of the influence of drought on grass productivity at some level. The further intensification of climate change increases the uncertainty of the impact of drought on grassland, and also increases the vulnerability of the grassland ecosystems [33,52,53]. Climate change affects grassland ecosystems in different ways, while its impact is not equal to the sum of the impact of every single factor [54]. This study also suggests that the influences on the ecological system of drought, precipitation, and temperature changes are not equal to the sum of their single impacts, but the complex interactions. In the temperate grassland of Inner Mongolia, the precipitation increase can raise the variation of NPP significantly. The response amplitudes of precipitation change have been shown to be different in the meadow, typical, and desert steppes in northern China, which is similar to the results of this study [43]. Moderate drought and warming did not enhance the resistance and resilience of the grassland ecosystem to subsequent extreme drought. However, warming and extreme drought can strongly stimulate the decomposition of soil organic carbon in grasslands, enhancing soil respiration mainly by stimulating soil microbial activity, root activity, and nitrogen mineralization rates, further reducing the ecosystem carbon sequestration function. At the same time, researchers have found that drought did not lead to a decrease in NPP of an ecosystem, which may be caused by the fact that the temperature promotes vegetation photosynthesis and offsets the negative influence of drought on NPP [55]. Climate warming and elevated CO$_2$ concentration can increase soil moisture content and productivity of semi-arid grasslands to a certain extent [22]. This study supported this conclusion because it was found that the NPP increased in the desert and meadow steppe areas. A temperature increase of 2°C can decrease C3 grassland carbon sequestration ability, and enhance C3-C4 and C4 grass carbon sequestration ability [56].

In this study, there is a large difference in different grassland ecosystem responses to drought, precipitation, and temperature change. Nevertheless, precipitation variation in Inner Mongolia is the main driving factor of grassland productivity annual fluctuation [57,58]. In the Inner Mongolia grassland, the serious water deficit in the ecosystem caused by decreased precipitation and increased temperature, cause a serious drop in the NPP [59]. The results of this study also show that the influence of drought on grassland productivity in Inner Mongolia is mainly caused by the precipitation deficit variation.

4. Conclusions

In this paper, we assessed the influence of drought on grassland ecological system productivity under the background of climate change. Based on the literature, the design of different simulation experiment scenarios based on the Biome-BGC ecological process model were carried out to further analyze the characteristics of precipitation and temperature changes over the past 50 years and to pave the way for further analysis of the net effects of drought. The interaction of precipitation and temperature changes on drought effects was studied at a regional scale, and the net effect of drought on NPP was analyzed at point and regional scales. The results indicate the following:

1. On the regional scale, the current pattern of climate change plays a negative role in the grassland productivity in Inner Mongolia, aggravating the influence of drought on the grassland ecosystem to some degree. It is mainly controlled by precipitation deficit, but the temperature interferes with the precipitation during drought significantly ($p > 0.05$). The grassland productivity decreased slightly over the past 50 years under climate change, which reveals that the decreased impact of precipitation change is larger than the increased impact of temperature change on NPP.

2. From the analysis of the overall loss level of NPP caused by drought in grassland, the total change of NPP caused by a single factor of drought ranged from $-1140.30$ to $15,003.30$ gC/m$^2$/52a over the past 50 years. Specifically, the regional average losses of meadow, typical, and desert steppes are $7005.73$ gC/m$^2$/52a, $8466.10$ gC/m$^2$/52a, and $4753.25$ gC/m$^2$/52a, respectively. As compared with the mixed influence of drought on grassland under the background of global change, the severity of the net impact of drought as a single factor on grassland NPP are as follows: typical grassland
> meadow steppe > desert steppe. Therefore, climate change may, to a certain degree, complicate the impact of drought on grassland ecosystem productivity.

3. The net influence of drought on the NPP of different types of grassland types is varied. The percentages of the study area where drought has caused severe NPP losses (the values of NPP change are greater than zero) are about 95.4%, 95.4%, and 95.4% for meadow, typical, and desert steppe, respectively, while the areas where the NPP increased (the values of NPP change are less than zero) are about 4.6%, 8.4%, and 63.2%, respectively. Therefore, climate change increases the complexity of influence on grassland productivity by drought to some extent.

The analysis of our proposed method revealed that drought due to precipitation deficit and temperature change is the main factor that reduces grassland NPP, and the practical application in the Inner Mongolia grassland also verified the validity of our method. However, there are still some limitations in this study. First, only the effects of precipitation and temperature changes on the NPP of grasslands were considered in this study, and other factors such as weathering and topographical changes were not considered. Second, human activities such as grazing, population change, water utilization, and drought resistance may also have an impact on the NPP of grasslands. Third, we only considered 50 years of data variation and did not refine the time series, such as the effect of drought on grassland NPP under a 10-year span, 5-year span, 3-year spatial span, and a 1-year span. These are the focus of our future research.

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