Estimation and Climate Factor Contribution of Aboveground Biomass in Inner Mongolia’s Typical/Desert Steppes

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Abstract: Grassland biomass is an essential part of the regional carbon cycle. Rapid and accurate estimation of grassland biomass is a hot topic in research on grassland ecosystems. This study was based on field-measured biomass data and satellite remote sensing data from the Moderate resolution imaging spectroradiometer (MODIS). A generalized linear model (GLM) was used to analyze the aboveground biomass (AGB), dynamic changes, and relevance of climatic factors of the typical/desert steppe in Inner Mongolia during the growing seasons from May 2009 to October 2015. The results showed that: (1) The logarithmic function model with the ratio vegetation index (RVI) as the independent variable worked best for the typical steppe area in Inner Mongolia, while the power function model with the normalized differential vegetation index (NDVI) as the independent variable worked best for the desert steppe area. The R² values at a spatial resolution of 250 m were higher than those at a spatial resolution 500 m. (2) From 2009 to 2015, the highest values of AGB in the typical steppe and desert steppe of Inner Mongolia both appeared in 2012, and were 41.9 Tg and 7.0 Tg, respectively. The lowest values were 30.7 Tg and 5.8 Tg, respectively, in 2009. (3) The overall spatial distribution of AGB decreased from northeast to southwest. It also changed considerably over time. From May to August, AGB at the same longitude increased from south to north with seasonal variations; from August to October, it increased from north to south. (4) A variation partitioning analysis showed that in both the typical steppe and desert steppe, the combined effect of precipitation and temperature contributed the most to the aboveground biomass. The individual effect of temperature contributed more than precipitation in the typical steppe, while the individual effect of precipitation contributed more in the desert steppe. Thus, the hydrothermal dynamic hypothesis was used to explain this pattern. This study provides support for grassland husbandry management and carbon storage assessment in Inner Mongolia.

Keywords: Inner Mongolia typical/desert steppes; aboveground biomass; MODIS product; generalized linear model; climate

1. Introduction

Grassland is one of the most abundantly distributed terrestrial ecosystems on the earth [1,2]. In grassland ecosystems, grassland biomass represents primary productivity, determines the livestock capacity of the pasture, and is also the main carbon pool [3–5]. An accurate understanding of grassland’s
biomass and its changing patterns is important for the carbon cycle of a study area and the proper use of grassland resources [6,7]. However, there is still controversy surrounding the estimation of the magnitude and variation of grassland biomass and the understanding of the relationship between grassland biomass dynamics and environmental factors [8,9].

One-third of China’s land area is covered by grassland [10]. In particular, the Inner Mongolia grassland, located in arid and semi-arid regions, is an important part of the Eurasian steppe [11]. In the mid-western part of Inner Mongolia, the typical steppe and desert steppe areas are sensitive to global changes due to the fragility and volatility of their climatic conditions and the complex social factors associated with human activities [12]. At present, many researchers around the world have made tremendous efforts to simulate Inner Mongolia grassland and national-scale grassland biomass [12–16]. However, due to limitations in observational data and research methods, there is still great uncertainty in the estimation of biomass.

Remote sensing techniques have been widely used in the field of vegetation monitoring [17], especially for grassland ecosystems [18]. Moreover, combined with field surveys of typical areas, it has become possible to carry out long-term, dynamic studies on the vegetation biomass of a grassland ecosystem at large and medium spatial scales [19]. Zhao et al. [20] used MODIS data, along with biomass data of the Xilin Gol grassland from 2005 to 2012, to establish a regression model. The inversion of the Xilin Gol steppe aboveground biomass (AGB) was carried out using the model, and the spatial and temporal distribution of AGB was analyzed. Nevertheless, this study did not address the temporal and spatial patterns of aboveground biomass and its relationship with climatic factors. Ma et al. [21] examined changes in biomass between 1982 and 2006 and explored the driving factors in interannual biomass variation at the regional level. Yang et al. [22] combined the ground measured data and the MODIS-enhanced vegetation index of Tibet from 2001 to 2004, so as to estimate the grassland AGB of alpine meadow and alpine steppe and to explore the relationship between precipitation, temperature, and biomass. Xin et al. [23] combined the survey data of grassland biomass and normalized differential vegetation index (NDVI) data at the corresponding time period so as to analyze the changing characteristics of the spatial pattern of grassland biomass in China from 1982 to 2003, as well as its relationship with climate change. While remote sensing has achieved some results in estimating grassland biomass, many MODIS products are derived from the band data, and their algorithms are intended for global coverage. The precision of regional application needs further analysis. Therefore, it is necessary to use the recent regional ground-observed results to verify and improve the accuracy of MODIS products [24]. In addition, some researchers estimated the AGB using a single model for a large spatial scale, but they ignored the relationship between AGB and the vegetation index (VI) under various ecosystem conditions [25]. At the same time, the differences in the sensitivity and response of different types of vegetation to the hydrothermal factors were also neglected [26]. For this reason, in-depth systematic research should be conducted in this regard.

Climate is a key influential factor of grassland AGB [18,27,28]. Precipitation is generally considered to be the main controlling factor affecting spatial changes of AGB in arid and semi-arid regions. There are many studies showing a positive linear relationship between grassland AGB and mean annual precipitation [29–32]. However, some researchers believe that the increase in temperature has a significant impact on the biomass of different steppe ecosystems [33]. It has also been reported that AGB is mainly related to the average temperature of the growing season [34]. Therefore, it is necessary to analyze the effects of temperature and precipitation changes on the AGB of different grassland ecosystems.

The main objectives of this study are as follows: (1) Based on the generalized linear model (GLM), 285 sample data points collected by fixed-point monitoring from May 2009 to October 2015 and 16-day synthetic MODIS series EVI (enhanced vegetation index), NDVI (normalized differential vegetation index), and RVI (ratio vegetation index) data were used to establish a model at 250/500 m spatial resolution. The optimal model was selected for each area, and then the AGB of the typical/desert steppe in Inner Mongolia during the growing seasons was estimated through remote sensing. (2) The relative
contributions of different climatic factors to the spatial distribution patterns of grassland biomass in different steppes were determined.

2. Materials and Methods

2.1. Study Area

In the Inner Mongolia Autonomous Region, the steppe occupies a total area of 88 million hectares, accounting for 74% of the region’s area and more than 20% of the country’s steppe area. The grasslands are distributed from northeast to southwest across Inner Mongolia, comprising a forest area, meadow steppe area, typical steppe area, desert steppe area, steppified desert area, and desert area (Figure 1). In this paper, the study area was located in the typical steppe and desert steppe areas in Inner Mongolia, with a temperate continental semi-arid climate.

The selected plots of the typical steppe area in Inner Mongolia include three types of zonal vegetation: *Leymus chinensis* community, *Stipa grandis* community, and *S. Krylov Needlegrass* community. The mean annual temperature is 0.92 °C, and the mean annual precipitation is 346 mm, with June to August accounting for 70% of the precipitation for the whole year [35]. The major dominant plant species of the steppe are *Leymus chinensis*, *Stipa grandis*, *S. Krylov Needlegrass*, *Cleistogenes squarrosa*, and *Agropyron cristatum*. The major soil type is typical chestnut soil.

The selected plots of the desert steppe area in Inner Mongolia include three types of zonal vegetation: *S. brevflora* community, *S. klemenzii* community, and *S. plareosa* community. The mean annual temperatures is 2.5 °C, and the mean annual precipitation is 280 mm, mainly concentrated from May to August [36]. The major dominant plant species of the steppe are *Artemisia frigida*, *S. brevflora*, *S. klemenzii*, *S. plareosa*, *Cleistogenes mutica*, and *Allium polyrhizum*. The major soil types are light chestnut soil and brown soil.

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**Figure 1.** Distribution of field monitoring sampling sites and sampling sites selected for meteorological stations in the typical steppe and desert steppe areas in Inner Mongolia.
2.2. Data Acquisition

2.2.1. Sample Data Collection

Field sample data were obtained through cultivation by the Ministry of Agriculture of China’s national pasture industry technical system and the field experiments organized by the grassland management laboratory. A field survey was conducted in the typical and desert steppe areas in Inner Mongolia from 2009 to 2015. For the typical steppe area, three typical vegetation types including *Leymus chinensis* community, *Stipa grandis* community, and *S. Krylov Needlegrass* community were selected. For the desert steppe area, three typical vegetation types including *S. klemenzii* community, *S. breviflora* community, and *S. plareosa* community were selected. Monthly dynamic monitoring of biomass was carried out. The monitoring station was built on the natural grassland. The same method was used to sample once a month at each sampling site from May to October. As designed, five sampling sites were set for each area, and a 1 m² AGB sample block was collected from each sampling site. All species were cut off at ground level, put into different types of envelopes, brought indoors, and dried in an oven at 65 °C to a constant weight. Then the samples were weighed, the AGB of each species was recorded, and the average AGB of the five sample blocks was calculated. Given that the data quality of the ground sampling of the established model has a great influence on the estimation accuracy, data with missing location and AGB information were eliminated, and abnormal data were excluded. A total of 285 samples (285 × 5 sample blocks) at 10 field monitoring sites were monitored dynamically.

2.2.2. Remote Sensing and Climate Dataset

The remote sensing data were primarily obtained using TERRA/MODIS vegetation index products MOD13Q1 and MOD13A1, which are intended for terrestrial subjects. The data consisted of a 16-day synthetic vegetation index of NDVI/EVI at 250 m and 500 m resolution. In addition, the MODIS multi-spectrum near-infrared/infrared band data were downloaded, and the ENVI tool was used to calculate the vegetation index RVI after atmospheric correction. Finally, the vegetation index NDVI/EVI/RVI (referred to as VI) on the most recent date from the sampling time point was calculated and extracted in turn. The time span was from May 2009 to October 2015. For the selection of the vegetation index, given that the combination of reflectance in the visible-near-infrared band has a good correlation with green biomass [37–39], three kinds of vegetation indices were selected to invert the grassland biomass [40–42]. RVI (Equation (1)) is suitable for monitoring vegetation with strong growth and high coverage [43]. NDVI (Equation (2)) is suitable for dynamically monitoring vegetation at the early and middle growth stages, but high-biomass areas are prone to saturation [44]. In contrast, the enhanced vegetation index EVI (Equation (3)) can achieve increased sensitivity in high-biomass areas. The monitoring of vegetation could be improved by weakening the background signal of the canopy and reducing the effects of the atmosphere [45].

\[
\begin{align*}
\text{RVI} & = \frac{B4}{B3} \\
\text{NDVI} & = \frac{B4 - B3}{B4 + B3} \\
\text{EVI} & = \frac{B4 - B3}{B4 - 6B3 + 7.5B1 + 1} \times 2.5
\end{align*}
\]

where \(B4\) denotes the near red band, \(B3\) denotes the red band, and \(B1\) denotes the blue band.

The monthly VI data were obtained by the maximum synthesis method, which calculates the average of the growing seasons (from May to October), based on the monthly VI, and finally converts these into 250 m × 250 m and 500 m × 500 m raster images. In areas with a low coverage of vegetation, the VI value could be greatly affected by soil spectral characteristics; in some areas where vegetation
index pixels are filled with invalid values and noise, the noise mainly occurs in areas with basically no vegetation coverage, so only the areas with VI > 0.1 were considered [14].

The zoning map of grassland types in Inner Mongolia was plotted by Li et al. [46] through digitization of field observations in early attempts. Ten sample sites were selected across the range of typical steppe and desert steppe areas, covering six community types. The relationship between the AGB and the average monthly VI during the growing seasons in the corresponding years (from May 2009 to October 2015) was established, and then the AGB was calculated based on the VI value of each pixel. As a result, the spatial distribution map of grassland AGB of the typical/desert steppe in Inner Mongolia during the growing seasons was plotted.

Ground meteorological data were obtained from the Inner Mongolia meteorological bureau, including average monthly temperature and precipitation data from 2009 to 2015 collected from 119 meteorological stations. Through Kriging interpolation, according to the latitude and longitude of the plot, the mean values of meteorological factors such as precipitation and temperatures from May to October were extracted from the interpolation results.

2.3. Data Analysis

2.3.1. Establishment and Verification of the Biomass Model

Since Inner Mongolia has a vast territory and diverse grassland types, it is difficult to characterize the differences between different steppes using one single model. Therefore, the typical vegetation types were selected for the typical/desert steppe areas in Inner Mongolia, and an independent AGB estimation model was established for each area.

The GLM (generalized linear model) is an extension of general linear regression model. It can analyze not only positive linear model but also non-normal data [47]. Therefore, the GLM was used to establish a functional relationship between the field-surveyed sample and the vegetation indices, including linear, quadratic, logarithmic, power, and exponential relationships. Regression analysis was performed using R 3.5.1 (R Development Core Team 2018) to analyze and calculate the VI at 250 m and 500 m resolutions and the actually sampled grassland biomass data for regression analysis (Table 1).

<table>
<thead>
<tr>
<th>Region</th>
<th>Function</th>
<th>Model</th>
<th>R²</th>
<th>RMSE</th>
<th>REE</th>
<th>x (VI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical</td>
<td>Linear</td>
<td>( y = 503.038x - 60.099 )</td>
<td>0.583</td>
<td>28.52</td>
<td>35.2</td>
<td>NDVI-250</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>( y = 221.459x^2 + 336.377x - 32.778 )</td>
<td>0.585</td>
<td>28.46</td>
<td>41.7</td>
<td>NDVI-250</td>
</tr>
<tr>
<td></td>
<td>Logarithmic</td>
<td>( y = 210.052\ln(x) - 41.761 )</td>
<td>0.586</td>
<td>31.65</td>
<td>34.5</td>
<td>RVI-250</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>( y = 786.585x^{2.001} )</td>
<td>0.519</td>
<td>42.47</td>
<td>29.3</td>
<td>NDVI-250</td>
</tr>
<tr>
<td></td>
<td>Exponential</td>
<td>( y = 11.605x^{3.685} )</td>
<td>0.475</td>
<td>29.25</td>
<td>43.8</td>
<td>NDVI-250</td>
</tr>
<tr>
<td>Desert</td>
<td>Linear</td>
<td>( y = 382.925x - 21.357 )</td>
<td>0.316</td>
<td>36.54</td>
<td>28.4</td>
<td>NDVI-250</td>
</tr>
<tr>
<td></td>
<td>Quadratic</td>
<td>( y = 506.875x^2 + 1074.173x - 855.277 )</td>
<td>0.384</td>
<td>41.32</td>
<td>31.3</td>
<td>RVI-250</td>
</tr>
<tr>
<td></td>
<td>Logarithmic</td>
<td>( y = 81.279\ln(x) + 190.723 )</td>
<td>0.350</td>
<td>66.64</td>
<td>27.3</td>
<td>NDVI-250</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>( y = 1641.21x^{2.203} )</td>
<td>0.404</td>
<td>30.40</td>
<td>38.6</td>
<td>NDVI-250</td>
</tr>
<tr>
<td></td>
<td>Exponential</td>
<td>( y = 5.597e^{9.990x} )</td>
<td>0.342</td>
<td>34.76</td>
<td>42.5</td>
<td>NDVI-250</td>
</tr>
</tbody>
</table>

Table 1. Statistical model of aboveground biomass (AGB) and the most suitable vegetation index in inner Mongolian typical/desert steppe.

Note: The numbers of the typical and desert steppe training and test samples were 104 and 26, and 124 and 31, respectively. \( x \) is the vegetation index (NDVI-250 and RVI-250 presents normalized differential vegetation index and ratio vegetation index at 250 m spatial resolution, respectively) and \( y \) is the estimated aboveground biomass. NDVI—normalized differential vegetation index.

We calculated the root mean squared error (RMSE) and the mean relative estimate error (REE) to evaluate the precision of the models based on the reserved samples (20% of the total samples). RMSE and REE, respectively, were calculated as follows:

\[
RMSE = \sqrt{\frac{\sum(Y_i - \bar{Y_i})^2}{N}},
\]

(4)
where $Y_i$ is the actual aboveground biomass (fresh weight), $Y_i'$ is the aboveground biomass estimated by the model, and $N$ is the sample size.

### 2.3.2. Spatial Distribution and Dynamic Changes of AGB

In this study, the optimal model suitable for two regions to estimate spatial distribution patterns of AGB of the typical/desert steppe in Inner Mongolia during the growing seasons was determined. The raster datasets of the two regions were combined into one with the geographic coordinates as a reference, and ArcGIS was used to obtain the raster data through the Mosaic method. AGB changes regularly during the growing seasons in different types of grasslands. Considering that the change in grassland biomass is affected by seasonal changes, the variation of grassland biomass was calculated based on the monthly scale.

### 2.3.3. Effects of Climatic Factors on Aboveground Biomass

The variation partitioning analysis was used to understand the impact of climate on the dynamic changes and spatial distribution of AGB using the “vegan” package of R 3.5.1 software.

### 3. Results

#### 3.1. The Best Remote Sensing Vegetation Index, Models, and Aboveground Biomass Estimation of a Typical Desert Steppe in Inner Mongolia

Regression analysis showed that the logarithmic function model with RVI of the typical steppe area as the independent variable had the highest accuracy; the power function model with NDVI of the desert steppe area as the independent variable had the highest accuracy. At the same time, the VI value of the two steppe areas at 250 m spatial resolution resulted in the best regression analysis. Therefore, the logarithmic function model (RVI) was used to estimate the AGB of the typical steppe during the growing seasons (Table 2), and the power function model (NDVI) was used to estimate the AGB of the desert steppe during the growing seasons (Table 3).

<table>
<thead>
<tr>
<th>Month</th>
<th>Total Aboveground Biomass (Tg)</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td></td>
<td>24.1</td>
<td>17.4</td>
<td>15.7</td>
<td>17.9</td>
<td>21.2</td>
<td>22.0</td>
<td>19.3</td>
<td>19.6</td>
</tr>
<tr>
<td>June</td>
<td></td>
<td>28.8</td>
<td>36.6</td>
<td>27.6</td>
<td>34.2</td>
<td>37.7</td>
<td>43.0</td>
<td>36.6</td>
<td>34.9</td>
</tr>
<tr>
<td>July</td>
<td></td>
<td>44.5</td>
<td>48.0</td>
<td>54.9</td>
<td>69.7</td>
<td>66.9</td>
<td>59.4</td>
<td>56.1</td>
<td>57.1</td>
</tr>
<tr>
<td>August</td>
<td></td>
<td>43.3</td>
<td>50.2</td>
<td>60.7</td>
<td>68.5</td>
<td>66.6</td>
<td>53.5</td>
<td>58.4</td>
<td>57.3</td>
</tr>
<tr>
<td>September</td>
<td></td>
<td>28.9</td>
<td>31.5</td>
<td>33.3</td>
<td>42.0</td>
<td>39.5</td>
<td>35.9</td>
<td>37.8</td>
<td>35.6</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td>14.5</td>
<td>16.2</td>
<td>16.9</td>
<td>19.1</td>
<td>19.0</td>
<td>17.4</td>
<td>17.1</td>
<td>17.2</td>
</tr>
<tr>
<td>Annually average</td>
<td></td>
<td>30.7</td>
<td>33.3</td>
<td>34.9</td>
<td>41.9</td>
<td>41.8</td>
<td>38.5</td>
<td>37.5</td>
<td>36.9</td>
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<table>
<thead>
<tr>
<th>Month</th>
<th>Total Aboveground Biomass Density (g·m⁻²)</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td></td>
<td>63.6</td>
<td>45.9</td>
<td>41.6</td>
<td>47.3</td>
<td>55.9</td>
<td>58.1</td>
<td>51.0</td>
<td>51.9</td>
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<tr>
<td>June</td>
<td></td>
<td>76.2</td>
<td>96.6</td>
<td>72.9</td>
<td>90.5</td>
<td>99.5</td>
<td>113.5</td>
<td>96.8</td>
<td>92.3</td>
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<tr>
<td>July</td>
<td></td>
<td>117.4</td>
<td>126.9</td>
<td>145.0</td>
<td>184.1</td>
<td>176.7</td>
<td>157.0</td>
<td>148.3</td>
<td>150.8</td>
</tr>
<tr>
<td>August</td>
<td></td>
<td>114.5</td>
<td>132.7</td>
<td>160.4</td>
<td>180.9</td>
<td>176.0</td>
<td>141.4</td>
<td>154.2</td>
<td>151.4</td>
</tr>
<tr>
<td>September</td>
<td></td>
<td>76.4</td>
<td>83.2</td>
<td>88.1</td>
<td>111.1</td>
<td>104.3</td>
<td>94.8</td>
<td>99.7</td>
<td>93.9</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td>38.4</td>
<td>42.8</td>
<td>44.6</td>
<td>50.4</td>
<td>50.1</td>
<td>45.9</td>
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<td>45.4</td>
</tr>
<tr>
<td>Annually average</td>
<td></td>
<td>81.1</td>
<td>88.0</td>
<td>92.1</td>
<td>110.7</td>
<td>110.4</td>
<td>101.8</td>
<td>99.2</td>
<td>97.6</td>
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</table>
Table 3. Biomass of the desert steppe in Inner Mongolia during the growth season from 2009 to 2015.

<table>
<thead>
<tr>
<th>Month</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>Average</th>
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<tbody>
<tr>
<td>May</td>
<td>4.2</td>
<td>2.4</td>
<td>2.4</td>
<td>3.1</td>
<td>3.0</td>
<td>2.7</td>
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<td>3.0</td>
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<td>5.1</td>
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<td>5.8</td>
<td>4.7</td>
<td>5.2</td>
<td>5.1</td>
</tr>
<tr>
<td>July</td>
<td>8.1</td>
<td>9.3</td>
<td>8.5</td>
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<td>11.6</td>
<td>8.9</td>
<td>10.2</td>
<td>10.1</td>
</tr>
<tr>
<td>August</td>
<td>9.4</td>
<td>9.3</td>
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<td>16.6</td>
<td>11.8</td>
<td>10.1</td>
<td>8.9</td>
<td>11.1</td>
</tr>
<tr>
<td>September</td>
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<td>6.6</td>
<td>6.0</td>
<td>9.9</td>
<td>6.9</td>
<td>8.2</td>
<td>6.1</td>
<td>7.0</td>
</tr>
<tr>
<td>October</td>
<td>2.3</td>
<td>2.8</td>
<td>2.9</td>
<td>3.1</td>
<td>3.2</td>
<td>2.7</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Annually average</td>
<td>5.8</td>
<td>5.9</td>
<td>5.9</td>
<td>8.6</td>
<td>7.0</td>
<td>6.2</td>
<td>6.0</td>
<td>6.5</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Month</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>37.1</td>
<td>21.3</td>
<td>20.8</td>
<td>27.0</td>
<td>26.1</td>
<td>23.8</td>
<td>26.3</td>
<td>26.1</td>
</tr>
<tr>
<td>June</td>
<td>44.7</td>
<td>45.4</td>
<td>36.8</td>
<td>46.1</td>
<td>50.8</td>
<td>40.9</td>
<td>45.8</td>
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</tr>
<tr>
<td>July</td>
<td>71.5</td>
<td>81.5</td>
<td>74.3</td>
<td>121.9</td>
<td>102.1</td>
<td>78.1</td>
<td>89.8</td>
<td>88.5</td>
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<tr>
<td>August</td>
<td>82.5</td>
<td>81.3</td>
<td>102.3</td>
<td>146.0</td>
<td>103.7</td>
<td>88.7</td>
<td>78.3</td>
<td>97.5</td>
</tr>
<tr>
<td>September</td>
<td>48.1</td>
<td>58.2</td>
<td>53.1</td>
<td>86.7</td>
<td>60.5</td>
<td>72.4</td>
<td>53.5</td>
<td>61.8</td>
</tr>
<tr>
<td>October</td>
<td>20.4</td>
<td>24.4</td>
<td>25.2</td>
<td>27.3</td>
<td>27.8</td>
<td>24.0</td>
<td>23.7</td>
<td>24.7</td>
</tr>
<tr>
<td>Annually average</td>
<td>50.7</td>
<td>52.0</td>
<td>52.1</td>
<td>75.8</td>
<td>61.8</td>
<td>54.6</td>
<td>52.9</td>
<td>57.1</td>
</tr>
</tbody>
</table>

The results showed a significant correlation between the VI and AGB of the two types of grasslands ($p < 0.01$), which is in line with the statistical analysis hypothesis. Given the field sampling span of seven years, the model was stable enough. Finally, the linear slope between the measured and estimated AGBs was used to evaluate the accuracy of the model (Figure 2).

![Graph showing relationship between estimated and actual AGB of typical/desert steppe.](image.png)

Figure 2. Relationship between estimated and actual AGB of typical/desert steppe.

From 2009 to 2015, the average total aboveground biomass of the typical steppe in Inner Mongolia during the growing seasons was $36.9 \text{Tg}$ ($1 \text{Tg} = 10^{12} \text{g}$), and that of the desert steppe was $6.5 \text{Tg}$. During the seven years, the average total grassland aboveground biomass of the typical/desert steppe during the growing seasons was the highest in 2012, i.e., $41.9 \text{Tg}$ and $7.0 \text{Tg}$, respectively. The values were the lowest in 2009, i.e., $30.7 \text{Tg}$ and $5.8 \text{Tg}$, respectively. In other years, the average total grassland biomass of the typical/desert steppe during the growing seasons showed identical changing patterns, sorted in descending order of $2013 > 2014 > 2015 > 2011 > 2010$. This indicated that the changing patterns of the total biomass of the two grassland types in recent years were not significantly affected by the grassland types but were significantly affected by other factors such as climate.

According to the AGB density analysis tables (Tables 2 and 3), from 2009 to 2015, the average density of AGB of the typical steppe in Inner Mongolia was $97.6 \text{g}\cdot\text{m}^{-2}$, and that of the desert steppe was $57.1 \text{g}\cdot\text{m}^{-2}$. Moreover, the average AGB of the typical steppe and desert steppe was the highest in August, i.e., $151.4 \text{g}\cdot\text{m}^{-2}$ and $88.4 \text{g}\cdot\text{m}^{-2}$, respectively, and the lowest in October, i.e., $45.3 \text{g}\cdot\text{m}^{-2}$ and $24.7 \text{g}\cdot\text{m}^{-2}$, respectively. From 2009 to 2015, the average density of AGB of the typical steppe during
the growing seasons was almost twice that of the desert steppe. The vegetation generally grew well in
the typical steppe in Inner Mongolia, with relatively lower density and poorer growth compared to the
desert steppe area.

3.2. Spatial Distribution of AGB During Different Growing Seasons

Natural vegetation has periodic variation and obvious temporal characteristics. Satellite imaging
provides transient information at a certain growth phase of the vegetation. The repeated imaging
feature of satellites can be used to monitor and track plant dynamic changes. However, since the plants
themselves and the background parameters change at different times, the images were acquired at
different time points. Observed results for the same area were significantly different, as shown in
Figure 3. From 2009 to 2015, the distribution of the mean average AGB of the typical steppe and desert
steppe in Inner Mongolia from May to October showed significant spatial heterogeneity. Plants grew
rapidly from May and June, and the high-density area (> 60 g·m⁻²) gradually expanded to a peak in
July and August and gradually declined in September and October. The general distribution decreased
from northeast to southwest.

**Figure 3.** Spatial distribution of AGB of typical/desert steppe in Inner Mongolia during the growing
seasons (g·m⁻²) from 2009 to 2015.
The grassland biomass varied greatly during the growing seasons. From May to August, the grassland biomass at the same longitude increased from south to north with seasonal variations; from August to October, it increased from north to south. By July and August, there were almost no low-density areas in the typical steppe and desert steppe. By May and October, most of the desert steppe area densities were less than 15 g·m$^{-2}$. Therefore, the varying time of image acquisition by the satellite may lead to different estimated grassland biomass. That is to say, different grassland types have different spectral characteristics in different periods, so this factor should be taken into account in the calculation of grassland biomass.

3.3. Relationship Between AGB and Climatic Factors

Correlation analysis showed that the biomass of the two types of steppes was significantly correlated with precipitation and temperature (Figure 4). Variation partitioning analysis showed in both the typical steppe and desert steppe, the combined effect of precipitation and temperature contributed the most to the aboveground biomass. The individual effect of temperature contributed more than precipitation in the typical steppe, while the individual effect of precipitation contributed more in the desert steppe (Figure 5).

![Figure 4. The relationship between AGB and precipitation and temperature of typical (a,b) and desert (c,d) steppes in Inner Mongolia.](image-url)
while that with NDVI worked best for the desert steppe area (Table 1). However, the measurement of using RVI to evaluate the grassland AGB is identical to that of NDVI. Secondly, EVI revised the surface reflectance to improve the sensitivity to high-biomass areas, which is suitable for areas with a high-coverage of vegetation. With the arid and semi-arid climate, both the typical and desert steppe areas in Inner Mongolia were not that sensitive to EVI. Compared with the other vegetation indices, EVI partially eliminated the effects of atmospheric noise and soil background and was less saturated in areas with a greater coverage of vegetation. Therefore, some studies have shown that EVI is widely used in agricultural remote sensing with a high accuracy [48].

Moreover, when the coverage of vegetation is significantly greater than 80%, the sensitivity of NDVI to vegetation decreases, and RVI becomes very sensitive to vegetation [40]. Therefore, the potential of using RVI to evaluate the grassland AGB is identical to that of NDVI. Secondly, EVI revised the surface reflectance to improve the sensitivity to high-biomass areas, which is suitable for areas with a high-coverage of vegetation. With the arid and semi-arid climate, both the typical and desert steppe areas in Inner Mongolia were not that sensitive to EVI. Compared with the other vegetation indices, EVI partially eliminated the effects of atmospheric noise and soil background and was less saturated in areas with a greater coverage of vegetation. Therefore, some studies have shown that EVI is widely used in agricultural remote sensing with a high accuracy [48].

How representative the ground measurement points are of remote sensing pixels and how much the spatial resolution can truly reflect the actual situation are important issues in quantitative remote sensing. In this paper, the grid sizes of 250 m and 500 m represented different scales, and remote sensing images of different resolutions had certain influences on AGB modeling. The results showed that 250 m was better than 500 m when estimating AGB by index because the heterogeneity of environmental factors within the plant community affected the horizontal structure of the community, which was manifested as patches in space, and the patch area was inconsistent from small to large [49]. Therefore, the pixel information of 250 m resolution remote sensing data was more representative of the vegetation in this region. Therefore, in the remote sensing estimation of the typical and desert steppe, the remote sensing data with a resolution of 250 m had a higher accuracy than that of 500 m resolution.

4. Discussion

4.1. Sensitivity of Different Grassland Types to Vegetation Indices

Based on the distribution of grassland types in Inner Mongolia, a model was established to estimate the field samples and the vegetation indices of the typical/desert steppe areas. Studies have shown that the estimation model with RVI worked best for the typical steppe area in Inner Mongolia, while that with NDVI worked best for the desert steppe area (Table 1). However, the measurement coefficient between EVI and grassland AGB was lower than those of RVI and NDVI. MODIS products are modified on the basis of existing vegetation indices in order to make them suitable for worldwide use. This product only includes NDVI and EVI products [24], while not including RVI. However, studies have shown that the RVI of the typical steppe area is more sensitive to AGB than is NDVI. Therefore, the potential of using RVI to evaluate the grassland AGB is identical to that of NDVI. Secondly, EVI revised the surface reflectance to improve the sensitivity to high-biomass areas, which is suitable for areas with a high-coverage of vegetation. With the arid and semi-arid climate, both the typical and desert steppe areas in Inner Mongolia were not that sensitive to EVI. Compared with the other vegetation indices, EVI partially eliminated the effects of atmospheric noise and soil background and was less saturated in areas with a greater coverage of vegetation. Therefore, some studies have shown that EVI is widely used in agricultural remote sensing with a high accuracy [48].

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4.2. Comparison with Previous Findings

This study estimated the average AGB density of the typical steppe in Inner Mongolia to be 97.6 g m⁻² and that of the desert steppe to be 57.1 g m⁻². Some of the values are similar to previous estimates, but others are not (Table 4). For example, Piao [8] estimated the AGB of the typical steppe...
and desert steppe in China based on grass yield. The value of the typical steppe was close to the estimates in this study, but the value of the desert steppe was lower. Ma [50] collected samples from 131 plots in Inner Mongolian grassland and estimated the AGB of the typical steppe and desert steppe in Inner Mongolia. The value of the desert steppe was close to the estimate in this study, but that of the typical steppe was much higher. Zhao [20] used field surveys from 1205 sites of the Xilin Gol steppe from 2005 to 2012 and MODIS data to estimate grassland biomass densities of the typical steppe and desert steppe, which were significantly lower than the estimates in this study. In particular, the value of the desert steppe was only 27.2 g/m², which is almost half of our value. These differences are caused by different sources of data, including remote sensing image acquisition, field surveys, and vegetation classification systems. On the other hand, these different research scales, times, and methods will also result in differences. Previous research was mostly carried out using biomass remote sensing data at the peak stage of biomass. Compared with this study, the use of multi-time remote sensing data can reduce the influence of soil background and improve the accuracy of grassland AGB estimation.

### Table 4. Aboveground biomass densities from different studies.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Aboveground Biomass Densities (g·m⁻²)</th>
<th>Data Resource and Approach</th>
<th>Study Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Steppe</td>
<td>Desert Steppe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piao et al. (2007)</td>
<td>91.5</td>
<td>Grassland resource survey</td>
<td>China</td>
</tr>
<tr>
<td>Ma et al. (2008)</td>
<td>133.4</td>
<td>AVHRR-NDVI Field biomass</td>
<td>Inner Mongolia</td>
</tr>
<tr>
<td>Zhao et al. (2014)</td>
<td>69.1</td>
<td>Field biomass measurements and MODIS-NDVI</td>
<td>Xilingol</td>
</tr>
<tr>
<td>This study</td>
<td>97.6</td>
<td>Field biomass measurements and MODIS-RVI, NDVI</td>
<td>Inner Mongolia</td>
</tr>
</tbody>
</table>

4.3. Spatial Distribution and Climatic Factors of AGB of Typical/Desert Steppe in Inner Mongolia

Climate change affects the living environment of plants, which in turn affects the growth status of plants [51]. Hydrothermal factors are the dominant factors in the formation of zonality of vegetation, and the sensitivity and response of different types of grasslands to the hydrothermal factors are different [26]. To understand how the AGB of the typical/desert steppe in Inner Mongolia responds to hydrothermal factors, variation partitioning analysis was used to explore the effects of temperature and precipitation on the biomass of steppe grassland in Inner Mongolia. Three groups of regression analysis between climatic factors and AGB showed that the hydrothermal drives were different between different steppe areas (Figure 5). The two types of steppe were combined for analysis, and results showed that precipitation contributed more than temperature. Intra-group regression of the typical steppe and desert steppe in Inner Mongolia showed that temperature contributed more in the typical steppe, while precipitation contributed more in the desert steppe. This indicated that the climatic constraints differed between the two types of steppe.

Some studies showed that the vegetation activities were significantly more correlated with monthly temperature and precipitation than with the yearly scale [10], suggesting that the seasonal fluctuation of the hydrothermal factors had a greater impact on pasture growth than interannual hydrothermal conditions. The grassland biomass of the desert steppe in Inner Mongolia was significantly positively correlated with the average monthly temperature and precipitation during the growing seasons \((p < 0.01, \text{Figure 4})\). Moreover, precipitation contributed more than temperature did, which was consistent with most research [52,53]. The underlying reason was that the desert steppe is distributed in this region, with less precipitation. The moisture condition is the major limiting factor for the growth of vegetation. The correlation was also positive in the typical steppe area \((p < 0.01, \text{Figure 4})\), but temperature contributed more than precipitation did. The underlying reason might be that this area is closer to the east than the desert steppe. The precipitation gradient of Inner Mongolia steppe increases from west to east, so the moisture limitation is greatly reduced compared with the desert steppe.
In general, temperature and precipitation contributed similarly. Based on the hydrothermal dynamic hypothesis of modern climates [54,55], it is believed that the spatial distribution pattern of species is jointly determined by water and energy. In the physiological activities of plants, liquid water is not only an important solvent for biochemical processes, but also a key reactant for photosynthesis. The amount of water and energy combined determines the intensity of photosynthesis and the accumulation of biomass, thereby affecting a plant’s spatial pattern [56]. In this hypothesis, the energy is usually expressed by the temperature measure, while the water is expressed by the average precipitation of a region. In this study, the precipitation and temperature explained 7% and 13% for the AGB of the typical-steppe in Inner Mongolia, respectively, and explained 23% and 6% that of the desert steppe, respectively. With combined typical and desert steppe, the precipitation and temperature explained 15% and 10%, respectively, and the total contribution rate was 76%. This reflected that hydrothermal factors had a decisive effect on the grassland aboveground biomass, thus supporting the hydrothermal dynamic hypothesis.

For AGB, the unexplainable part of climate factors may come from the following two aspects: (1) Soil factors that were not introduced, but considering that our study was carried out at a large scale and soil is a hydrothermal derivative product at a large scale, its contribution to AGB was relatively limited; (2) topographic and geomorphic features, geohistory, and other factors.

5. Conclusions

The grassland biomass of the typical/desert steppe in Inner Mongolia during the growing seasons and its spatial and temporal patterns were investigated. The biomass data and 16-day synthetic MODIS data from 2009 to 2015 were collected through fixed-point monitoring in Inner Mongolia, and the most suitable GLM model was established for each region. The results showed that the AGB had some fluctuations in the typical/desert steppe in Inner Mongolia. The average density in the typical steppe was 97.6 g m\(^{-2}\), while that in the desert steppe was 57.1 g m\(^{-2}\). The spatial distribution pattern decreased gradually from northeast to southwest, alternating with the seasons. During the growing seasons from May to October, the grassland AGB changes significantly and is affected by seasonal variations. Finally, the response of the grassland biomass to the hydrothermal factors was explored. The correlation analysis showed a significant correlation between biomass and precipitation and temperature in the two types of steppe areas. Variation partitioning analysis showed that the hydrothermal drivers were different between different steppe areas: Temperature contributed more in the typical steppe, while precipitation contributed more in the desert steppe. Furthermore, the combined effect of precipitation and temperature contributed the most to the aboveground biomass. The hydrothermal dynamic hypothesis was employed to explain such a distribution pattern in the results. In the future, other aspects of research work, such as the effects of soil and human activities on the distribution of grassland, should be carried out to comprehensively reveal the spatial distribution pattern of grassland biomass in Inner Mongolia.

Author Contributions: X.W., J.D., conducted the field experiment and analyzed the data. X.W., J.D., Y.B. contributed to drafting the paper. T.B. contributed to the concept and design of the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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