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Response of Carbon Dynamics to Climate Change Varied among Different Vegetation Types in Central Asia

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Abstract: The effect of climate change on the spatio-temporal patterns of the terrestrial carbon dynamics in Central Asia have not been adequately quantified despite its potential importance to the global carbon cycle. Therefore, the modified BioGeochemical Cycles (Biome-BGC) model was applied in this study to evaluate the impacts of climatic change on net primary productivity (NPP) and net ecosystem productivity. Four vegetation types were studied during the period 1979 to 2011: cropland, grassland, forest, and shrubland. The results indicated that: (1) The climate data showed that Central Asia experienced a rise in annual mean temperature and a decline in precipitation from 1979 to 2011; (2) the mean NPP for Central Asia in 1979–2011 was 281.79 gC m^{-2} yr^{-1}, and the cropland had the highest NPP compared with the other vegetation types, with a value of 646.25 gC m^{-2} yr^{-1}; (3) grassland presented as a carbon source (-0.21 gC m^{-2} yr^{-1}), whereas the other three types were carbon sinks; (4) the four vegetation types showed similar responses to climate variation during the past 30 years, and grassland is the most sensitive ecosystem in Central Asia. This study explored the possible implications for climate adaptation and mitigation.

Keywords: climate change; Central Asia; Biome-BGC; carbon cycle

1. Introduction

In view of the global climate system, the terrestrial carbon cycle in the context of increasing atmospheric CO_2 concentration and changing climate remains unclear [1,2]. Central Asia, which lies in the interior of the Eurasian continent, covers Xinjiang Autonomous Region of China, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan [3,4]. The effect of climate change on the regional and interannual patterns of the terrestrial carbon dynamics have not been adequately quantified though it occupies vast land area (~5.6 million km^2) and has potential importance and contribution to the global carbon cycle.

An analysis of meteorological data has shown that the annual mean surface temperature over Central Asia increases at a mean decadal rate of 0.39 °C, which is larger than the average rate of 0.29 °C on the global scale [5]. Surface temperature trends are found to be highly inhomogeneous in space. The uncertainty in estimated tendencies for precipitation is considerably greater than that for surface temperature. Lioubimtseva and Henebry [6] reported that the regional amount of precipitation had slightly decreased during the past 50–60 years, whereas Xinjiang, China had increased by 7–16% from 1981 to 2007 [3]. The inhomogeneity of climate changes should predetermine a complex and ambiguous response of the carbon dynamics to these changes among different regions and vegetation species.

Central Asia has four dominant vegetation types, namely, forest, cropland, shrubland, and grassland. The differences in water supply and nutrients among these types result in possible differences in biogeochemical processes and carbon dynamics. Therefore, different vegetation types are expected to respond differently to climate variability and change. As forests are considered to be a significant carbon sink under changing climate and occupy large fractions of global terrestrial carbon, their carbon dynamics are of great importance. Agroecosystem can be a large source of carbon emission in the consideration of many cropland practices [7]; however, cropland in Central Asia is classified as irrigated cropland and rainfed cropland, which could lead to different carbon dynamics arising [8]. Shrubland ecosystems are widely distributed in both arid and semi-arid regions, and their carbon uptake/release are controlled mainly by water availability [9–11]. Many prior works have shown that shrublands have different growth patterns distinguishing them from other vegetation types [12,13]. Degradation of grassland is a predominant issue for Central Asia, and this can be attributed to climate change and grazing. Grazing alters grassland carbon stocks by stimulating regrowth of plant or just reducing above-ground biomass [14,15]. Therefore, grassland carbon cycling is not only affected by climate variation, but also by human activity.

It is a great challenge to study terrestrial carbon cycle through direct field observations. Inventory studies and carbon flux measurements are beneficial for evaluating the dynamics of ecosystem carbon storage for independent sites research; however, extrapolating to regional scales is considerably challenging [1]. Therefore, terrestrial ecosystem models have coupled the fundamental mechanisms in studying the interactions between climate change and carbon cycle. Among the existing terrestrial ecosystem models, biogeochemical models are the most important and widely used, such as Biome-BGC (BioGeoChemical Model) [16], CENTURY [17], DeNitrification DeComposition (DNDC) [18], Dynamic Land Ecosystem Model (DLEM) [19], and Carnegie–Ames–Stanford Approach (CASA). Although the structure and function of these terrestrial ecosystem models have been improved, and most of them can be used to study regional or global carbon and nitrogen cycles, little attention has been paid to the processes of human activities, such as grazing processes and the effects of grazing on carbon and water cycles in ecosystems. Among the above mentioned models, the CENTRUY model considered the effect of grazing on NPP in terrestrial ecosystem, but only simplified the effect into four types (no effect, mild, moderate, and severe), and failed to reflect the effect of different grazing intensity on carbon dynamics. Biome-BGC model is a process-based computer program that can be used to estimate carbon, nitrogen, water, energy states, and has already been proved useful for large-scale terrestrial ecosystems. Chiesi et al. [20] employed the Biome-BGC model to analyze the evapotranspiration and gross primary productivity within Mediterranean macchia, and they indicated that Biome-BGC can be applied to estimate water and carbon flux with good accuracy. Han et al. [14] utilized the modified Biome-BGC model to simulate the grazing process in arid grassland in Xinjiang, China, and their simulated results agreed well with field data. Wang et al. [21] made use of Biome-BGC model to simulate carbon and water storage for crops over china, which also approved the feasibility of the model. In summary, Biome-BGC model allowed fully coupled investigations on the ecosystem sustainability, and obtaining feedback between climate change and carbon cycle.

Numerous studies have focused on the carbon stock and fluxes in Central Asia [4,22,23]. However, these studies have failed to investigate the different responses of the various vegetation types to climate change. Therefore, in this study, we examined the temporal–spatial variations of carbon dynamics under four vegetation types during 1979–2011 in Central Asia using the Biome-BGC model. This study aims (1) to evaluate the spatial and temporal trends of carbon dynamics in Central Asia for the four vegetation types and (2) assess and compare the carbon responses of the four vegetation types subjected to different climate factors. The results of this study will provide a scientific basis for sustainable ecosystem restoration at the regional scale and a deep understanding of relationships among climate change, vegetation type, and carbon budget. The paper is structured as follows: Section 2 describes the input data for Biome-BGC model and how the outputs are analyzed; Section 3 illustrated the climate conditions during 1979–2011 and the corresponding response of carbon dynamics; Section 4 compare results from this research with previous studies and discuss the underlying implications for future study; and Section 5 concludes the entire research.

2. Materials and Methods

2.1. Study Area

Central Asia (34.3°–55.4° N, 46.5°–96.4° E) covers Xinjiang Uygur Autonomous Region (XJ), China, Kazakhstan (KAZ), Kyrgyzstan (KYZ), Tajikistan (TJK), Turkmenistan (TKM), and Uzbekistan (UZB). Vegetation types of Central Asia was divided into: deciduous broadleaf forest, evergreen needleleaf forest, irrigated cropland, rainfed cropland, summer pastures, spring-autumn pastures, winter pastures, shrubland. In this study, we combine them into four vegetation types, namely, forest, grassland, cropland, and shrubland (Figure 1). The study area is located deep inside the Eurasian continent; thus, it has arid and semi-arid climates [4].

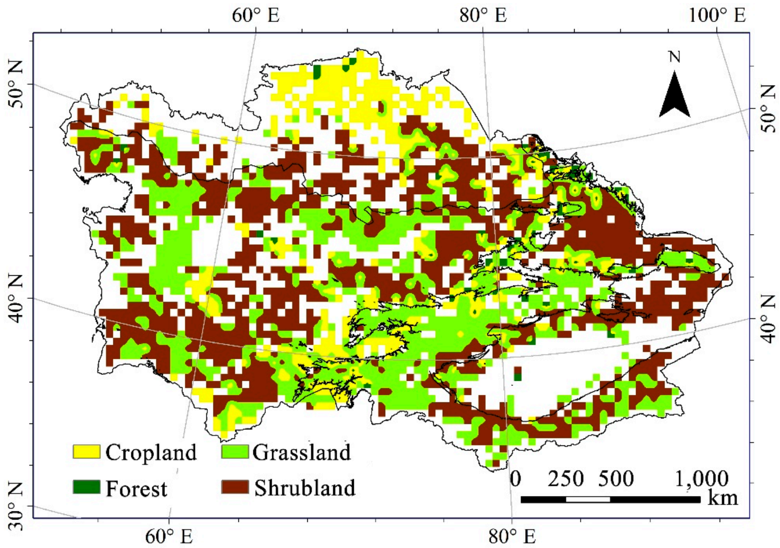

Figure 1. The study area and the distribution of major land cover types in Central Asia.

2.2. Biome-BGC Model

The Biome-BGC model is a process-based ecosystem model that operates using a daily time step that simulates the dynamics of carbon, water, and nitrogen in a specific terrestrial ecosystem [24]. The carbon dynamics simulated by Biome-BGC includes net primary productivity (NPP), gross primary production (GPP), net ecosystem productivity (NEP), and net ecosystem exchange (NEE). Farquhar biochemical model [25] was adopted by Biome-BGC model to estimate GPP. NPP is the residue of GPP from plant growth and maintenance respiration as shown in Equation (1) [26]. NEP equals to NPP minus soil heterotrophic respiration [26], according to Equation (2).

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{gr} - \mathrm{mr} \tag{1}$$

where NPP is the net primary productivity, GPP is the gross primary production, gr is the plant growth, and mr is maintenance respiration.

$$\mathrm{NEP} = \mathrm{NPP} - \mathrm{hr} \tag{2}$$

where NEP indicates net ecosystem productivity and hr indicates heterotrophic respiration.

The model has been successfully applied and validated over a number of ecosystems, spatial–temporal scales, and climate regimes, including various forest ecosystems from different continents [21,22,27–29]. The model has been evaluated via sensitivity analyses as well as validations that compared with field measured evapotranspiration (ET), primary productivities, and carbon dynamics at several sites. The model, its physiological and ecological parameters, and the validation results have been described extensively in previous studies [14,21,22]. The sand dunes in the desert and built-up areas were excluded from the simulation in this study because of their extremely low biological activities.

2.3. Model Inputs

Three types of input data are needed for Biome-BGC model, namely, meteorological data, general stand information, and eco-physiological parameters. The meteorological data included daily maximum temperature (Tmax), daily minimum temperature (Tmin), daily mean temperature (Tavg), vapor pressure deficit (VPD), daily precipitation (Prcp), daylenth, and shortwave radiation (Srad). The stand information data refers to soil texture, soil depth, altitude, slope, aspect, albedo, and so on. The eco-physiological data involved 34 parameters, such as annual turnover rate, carbon/nitrogen (C/N) ratio, phenology, and so on. The climate dataset for the research period was developed by integrating the six-hourly Climate Forecast System Reanalysis produced by the National Centers for Environmental Prediction [30–32]. The vegetation type map was combined by the vegetation map of China (10 × 10 km in resolution) and the vegetation map of the five Central Asia states (25 × 25 km in resolution) [33]. GlobCover 2009 land cover dataset (due.esrin.esa.int/globcover/) was used to describe the distribution of irrigated cropland, rain-fed cropland, and settlements areas (Figure 1). The soil maps (i.e., volumetric content of sand and clay, bulk density, and soil pH) were downloaded from the Harmonized World Soil Database [34] with a resolution of approximately 1 km.

2.4. Simulation Design and Model Validation

After standardizing the input data, the model was run for different vegetation types. The first step is to run a spin-up simulation, which starts with very low initial levels of carbon and nitrogen state until the total carbon levels stabilize for 6000 years. The second step is to run a normal simulation, which runs for a 33-year meteorological data file.

In order to testify that this model is practically feasible, model validation should be performed at the beginning of the analysis. Model validation is the process of evaluating the consistency and accuracy of the modeled results relative to field measurements. Biome-BGC has been assessed by performing sensitivity analyses [35] and validations against measured data, including forest [36–38], cropland [21], grassland [22,39], and all ecosystems [40]. In this study, we used field data collected from previous studies to evaluate the model's performance in predicting NPP dynamics (as shown in Table 1 for supporting information). NEP was validated using eddy covariance data from Fukang Station of Desert Ecology, Chinese Academy of Sciences. All the procedures are shown in Figure 2.

2.5. Statistical Analysis

A software package called EddyPro Version 5.1.1 (LI-COR, Lincoln, NE, USA) was inhabited for acquisition and processing of eddy covariance data. In order to verify the reliability of the model results, measured data and simulated data were linear fitted, and r values were obtained as an index. Spatial variability of NPP/NEP from 1979–2011 in Central Asia was calculated in ArcGIS version 9.3 (ESRI, Redlands, CA, USA). The averaged NPP/NEP was calculated in ArcGIS using the "Raster calculator" tool from NPP/NEP data from 1979–2011. NPP/NEP values and standard deviation for different vegetation types was extracted by the "Classification statistics" tool in ArcGIS. The temporal variation and trend of NPP/NEP values was analyzed in the Origin software version 8 (OriginLab, Northampton, MA, USA) using "linear fitting".

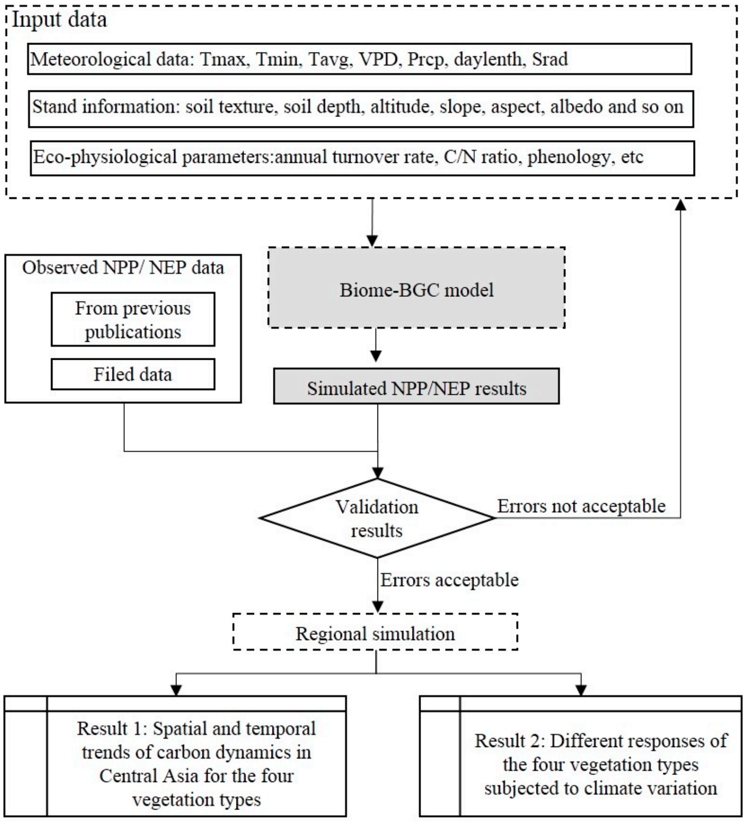

Figure 2. Research flowchart. VPD—vapor pressure deficit; NPP—net primary productivity; NEP—net ecosystem productivity; Biome-BGC—BioGeochemical Cycles.

Table 1. Validation points across Central Asia's grassland biomes.

Longitude (°)	Latitude (°)	Value	References
81.28	43.257	354	[41]
87.358	43.628	382	[42]
81.238	42.641	429.92	[43]
80.75	41.772	315	[41]
93.87	35.51	73.55	[41]
90.18	46.11	79.585	[44]
86.82	47.53	124.03	[44]
86.18	47.28	168.85	[44]
86.02	46.6	182.70	[44]
89.49	47.06	195.20	[44]
81.15	45.02	198.05	[44]
86.1	46.69	211.40	[44]
87.75	47.73	224.21	[44]
87.75	47.73	224.91	[44]
92.3	43.69	228.56	[44]
90.05	46.44	232.01	[44]
84.03	43.3	271.12	[44]
87.01	48.07	281.72	[44]
94.01	43.42	297.03	[44]
84.22	45.58	300.53	[44]
84.42	43.45	302.43	[44]
84.83	44.14	315.29	[44]

Table 1. *Cont.*

Longitude (°)	Latitude (°)	Value	References
90.3	43.76	323.14	[44]
90.01	46.54	337.54	[44]
81.61	44.6	347.19	[44]
86.65	47.13	358.35	[44]
84.37	43.15	384.50	[44]
83.56	45.79	390.16	[44]
83.65	45.59	400.91	[44]
86.52	46.97	408.21	[44]
85.77	43.96	408.21	[44]
83.5	43.41	425.71	[44]
82.24	43.39	426.92	[44]
84.4	43.66	428.32	[44]
81.46	44.61	436.77	[44]
90.61	43.65	461.82	[44]
83.72	42.9	464.83	[45]
87.17	43.47	467.98	[44]
81.15	44.49	469.33	[44]
81.38	44.62	482.73	[44]

3. Results

After validating the model, spatio-temporal variability of carbon dynamics of four major vegetation types in Central Asia were investigated. Biome-BGC model can simulate NPP/NEP to a reasonable extent over a regional scale. The climate data showed that Central Asia experienced a rise in annual mean temperature and decline in precipitation from 1979 to 2011, which resulted in the unique pattern of carbon dynamics in this region. In addition, the responses of different vegetation types to climate change have also been evaluated.

3.1. Model Validation

The comparisons of simulated NPP and NEP against observations were shown in Figure 3. The square of the Pearson correlation coefficient suggested that the Biome-BGC could realistically assess the effect of climate on NPP across various vegetation types in Central Asia. The daily values of measured NEP can be largely explained by the model (R^2 = 0.64, slope of the regression = 1.09, $p < 0.01$, Figure 3b). NPP was predicted with some values being somewhat overestimated (R^2 = 0.83, slope of the regression = 0.87, $p < 0.01$, Figure 3a). Parameterization and validation of NPP/NEP is a crucial task for correct predictions of water and carbon fluxes by models. This is valid especially for arid and semi-arid ecosystems.

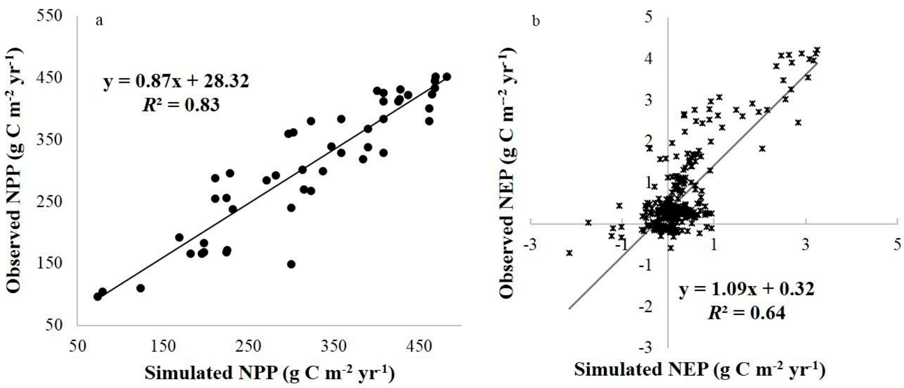

Figure 3. Comparison of simulated and observed NPP (**a**) and NEP (**b**).

3.2. Precipitation and Temperature Changes in 1979–2011

Central Asia had a mean annual temperature of 7.18 °C and precipitation of 457.92 mm. As shown in Figure 4a,c, the mean annual temperature and precipitation exhibited a large variability and complex characteristics. Although the lowest temperature appeared over the mountainous area compared with that of the other regions, precipitation was the highest. Southwestern Central Asia had high temperature and low precipitation values, whereas northern Central Asia had moderate climate conditions.

The climate data showed that Central Asia experienced a rise in annual mean temperature and decline in precipitation from 1979 to 2011 (Figure 4b–d). The results from linear fitting analysis showed that the region's annual mean temperatures slightly increased at an average rate of 0.34 °C decade^{-1} from 1979 to 2011 (Figure 4a). This rate was higher than the average warming rates of 0.30 decade^{-1} and 0.15 decade^{-1} in the last five decades (1960–2011) and 11 decades (1901–2009), respectively (Hu, Zhang, Hu and Tian [5]). For 1979–2011, the annual precipitation showed a decreasing trend at a rate of 2.79 mm yr^{-1} over the entire study area (Figure 4b).

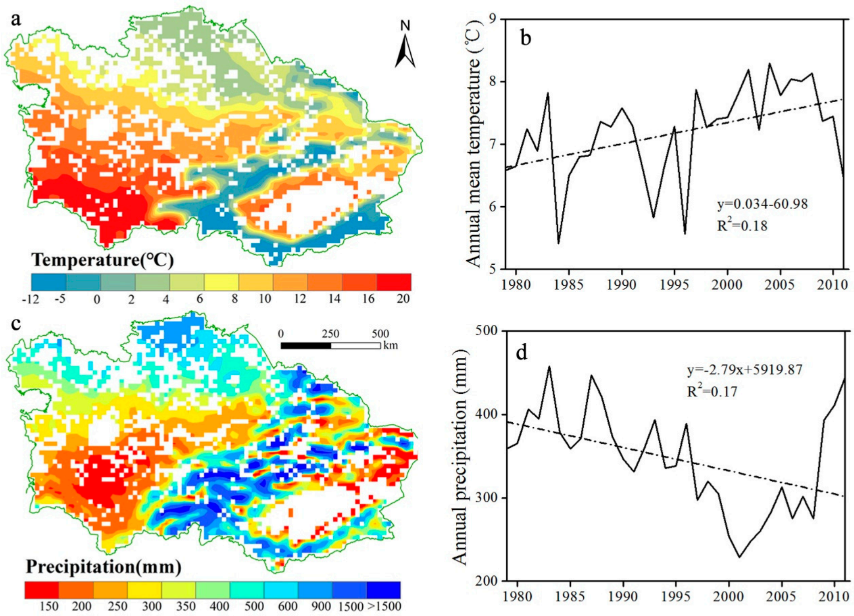

Figure 4. Spatial variation of annual mean temperature (**a**) and precipitation (**c**) in Central Asia; trends of annual mean temperature (**b**) and precipitation (**d**) change from 1979 to 2011.

3.3. Spatial and Temporal Distribution of NPP/NEP for Different Vegetation Types

The mean NPP for Central Asia in 1979–2011 was 281.79 gC m^{-2} yr^{-1}. NPP differed notably among the four vegetation types. The cropland had the highest NPP compared with other types, with a value of 646.25 gC m^{-2} yr^{-1}. The forest had the second highest NPP, which was significantly higher than those of the shrubland and grassland. The dominant land cover types, that is, shrubland and grassland, presented the lowest NPP at approximately 112.50 gC m^{-2} yr^{-1} and 90.52 gC m^{-2} yr^{-1}, respectively (Figure 5a).

The results of NEP for the four vegetation types differed from NPP changes (Figure 5b). Grassland released carbon by by −0.21 gC m^{-2} yr^{-1}, whereas the other three types were carbon sinks. Forest and shrub land had the highest carbon sequestration potential, and their NEP were 1.86 gC m^{-2} yr^{-1} and 1.91 gC m^{-2} yr^{-1}, respectively. NEP for cropland was 0.86 gC m^{-2} yr^{-1}, which presented as a weak carbon sink.

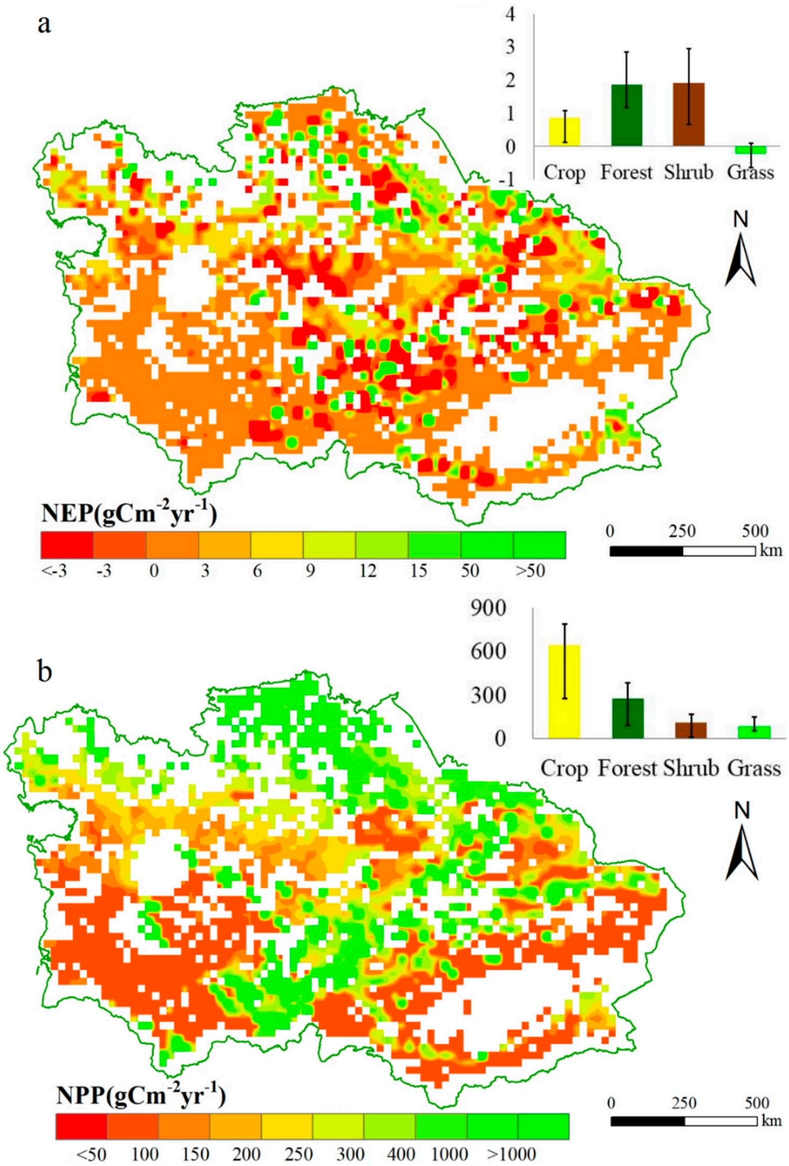

Figure 5. Spatial distributions of NPP (**a**) and NEP (**b**) under crop, forest, shrub, and grassland during 1979–2011 in Central Asia.

3.4. Responses of NPP and NEP to Climate Variation

The four vegetation types showed similar responses to a certain extent in increasing temperature and decreasing precipitation during the past 30 years. The NPP for grassland, which is the most sensitive ecosystem in Central Asia, decreased by 0.58 gC m^{-2} yr^{-1} (Figure 6d), with a decline rate of 0.64% compared with the annual NPP of 90.94 gC m^{-2} yr^{-1}. The NPP for forest and shrubland decreased with climate change, with values of 1.58 gC m^{-2} yr^{-1} and 0.51 gC m^{-2} yr^{-1}, respectively (Figure 6b,c). Among the four vegetation types, the response of cropland to climate change was the smallest, with a decline rate of 0.17% (1.10 gC m^{-2} yr^{-1} compared with annual NPP value of 646.25 gC m^{-2} yr^{-1}) (Figure 6a).

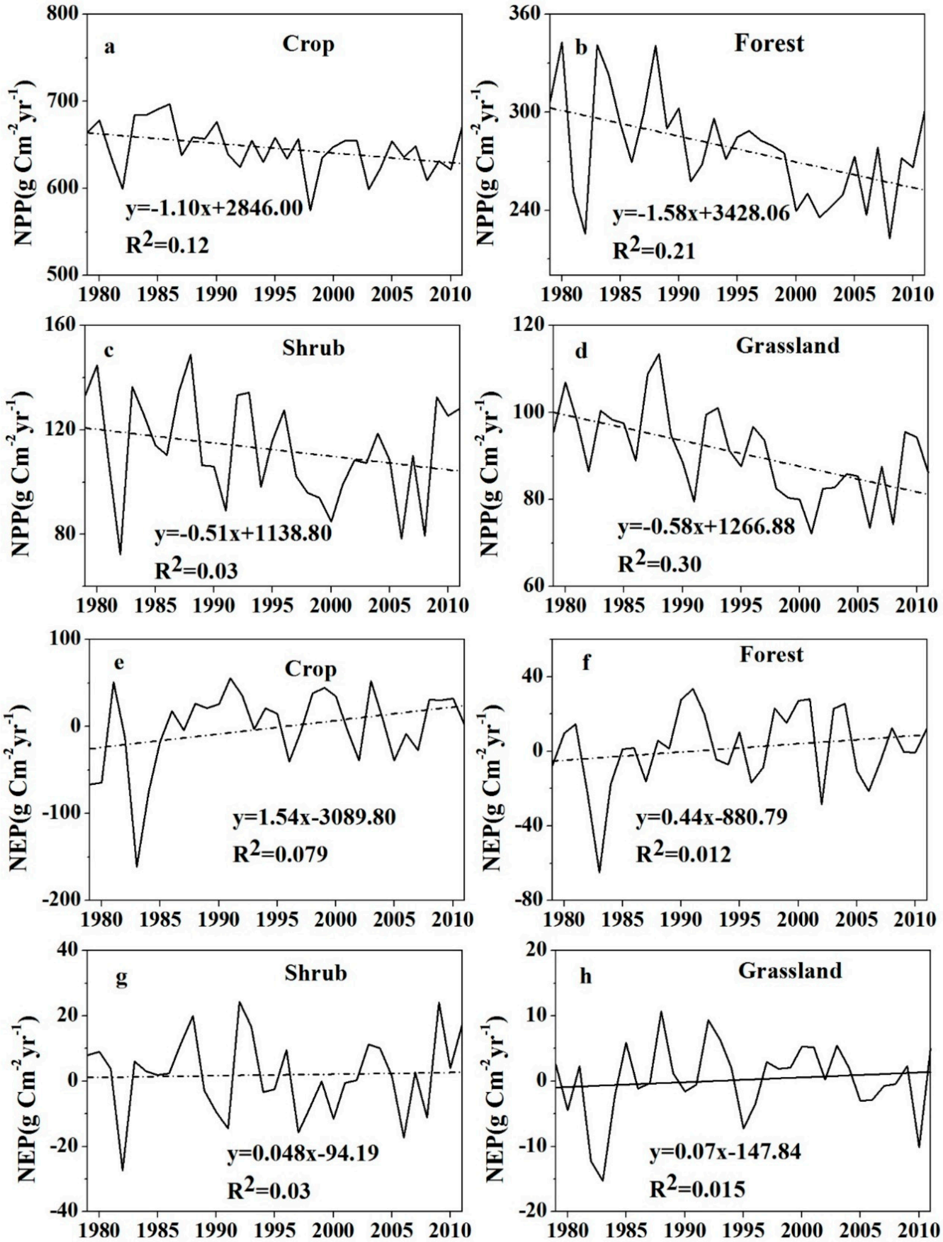

Figure 6. Temporal distribution of NPP (**a**–**d**) and NEP (**d**–**g**) for cropland, forest, shrub, and grassland in Central Asia during 1979–2011.

In comparison with NPP, the changes in NEP showed contrasting responses to climate change. For the cropland ecosystem, NEP increased by 1.54 gC m^{-2} yr^{-1}, which showed the largest increase in carbon sequestration potential among the four ecosystems (Figure 6e). The NEP for forest increased by 0.44 gC m^{-2} yr^{-1} (Figure 6f), which experienced the second largest increase. The NEP for grassland increased by 0.07 gC m^{-2} yr^{-1} (Figure 6h), with an increase rate of 32% compared with the annual NEP of 0.21 gC m^{-2} yr^{-1}. Among the four vegetation types, the response of shrubland to climate change was the smallest, with an increase rate of 2.52% (0.048 gC m^{-2} yr^{-1} compared with the annual NEP value of 1.91 gC m^{-2} yr^{-1}) (Figure 6g).

4. Discussion

4.1. Comparison with Previous Studies

The modeled NPP is comparable with reported field observations or satellites estimates. The results of this study demonstrated that the mean NPP for Central Asia in 1979–2011 was 281.79 gC m^{-2} yr^{-1}, which is higher than the simulation of Zhang and Ren [46] of 218 gC m^{-2} yr^{-1}. The cropland had the highest NPP (646.25 gC m^{-2} yr^{-1}) compared with the other types, which is between the range of Zhang and Pan [47] and Li, et al. [48]. Annual NPP for forest was 277.49 gC m^{-2} yr^{-1}, which is smaller than NPP in East China from 2001 to 2008 [16]. Shrubland and grassland presented the lowest NPP at approximately 112.50 gC m^{-2} yr^{-1} and 90.94 gC m^{-2} yr^{-1}, respectively, which are lower than the average NPP in China, as reported by Feng, et al. [49], as a result of the lower precipitation in Central Asia compared with China (Table 2).

Table 2. Global comparison of net primary productivity (NPP).

Vegetation Type	This Study (gC m^{-2} yr^{-1})	Other Studies (gC m^{-2} yr^{-1})
All types in Central Asia	281.79	218 [46]
Cropland	646.25	375.27 [47], 863.90 [48], 341.9 [49]
Forest	277.49	684 [16], 456.8 [49]
Shrubland	112.50	363.1 [49]
Grassland	90.94	122.6 [49]

Grassland lost its carbon storage by −0.21 gC m^{-2} yr^{-1}, whereas the other three types were carbon sinks. Comparison with previous studies reveal that the carbon dynamics of the present work is comparable and realistic. Greenhouse gas emissions come from various practices in the grassland ecosystem, and in this study, grazing exerted a strong impact on terrestrial carbon balance over the past 33 years, which was confirmed by Han et al. [22]. Forest and shrubland had the highest carbon sequestration potential, and numerous studies have reported that the forest ecosystems was an indispensable carbon sink in China and Asia [10,50–52]. Chen et al. [23] illustrated that forest land use in Central Asia acts as a carbon sink, and accelerated afforestation leads to strong carbon sequestration. Jia et al. [13] examined how ecosystem production in one shrubland in Northern China varied during 2012–2014, and their results indicated a shift from an annual sink to a carbon source.

Spatio-temporal patterns of carbon dynamics have been estimated in many regions around the world. Nevertheless, the arid and semi-arid regions of Central Asia were poorly analyzed and with great uncertainty. Only a few studies have been conducted in this region, but with varied limitations. Li et al. [4] estimated carbon stocks in Central Asia without analyzing the differences between different vegetation types. Chen et al. [23] reveal the value of carbon budget in Central Asia, but only concerning the forest land use and management process. Han et al. [53] conducted an experimental study on fencing effects in a meadow steppe in Central Asia, however, their research is limited to only a few sites. Lee et al. [54] and Li et al. [55] examined the effects of environmental factors on soil organic carbon in Central Asia, without considering the above ground carbon dynamics. This study, focusing on the differences between the dominant vegetation types, could give guidance to stakeholders and decision makers in increasing the regional adaptive capacity to climate change.

4.2. Different Responses of NPP/NEP to Climate Change

The Eurasian continent has been suggested to be a large carbon sink for the world in past decades, especially because of the carbon sequestration capacity of forests of high-latitude [56–58]; however, dryland ecosystem in this region is less concerned. In 1979–2011, the arid and semi-arid ecosystems of Central Asia experienced significant climate change, which experienced about twice the warming trend than that in Europe [59]. A decadal drought from 1998 to 2008 was also endured by the drylands. Vegetation activities were considerably affected by climate change, especially warming and altered precipitation regime [60–62]. Trend lines of NPP are similar to variations of precipitation, which indicates that water is the main factor limiting vegetation growth in this region. The findings of this research are in agreement with the study of Li et al. [4], which discovered a strong positive correlation between vegetation carbon and precipitation.

As to the different vegetation types, we found that the regions in the arid, semi-arid climate zone with low vegetation cover, such as grassland, showed a stronger correlation between NPP and climate change than high-density vegetation types, such as forest. In addition, we found that cropland NPP was least related to climate change, which may be attributed to the agricultural practices of fertilizer substitution, crop straw, and conservation tillage. Accordingly, improved cropland practices can directly and indirectly mitigate carbon emissions, which benefits the sustainability of croplands. Shrubs in Central Asia, thanks to their root structure, are able to access moisture in deeper soil layers. Previous field experiments reported that desert shrubs in this region had averaged root depth of 3–4 m [4]. Therefore, shrubs are insensitive to changes in temperature and moisture. On the other hand, grasslands, most of which are annual herbs, are more sensitive to climate variability and human activity [14,15]. Forest is more obviously influenced by nitrogen deposition compared with other vegetation types [63,64], yet the effects of nitrogen deposition are opposite to rising temperature [65]; therefore, the results would be improved if nitrogen deposition effects were considered.

4.3. Limitations and Future Works

Based on highly incorporated ecological processes and mechanisms, ecosystem models can be used to extrapolate the in-site knowledge to large temporal–spatial scales [46]. The Biome-BGC model can simulate the different responses of carbon dynamics among the different arid and semi-arid ecosystems in Central Asia. However, this study showed that using a process-based ecosystem model has limitations, such as input data limitations. In addition, management effects on plant growth, such as cropland irrigation, fertilizer application, and insect control, have not been considered in this study. Although we analyzed the direct effect of temperature on NPP and NEP, we did not comprehensively analyze the impacts of changing vapor pressure deficit (VPD) on stomata conductance under the context of temperature increasing, because there are studies indicating that VPD might have more influence on grassland carbon dynamics precipitation [46,66]. In addition, there are also researchers who found that seasonal difference in water availability affected plant primary productivity to a different extent. Therefore, monthly precipitation was supposed to be a better indicator than annual precipitation. In summary, the input data should be refined, a refined Biome-BGC model should be developed, and the carbon–nitrogen–water process should be analyzed comprehensively.

5. Conclusions

In this study, a Biogeochemical model was used to analyze the spatio-temporal variability of carbon dynamic for dominant vegetation types in Central Asia, and the responses of carbon cycling to climate change were also observed. The results suggested that warmer-drier climate in Central Asia would decrease the carbon sequestration capacity, however, with varied decline rate among different vegetation types. Therefore, this study illustrates the importance of considering different vegetation types while reducing carbon dioxide emissions. One remaining aspect to reflect upon consists of taking the nitrogen deposition effect into consideration, because anthropogenic nitrous pollutant emissions all over the world significantly increased during the last decades. Ultimately, this research provided an in-depth understanding of climate mitigation strategies in Central Asia and gives guidance to stakeholders and decision makers for regional sustainability.

Author Contributions: G.L. proposed the idea and Q.H. wrote the paper, C.L. modified the model and conducted the validation, S.L. did the formal data analysis.

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

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