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Evaluation of Future Impacts of Climate Change, CO₂, and Land Use Cover Change on Global Net Primary Productivity Using a Processed Model

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Citation: Hu, X.; He, Y.; Kong, Z.; Zhang, J.; Yuan, M.; Yu, L.; Peng, C.; Zhu, Q. Evaluation of Future Impacts of Climate Change, CO₂, and Land Use Cover Change on Global Net Primary Productivity Using a Processed Model. *Land* **2021**, *10*, 365. <https://doi.org/10.3390/land10040365>

Academic Editor: Marko Scholze

Received: 19 February 2021

Accepted: 31 March 2021

Published: 2 April 2021

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Abstract: Few studies have focused on the combined impact of climate change, CO₂, and land-use cover change (LUCC), especially the evaluation of the impact of LUCC on net primary productivity (NPP) in the future. In this study, we simulated the overall NPP change trend from 2010 to 2100 and its response to climatic factors, CO₂ concentration, and LUCC conditions under three typical emission scenarios (Representative Concentration Pathway RCP2.6, RCP4.5, and RCP8.5). (1) Under the predicted global pattern, NPP showed an increasing trend, with the most prominent variation at the end of the century. The increasing trend is mainly caused by the positive effect of CO₂ on NPP. However, the increasing trend of LUCC has only a small positive effect. (2) Under the RCP 8.5 scenario, from 2090 to 2100, CO₂ has the most significant positive impact on tropical areas, reaching 8.328 Pg C Yr^{−1}. Under the same conditions, climate change has the greatest positive impact on the northern high latitudes (1.175 Pg C Yr^{−1}), but it has the greatest negative impact on tropical areas, reaching −4.842 Pg C Yr^{−1}. (3) The average contribution rate of LUCC to NPP was 6.14%. Under the RCP8.5 scenario, LUCC made the largest positive contribution on NPP (0.542 Pg C Yr^{−1}) globally from 2010 to 2020.

Keywords: processed model; net primary productivity (NPP); land-use and land-cover change (LUCC); IBIS

1. Introduction

The speed at which plants in an ecosystem convert carbon dioxide and water into high-energy carbon compounds is the biomass produced by an ecosystem in a specific period of time [1,2]. Net primary productivity (NPP) plays a vital role in the carbon cycle of terrestrial ecosystems and is considered to be the result of environmental processes [3,4]. NPP describes the difference in the total amount of carbon accumulated by vegetation through photosynthesis and autotrophic respiration. As an important indicator of the carbon cycle, NPP is affected by many influencing factors, such as climatic factors, CO₂ concentration, topography, soil, plant and microbial characteristics and interference, and human activities [5].

In recent years, global climate change has been considered to be the focus of global environmental issues. It is expected that in the coming decades, long-term and continuous

changes may have a significant impact on the distribution and function of vegetation [6]. Climate change plays an important role in predicting the impact on ecosystem processes. And the temperature and precipitation changes between different latitudinal zones exert different degrees of impact [7,8]. Climate change affects the vegetation and soil carbon pools by affecting NPP and soil respiration and changes the yield and decomposition rate of litter. The impact of both on NPP has become a key component in the study of the terrestrial ecosystem carbon cycle [9]. Studies have indicated that climate change in the past few decades has led to an increasing trend of natural vegetation NPP [10]. After comprehensively analyzing the data of global terrestrial vegetation NPP and climate variation, Nemani et al. [11] concluded that climate change had increased the total global terrestrial vegetation NPP by 6%.

There are many related studies on the impact of CO₂ concentration on NPP. Ecosystems are sensitive to environmental factors that constantly change, such as climate and carbon dioxide fertilization [12–14]. Human activities could affect climate conditions, but the terrestrial biosphere net absorption of CO₂ in the atmosphere mitigates their impact by effectively reducing the speed of climate change [15]. For example, the forest in the Amazon River region can still be maintained as a carbon sink when the carbon pool is reduced. Studies have found that CO₂ promotes the absorption of atmospheric carbon by terrestrial ecosystems through NPP, and the effect of CO₂ fertilization is offset by 25%–30% of the carbon dioxide emissions that have caused climate change in recent decades [16].

In recent decades, the transformation of natural ecosystems by human activities has been extremely rapid, changes that have affected global climate change and intensified land use changes. Quantification of the carbon absorption rate of terrestrial vegetation currently relies on modeling and statistical methods. The calculation of NPP is generally performed through field observations [17,18], large-scale remote sensing [19,20] process-based modeling [21], and combinations of these methods [22].

Many studies have used models to evaluate the net primary productivity under the influence of historical models of CO₂, climate change, and land-use cover change (LUCC) factors. Zhu et al. [23] used the Integrated Biosphere Simulator (IBIS) model to simulate the historical biomass and NPP in the climate transition zone under climate change and CO₂ concentration changes. Kang et al. [24] used the BIOME-BGC (BioGeochemical Cycles) model to simulate and evaluate the relative impact of increasing atmospheric CO₂ concentration, climate change, and regional fire activity model driving factors on forest NPP in some northern coniferous forests in Canada. Liu et al. [25] used the IBIS process model and land cover disturbance data to estimate the carbon changes in the California ecosystem from 1951 to 2000. This study used the IBIS model to simulate the global NPP land use change of terrestrial ecosystems in the future, and to explore the spatial change model of global terrestrial ecosystems under different scenarios of NPP and climate factors, carbon dioxide concentrations, and LUCC conditions, as well as the contributions of various factors. It is hoped to provide a scientific basis for improving land use management measures globally in the future and reducing the negative impact of land use change on terrestrial ecosystem carbon sink.

2. Data and Methods

2.1. Introduction of the Model

The IBIS model was developed by Foley et al. [26], which is a comprehensive terrestrial biosphere model and belongs to the new generation of Dynamic Global Vegetation Models (DGVMs). It includes five modules: land surface process, canopy physiology, vegetation phenology, vegetation dynamics, and soil biogeochemistry. The various processes in the model can be carried out on different time scales, organically integrating the ecological, biophysical, and plant physiological processes that occur at different time scales (1 h to 1 year) [27].

Liu et al. [28] improved the IBIS model by considering the effects of LUCC and also taking into account the effects of atmospheric CO₂ fertilization, climate, fire, and LUCC,

and incorporating small-scale processes into a large-scale regional ecosystem framework. The revised model can quantitatively analyze the terrestrial carbon budget of different vegetation types and examine the impact of disturbance on ecosystem productivity and carbon storage. In addition, Yuan et al. [29,30] adjusted the parameters of IBIS to simulate the potential vegetation pattern and NPP of China more accurately. In this study, the IBIS model was used to simulate the impact of climate change, carbon dioxide concentration changes, and LUCC factors on the NPP of the global terrestrial ecosystem under different scenarios in the future, as well as the spatial pattern in different regions.

2.2. Model-Driven Data Construction

2.2.1. Background Information

In this study, the input data for the IBIS model mainly included digital elevation model (DEM) information, meteorological data, vegetation and soil data, and future land-use and land-change data. The DEM data used SRTM (Shuttle Radar Topography Mission, <http://www.cgiar-csi.org/> (accessed on 16 September 2020)) measurements. The distribution data of the GlobCover2009 was utilized as the reference for the initial vegetation data, and the soil texture data came from the Digital Soil Map of the World (DSMW, <http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116>) (accessed on 16 September 2020).

2.2.2. Climate-Driven Data

The climate data came from the CMIP5 simulation results collected by the U.S. Program for Climate Model Diagnosis and Intercomparison (PCMDI) [3]. The data originated from the PCMDI database (<https://pcmdi9.llnl.gov/search/cmip5/> (accessed on 16 September 2020)). The climate data, including monthly precipitation, temperature (maximum, minimum, and average), relative humidity, cloud cover, and wind speed, that were generated by four models under different future emission scenarios were selected to drive the model simulation. The future data period was from 2006 to 2100 (Table 1).

Table 1. Climate-driven data.

Model	Spatial Resolution (°, lat × lon)	Resolution Source
GFDL-ESM2M	90 × 144	Goddard Institute for Space Studies (NASA), USA
GISS-E2-H		
IPSL-CM5A-LR	96 × 96	Institut Pierre-Simon Laplace, France
MIROC5	128 × 256	Atmosphere and Ocean Research Institute, University of Tokyo

2.2.3. Representative Concentration Pathway (RCP) Emission Scenarios

In combination with the changes in CO₂ concentration, four emission scenarios, i.e., RCP2.6, RCP4.5, RCP6.0, and RCP8.5, were considered. These were the future scenario models released by researchers in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014. Among them, RCP4.5 and RCP6.0 are both medium emission scenarios, and relatively few simulation studies have used RCP6.0. For the comparability of the results of this study, three emission scenarios (RCP2.6, RCP4.5, and RCP8.5) were selected [31]. These emission scenarios were used to compare the radiative forcing reaching the Earth's surface and the atmospheric CO₂ concentration by the year 2100 [4]. They can be utilized to estimate the concentration of greenhouse gases over the next 100 years or even longer and to convert them into radiative forcing (W/m²). Table 2 lists the basic information of the three scenarios.

Table 2. Radiation forcing reaching the Earth’s surface and equivalent CO₂ concentrations by 2100 under the three different emission scenarios.

RCP Scenario	Radiative Forcing (W/m ²)	CO ₂ Concentration (μL/L)
RCP2.6	Reaches a peak of 3.0 W/m ² before 2100 and then drops to 2.6 W/m ²	Reaches a peak of 490 μL/L before 2100 and then drops
RCP4.5	Stabilizes after reaching 4.5 W/m ² by 2100	Reaches a peak of 650 μL/L before 2100 and then drops
RCP8.5	Reaches more than 8.5 W/m ² by 2100	Reaches more than 1370 μL/L by 2100 and then drops

2.2.4. Future LUCC Data

The land use data came from the Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) dataset, and the Land-Use Harmonization (LUH) is an input dataset to obtain this dataset [32]. The FROM-GLC dataset considers 11 variables that can reflect changes in land use, such as soil, temperature, and precipitation, and plots eight primary types (farmland, forest, grassland, shrubs, water, impervious surfaces, bare land, and snow/ice) as well as 28 detailed secondary land use types. This study used the land use distribution forecast data from 2010 to 2100 that were developed based on these data (including three RCP scenarios—RCP2.6, RCP4.5, and RCP8.5), with a spatial resolution of 1 km [33].

2.3. Methods

Since we have evaluated the performance of the IBIS model in our previous studies, the model was supposed to be reliable in NPP simulation in this study. For example, the model was used to analyze the terrestrial carbon budget of the United States from 1971 to 2015 with a resolution of 1 km by using the updated dynamic global vegetation model and comprehensive land cover change data [34]. Yang et al. [35] used IBIS to simulate and analyze the temporal and spatial variation characteristics and development trends of the carbon budget under the conditions of climate and CO₂ concentration changes in the historical period of China’s terrestrial ecosystem.

The model was firstly set up as a spin-up procedure running with multi-year (between 1960 and 2006) averaged historical meteorological data to allow the ecosystem carbon pools to reach a relative equilibrium state. Then, forced by the data mention above, the simulations were conducted between 2006 and 2100 under different scenarios listed in Table 3. In this study, we selected three time periods of 2010–2020, 2050–2060, and 2090–2100 to study the impact of climate change, CO₂ concentration, and LUCC on global NPP. These three periods represent the beginning, the middle, and the end of the century, respectively. In these three periods, after averaging the results of IBIS simulations forced by climate data of four CMIP5 climate models, the first period (2010–2020) was selected as the reference period. NPP changes were calculated between each period and the reference period for five different scenarios (Table 3), and then the contribution of each factor was evaluated.

Table 3. Five types of scenario settings for model simulation.

	Climate Data	CO ₂	LUCC
All	RCP2.6/RCP4.5/RCP8.5	RCP2.6/RCP4.5/RCP8.5	RCP2.6/RCP4.5/RCP8.5
Climate change only	RCP2.6/RCP4.5/RCP8.5	Constant after 2006	Constant after 2006
CO ₂ only	Constant after 2006	RCP2.6/RCP4.5/RCP8.5	Constant after 2006
LUCC only	Constant after 2006	Constant after 2006	RCP2.6/RCP4.5/RCP8.5
NA	Constant after 2006	Constant after 2006	Constant after 2006

In the choice of land use types studied, forest and grassland ecosystems have the most carbon content in the biosphere. The total NPP of forest and grassland ecosystems has exceeded 50% of the total NPP of global vegetation. Changes in their area and cover types

will lead to changes in the global carbon cycle. Therefore, we only discuss changes based on global forests and grassland plantations, which are affected by changes in land use types.

In this paper, the spatial resolutions of the input data and results were $0.5^\circ \times 0.5^\circ$.

3. Results

3.1. Changes in Global Terrestrial Ecosystem NPP under Three Future Climate Change Scenarios

Figure 1 shows the individual and combined effects of three factors—climate change (labeled CC in the figure) and changes in CO_2 and LUCC conditions—on global NPP. The values were the averages of the GFDL-ESM2M, GISS-E2-H, IPSL-CM5A-LR, and MIROC5 models under the RCP2.6, RCP4.5, and RCP8.5 scenarios. Individual effects are represented by histograms, and combined effects are represented by dashed lines. The observation year is listed in the legend. The three dashed lines represent the mean values of the combined effect under the RCP2.6, RCP4.5, and RCP8.5 scenarios from 2010 to 2100.

Figure 1. Global net primary productivity (NPP) in various periods from 2010 to 2100 relative to the total amount of NPP change in 2010.

At the global scale, climatic factors are projected to exert a negative impact on the total amount of NPP change (Figure 1). Under the same scenario, the negative impact exhibited an increasing trend from 2010 to 2100. In the same period, the negative impact increased with increasing radiative forcing, and the negative impact intensity under the RCP8.5 scenario reached its maximum ($-4.024 \text{ Pg C Yr}^{-1}$) by the end of the century. From 2010 to 2100, the CO_2 factor had a positive impact on NPP and increased considerably with increasing time and radiative forcing. The positive impact of CO_2 on NPP reached its maximum value by the end of the century under the RCP8.5 scenario ($12.744 \text{ Pg C Yr}^{-1}$). The LUCC factor had a positive effect on NPP, and the variation under different radiative forcing scenarios decreased slightly with the increase in the scenarios. The influence of LUCC on NPP under the RCP2.6 scenario was the largest, which was ($0.540 \text{ Pg C Yr}^{-1}$) from 2010 to 2100. The NPP variation under the combined effects of climate change, CO_2 , and LUCC from 2010 to 2100 increased with strengthening radiative forcing scenario (RCP2.6: $1.472 \text{ Pg C Yr}^{-1}$; RCP4.5: $2.943 \text{ Pg C Yr}^{-1}$; RCP8.5: $5.782 \text{ Pg C Yr}^{-1}$).

3.2. Response of Terrestrial Ecosystem NPP in Different Latitudinal Zones to Different Emission Scenarios

As revealed by the analysis of NPP changes in various latitudinal zones (Figure 2), the negative impact of CC under the global pattern was mainly dominated by the negative impact of tropical regions. The negative impact of the RCP4.5 and RCP8.5 scenarios was considerably stronger than that of the RCP2.6 scenario. The trend of NPP change by the end of the century under the RCP8.5 scenario was the most prominent, reaching $-4.842 \text{ Pg C Yr}^{-1}$. Under different scenarios, CC exhibited a significant positive impact

on global NPP in the northern latitudes, especially in northern high latitudes, where the impact intensity reached the maximum ($1.175 \text{ Pg C Yr}^{-1}$) by the end of the century under the RCP8.5 scenario. At the same time, it was observed that in the temperate regions of the northern mid-latitudes, the intensity of the positive impact caused by CC was projected to decrease from 2010 to 2100 in the temperate regions of the northern mid latitudes, and CC forecast to exert a negative impact on NPP during the remainder of the century under the RCP8.5 scenario.

Figure 2. Global NPP in various periods from 2010 to 2100 relative to total NPP changes in various latitudinal zones in 2010. Shows the individual and combined effects of three factors—climate change (labeled CC in the figure) and changes in CO₂ and land-use cover change (LUCC) conditions—on the NPP of different latitudinal zones around the world. Based on latitude, four climatic zones from (a) 60.0–90.0° N, (b) 30.0–60.0° N, (c) –30.0–30.0° N, and (d) –60.0–30.0° S were selected for the data.

CO₂ exhibited a positive effect on NPP in all latitudinal zones, most prominently in tropical regions. Under the influence of elevated CO₂ concentration, the trend of NPP change in tropical regions was the most prominent by the end of the century under the RCP8.5 scenario, with a value of $8.328 \text{ Pg C Yr}^{-1}$. The NPP change in the northern mid latitudes reached $3.495 \text{ Pg C Yr}^{-1}$. The intensity of the impact of CO₂ on the total amounts of NPP in the northern high latitudes and southern mid latitudes were relatively low, with predicted values of $0.502 \text{ Pg C Yr}^{-1}$ and $0.419 \text{ Pg C Yr}^{-1}$, respectively.

The impact of LUCC in each latitudinal zone was relatively small, with the strongest positive impact in tropical regions. Under the RCP2.6 scenario, the trend of NPP changes in tropical regions from 2010 to 2020 was the most prominent, with a value was $0.381 \text{ Pg C Yr}^{-1}$. The NPP change in the northern high latitudes was negatively impacted by LUCC, with the maximum value of $-0.163 \text{ Pg C Yr}^{-1}$ occurring by the end of the century under the RCP4.5 scenario.

Under each scenario, the combined influence of the three factors was the strongest in the northern mid latitudes, and the positive effect in each region was the highest under the RCP8.5 scenario. Although the positive impact of CO₂ in the tropics was substantially higher than the impact in other latitudinal zones, the negative impact caused by CC in this region produced a relatively large counteracting effect.

3.3. Characteristics of Global Forests and Grassland NPP Changes

On the global scale, the trend pattern of global forest NPP change and influence was essentially the same as the global NPP influence pattern (Figure 3). Under different scenarios, there was no major difference in the intensity of the impact of CC or CO₂ on global forests. Under the RCP8.5 scenario, the global forest NPP change caused by CC and the increase in CO₂ concentration reached its maximum by the end of the century relative to the change at the beginning of the century. Among the influencing factors, CC exerted a negative impact at the rate of $-2.209 \text{ Pg C Yr}^{-1}$, while CO₂ had a positive impact at the rate of $6.433 \text{ Pg C Yr}^{-1}$. Under LUCC conditions, the value of each time period was the largest under the RCP2.6 scenario, and the change in forest NPP displayed a decreasing trend with time. The relative changes of forest NPP under the combined effect of the three factors in the various emission scenarios were $\text{RCP8.5} > \text{RCP4.5} > \text{RCP2.6}$, with corresponding values of $3.613 \text{ Pg C Yr}^{-1}$, $1.845 \text{ Pg C Yr}^{-1}$, and $0.811 \text{ Pg C Yr}^{-1}$.

Figure 3. Global NPP in various periods from 2010 to 2100 relative to total forest NPP changes in 2010.

Figure 4 shows the results of global grassland NPP changes under different factors and scenarios from 2010 to 2100. The trend pattern of grassland NPP changes was generally the same as the above-mentioned global and forest NPP patterns. Under different radiation scenarios, there was a minor difference in the global grassland NPP affected by the CC or CO₂ factor. Under the RCP8.5 scenario, the changes in global grassland NPP caused by CC and the increase in CO₂ concentration reached a maximum by the end of the century relative to the concentration at the beginning of the century. Among the influencing factors, CC exerted a negative impact at the rate of $-1.739 \text{ Pg C Yr}^{-1}$, while CO₂ had a positive impact at the rate of $5.928 \text{ Pg C Yr}^{-1}$. Under LUCC conditions, the grassland NPP value of each time period was the largest under the RCP2.6 scenario, and the change in grassland NPP displayed an overall decreasing trend with time. Under the combined effect of the three factors, the relative increases of global grassland NPP in the different scenarios were $\text{RCP8.5} > \text{RCP4.5} > \text{RCP2.6}$, with corresponding values of $2.121 \text{ Pg C Yr}^{-1}$, $1.194 \text{ Pg C Yr}^{-1}$, and $0.678 \text{ Pg C Yr}^{-1}$.

Figure 4. Global NPP in various periods from 2010 to 2100 relative to total grassland NPP change in 2010.

Figure 5 shows the results of forest NPP changes in various latitudinal zones of the world under different factors and scenarios from 2010 to 2100. Climatic factors exhibited an apparent negative effect in the tropics. The negative effects under the RCP4.5 and RCP8.5 scenarios were significantly stronger than those under the RCP2.6 scenario. Among them, the NPP change trend by the end of the century was the most prominent under the RCP8.5 scenario, reaching $-2.209 \text{ Pg C Yr}^{-1}$. The climatic factors produced the greatest positive effect in the northern high latitudes, where the value reached its maximum of $0.3389 \text{ Pg C Yr}^{-1}$ by the end of the century under the RCP8.5 scenario. Climatic factors produced a positive effect in the northern mid latitudes, and the forest NPP changes were relatively stable. Under all scenarios, the forest NPP value from 2050 to 2060 was the largest, and decreased to some extent by the end of the century.

Figure 5. Changes in forest NPP of various latitudinal zones around the world under different factors and scenarios from 2010 to 2100. (a) $60.0\text{--}90.0^\circ \text{ N}$, (b) $30.0\text{--}60.0^\circ \text{ N}$, (c) $-30.0\text{--}30.0^\circ \text{ N}$, and (d) $-60.0\text{--}30.0^\circ \text{ S}$ were selected for the data.

CO_2 produced a positive effect in each latitudinal zone. The forest NPP changes under each scenario were in the relative order of $\text{RCP8.5} > \text{RCP4.5} > \text{RCP2.6}$, and the

changes exhibited an increasing trend with time. The change trend of forest NPP under the RCP8.5 scenario in each latitudinal zone was the most prominent by the end of the century. The forest NPP change rate in tropical areas ($4.694 \text{ Pg C Yr}^{-1}$) was the fastest, followed by the northern mid latitude region > the northern high latitude region > southern mid latitude region.

LUCC displayed the most prominent positive effect in tropical regions, and the amount of forest NPP change in each scenario showed a decreasing trend. A relatively balanced negative effect occurred in the northern high latitudes, while a relatively balanced positive effect under various scenarios occurred in the northern mid latitudes. Under the impact of the LUCC factor, the forest NPP change in the southern mid latitudes was unevenly distributed, except for the positive effect occurring between 2050 to 2060 and the end of the century under the RCP2.6 scenario, a negative effect was found in the rest of the region.

Under each scenario, the combined effect of the three factors on NPP changes was the strongest in the northern mid latitudes, and the highest positive effect in each region was reached under the RCP8.5 scenario. Although the positive impact of CO_2 in the tropics was significantly higher than those in the other latitudinal zones ($1.844 \text{ Pg C Yr}^{-1}$), the negative impact caused by CC in this region exerted a relatively large counteracting effect.

Figure 6 shows the predicted grassland NPP changes in various latitudinal zones of the world under different factors and scenarios from 2010 to 2100. Climatic factors exhibited an apparent negative effect in the tropics. The negative effects under the RCP4.5 and RCP8.5 scenarios were significantly stronger than the effect under the RCP2.6 scenario. Among them, under the RCP8.5 scenario, the NPP change trend by the end of the century was the most prominent, reaching $-2.058 \text{ Pg C Yr}^{-1}$. Climatic factors produced a positive effect in the northern high latitudes, the value of the RCP8.5 scenario was the largest of the three scenarios, and the value was the largest by the end of the century ($0.726 \text{ Pg C Yr}^{-1}$). Climatic factors produced a positive effect in the northern mid latitudes, but exerted some negative effects by the end of the century under the RCP8.5 scenario. The grassland NPP values under both the RCP4.5 and RCP8.5 scenarios exhibited decreasing trends by the end of the century.

Figure 6. Changes in grassland NPP of various latitudinal zones around the world under different factors and scenarios from 2010 to 2100. (a) 60.0–90.0° N, (b) 30.0–60.0° N, (c) –30.0–30.0° N, and (d) –60.0–30.0° S were selected for the data.

CO₂ produced a positive effect in each latitudinal zone. Overall, the changes in grassland NPP under each emission scenario were in the relative order of RCP8.5 > RCP4.5 > RCP2.6, although the grassland NPP value under the RCP2.6 scenario in the northern mid latitude and low latitude regions decreased by the end of the next century relative to that of the period 2050 to 2060. The change trend of grassland NPP under the RCP8.5 scenario in each latitudinal zone was the most prominent by the end of the century. Among them, the change rate in the tropical zone was the fastest, reaching 3.439 Pg C Yr⁻¹. The grassland NPP changes in other regions were in the relative order of northern mid latitudes > northern high latitudes > southern mid latitudes.

The positive effect of LUCC on grassland NPP changes was the most prominent in the northern mid latitudes. As time progressed, the grassland NPP change was relatively balanced under each scenario. While a small negative effect was found in the grassland NPP changes in the northern high latitudes and tropical regions, a small positive effect was found in the southern mid latitudes. The grassland NPP change was the largest under the RCP2.6 scenario, and the change in grassland NPP under each scenario exhibited a decreasing trend with time, from 2090 to 2100 was −0.013 Pg C Yr⁻¹.

The combined effect of the three influencing factors in the northern mid latitudes was the strongest under the RCP8.5 scenario, with a value of 1.238 Pg C Yr⁻¹. The negative combined effect in low latitudes was the largest (−0.419 Pg C Yr⁻¹) under the RCP2.6 scenario. Although the positive impact of CO₂ in the tropics was significantly higher than the impact in the other latitudinal zones, the negative impact caused by CC in this region exerted a relatively large counteracting effect.

3.4. Impact of LUCC on Forest and Grassland NPP

As shown in Figure 7, the forest area in the northern high latitudes decreased slightly under the RCP8.5 scenario, while the grassland area increased slightly under that scenario. The amount of change from 2010 to 2020 was the smallest, and the value from 2050 to 2060 was slightly greater than the value at the end of the century. The changes in the forest and grassland areas of the north temperate zone were more prominent, and the grassland area decreased under the RCP8.5 scenario. The areas of forest and grassland under each scenario increased with time, reaching their maxima by the end of the century. The area of grassland decreased, and the amount of change was the largest under the RCP8.5 scenario in the tropical regions −2.945 million·hm². The area change in each scenario increased with time, reaching their respective maxima by the end of the century. Under the RCP8.5 scenario, the forest area reduction in tropical areas was the most prominent by the end of the century, reaching −1.251 million·hm². Under the RCP4.5 and RCP8.5 scenarios, the forest areas in the southern mid latitudes were slightly reduced. The grassland area decreased substantially with time under the RCP8.5 scenario, reaching its minimum value by the end of the century.

Forests played a leading role in the northern high latitudes, and the forest NPP was negative and largest from 2010 to 2020. Climatic factors produced the greatest positive effect on forest NPP in the northern high latitudes, with the greatest positive effect under the RCP8.5 scenario occurring by the end of the century. Grassland played a leading role in the north temperate zone. Under the influence of LUCC, grassland NPP was relatively large, and the changes in each scenario and each period were relatively balanced. Climatic factors produced some negative effects by the end of the century under the RCP8.5 scenario in the northern mid latitudes, and the NPP value of grassland by the end of the century exhibited a decreasing trend under that scenario. Grassland played a leading role in tropical areas, and LUCC produced a negative impact on grassland NPP. Climatic factors displayed an apparent negative effect in the tropical regions. The NPP change trend under the RCP8.5 scenario was the most prominent by the end of the century (−2.058 Pg C Yr⁻¹), with the largest decrease in grassland area. Whether forests and grasslands played leading roles in the southern mid latitudes was not obvious. Under the influence of LUCC, the amount of NPP change was relatively small, and the forests produced a relatively large and balanced

positive impact under the influence of LUCC. The grassland area change was the most prominent under the RCP8.5 scenario, although the negative impact caused by climatic factors might counteract the positive impact caused by CO₂.

Figure 7. Changes in the forest and grassland land areas of various latitudinal zones around the world from 2010 to 2100 (a) 60.0–90.0° N, (b) 30.0–60.0° N, (c) –30.0–30.0° N, and (d) –60.0–30.0° S were selected for the data. The values are the forest and grassland area changes from 2010–2020, 2050–2060, and 2090–2100 under the RCP2.6, RCP4.5, and RCP8.5 emission scenarios. Notes: F: Forest, G: Grass.

3.5. Relative Contributions of Climatic Factors, CO₂, and LUCC to Changes in Global NPP

To study the contributions of climatic factors, CO₂, and LUCC to NPP, the relative effects of the three factors on forest and grassland NPP were calculated (i.e., the percentage of the contribution rate for each of the three influencing factors to NPP was obtained by calculating the ratio of the NPP change in the climatic factors, CO₂, or LUCC to the total NPP change in the three). For the total global NPP change, the maximum contribution rates of the CO₂ factor and the climatic factors were 69.27% and 24.58%, respectively, while the contribution of the LUCC factor was the smallest—only 6.14%.

Climatic factors played a leading role in the northern high latitudes, with a maximum contribution rate of 61.06%. The contribution rates of the CO₂ and LUCC factors were very similar (21.72% and 17.22%, respectively). The CO₂ factor in the northern mid latitudes exhibited the largest contribution rate to NPP, with a maximum value of 69.51%, while the contribution rate of the LUCC factor was 18.22%, and the contribution rate of the climatic factors was the smallest—only 12.27%. The CO₂ factor in the tropics played a leading role, although the climatic factors exerted an apparent counteracting effect. Their contribution rates to NPP were relatively close (52.56% and 43.03%, respectively), while the contribution rate of the LUCC factor was only 4.41%. The contribution rate of the CO₂ factor to NPP was the largest in the southern mid latitudes, reaching 72.51%, the contribution rate of climatic factors was 25.54%, and the contribution rate of the LUCC factor was the smallest—only 1.95%.

The influences and contributions of the three factors interacted with each other and were also related to the distribution of vegetation. Under LUCC conditions, the area of

forest in the northern high latitudes decreased slightly, forests played a leading role, and LUCC produced a small negative impact on NPP. In the temperate regions of the northern mid latitudes, the reduction in forest and grassland areas was prominent. Of these, the NPP of grassland was larger. Compared with other regions, LUCC produced a more apparent positive impact on NPP. At the same time, the reduction in grassland area played a leading role in tropical areas and exerted a negative impact on grassland NPP. When combined with forest NPP, LUCC produced a relatively small positive effect. The change in grassland area in the southern mid latitudes had a small negative effect on grassland NPP, and when combined with the positive effect on forest NPP, it had a small positive effect on the total NPP change.

In general, under future conditions, the amount of NPP change is predicted to continue increasing under the three influencing factors, and the influence intensity of each factor on NPP is also projected to continue increasing.

4. Discussion

4.1. Impacts of Climatic Change, CO₂, and LUCC on NPP

The influence of climatic factors on global NPP is unevenly distributed. Grosso et al. [9] estimated the NPP of global terrestrial ecosystems based on NPP data from the central and eastern United States and Australia. Similar to our results, climatic factors produced the greatest positive effect in the northern high latitudes. Overland et al. [36] found that in the northern high latitudes, the surface temperature rise caused by global warming was the most serious. The impact of climatic factors on the NPP of grassland varies among different regions, exhibiting a positive effect in high latitude areas and a negative effect in low latitude areas [37,38]. Our research results also demonstrated that climatic factors exerted a positive impact on NPP in northern latitudes and had the greatest negative impact in tropical regions, with grassland changes playing a leading role. In different regions, global terrestrial productivity and carbon storage respond differently to changes in climatic factors. The warming of the northern high latitudes may be a direct factor, and it has also been proposed that the carbon storage in vegetation can be increased by extending the growing season [39]. These studies may explain the forest NPP change in the northern latitudes and the grassland NPP change in the southern mid latitudes that were affected by the climatic factors in our research results.

Increasing CO₂ concentration has a positive impact on global NPP, especially in tropical regions. Miyazaki et al. [40] found that during the growing season, atmospheric CO₂ in the troposphere transported the CO₂ emitted from the mid high latitudes of the Northern Hemisphere to the tropical areas of the Northern and Southern Hemispheres, where it accumulated as a carbon sink. The temperate regions of the Northern Hemisphere are densely populated, and carbon emissions due to human activities during the non-growing season also increase the seasonal amplitude of atmospheric CO₂ concentration, which exerts a certain impact on NPP. There have been some related discussions concerning the impact of CO₂ concentration changes on the northern high latitudes. Phillips et al. [41] found that the contribution and promotion of the CO₂ concentration change in high latitudes were relatively small, but the fertilization effect of CO₂ was clearly reflected in tropical regions. For example, the forest in the Amazon River region can still be maintained as a carbon sink when the carbon pool is reduced. In our research results, after the division was carried out based on land cover type, the CO₂ factor contributed considerably to grassland NPP in the densely populated northern mid latitude regions.

Our results revealed that the LUCC factor exerted a relatively large impact on the NPP of grassland in the northern mid latitudes. In North America, for example, due to overgrazing, the destruction of the grassland soil structure has altered vegetation types, resulting in some irreversible changes and negative effects in this region [42]. Carbon sinks are generated in low latitude areas under the influence of CO₂ concentration. In addition, the establishment of global ecological reserves and nature reserves in recent years has improved the grassland ecosystem, resulting in an increase in its productivity. In our

study, the LUCC factor provided the largest contribution to the NPP of grassland in low latitude regions. Studies have also suggested that human activities can indirectly increase the carbon sink of forest land by increasing secondary forests [43]. This may be one of the reasons for the apparent positive impact produced by LUCC in the northern mid latitudes. LUCC is the main factor affecting NPP. Yu et al. [44] applied the previously used model to the North–South Transect of Eastern China (NSTEC) to examine the combined effects of climate and land use on vegetation distribution, primary productivity, and the nitrogen cycle. They found that the simulation with land use restrictions produced lower primary productivity than the simulation without land use restrictions. Accordingly, we should also take into account the change trends under the combined impacts of various factors.

Bondeau et al. [45] found that in the past century, the combined effects of land use change and land management (including irrigation and fertilization effects as well as the expansion of agricultural land) had almost no impact on global NPP. Eurasia is the region that contributes the most to the increase in the seasonal amplitude of carbon dioxide, although there has been little land use change in the past half-century [46]. For this reason, in 2017, Piao et al. [47] conducted a large number of studies on the seasonal changes in land use in the Northern Hemisphere. Compared with the seasonal changes in land use in 2019, their results revealed that the seasonal effect of CC on land use was small [48]. Similarly, in our research results, the NPP changes in all regions of the world under LUCC conditions were relatively small. This may be associated with the classification of vegetation types in the dataset used in this study. When the areas of forest and grassland were calculated, the LUCC data included the total percentage of forest and shrubs. Since the percentage of forest and shrubs was only 63% in the dataset we used, about 14.5% agricultural land, 2.9% shrubland, and 3.6% grassland were also regarded as forest land, which was only equivalent to 13.9% of the normal forest area [49]. In addition, when global NPP changes are analyzed, it is also necessary to consider the effects stemming from the interaction of different land types with climatic factors and CO₂, similar to the reasons for the fertilization effect of carbon dioxide. When forest NPP is analyzed, researchers should not only focus on rainfall, temperature, and commonly used soil conditions, but the strong correlation between forest NPP and multiple variables should also be taken into consideration [47–49]. The carbon feedback between land use change and CC can also be used to explain the forest and grassland NPP changes in specific areas [43,44]. To a large extent, due to the increase in the level of radiative forcing, this study comprehensively analyzed the three factors of CC, and CO₂, and LUCC. It was found that the simulation under the RCP8.5 scenario produced the largest combined effect, and the global NPP change trend was the most obvious by the end of the century.

4.2. Uncertainties and Limitations

Climatic factors, CO₂, and LUCC, influence NPP in multiple ways, and the uncertainty in examining model simulations cannot be ignored. Reyer et al. [50] proposed that the uncertainties of climate models and parameters exhibit greater changes than the NPP itself, and there may be more uncertainties in the process of the model prediction. The different definitions of vegetation types between the initial (LUH) dataset and the IBIS model could also cause uncertainties in the model simulation. Research relying only on individual model simulations still has inherent limitations. Therefore, some aspects in the analysis of global change feedback can be enhanced and improved using single factors and combined factors. In the simulation, prediction, and analysis of the future role of terrestrial carbon sinks, we must consider more global change factors in multi-factor research, improve the ability of indicators to quantify the productivity, biomass, and other characteristics, and explain the roles of different factors more rationally and scientifically [50].

5. Conclusions

Under three future emission scenarios, the total global forest and grassland NPP from 2010 to 2100 in the four model simulations increased with increasing radiative forcing, and the difference under each radiative forcing level also became more obvious.

In the global pattern, climate factors have a negative impact on NPP, while CO₂ and LUCC have a positive impact on NPP. Among them, the northern high latitude climate factors play a leading role in NPP and have the greatest positive impact on NPP. The CO₂ factor plays a leading role in the northern mid latitude, tropical, and southern mid latitude regions, and has the greatest positive impact on NPP. LUCC has a negative impact on NPP in northern high latitude and northern mid latitude regions, while it has a positive impact on NPP in the tropical and southern mid latitude regions.

Author Contributions: Conceptualization, C.P. and Q.Z.; Data curation, X.H., L.Y., and Q.Z.; Formal analysis, X.H.; Funding acquisition, Q.Z.; Investigation, Y.H. and Z.K.; Methodology, X.H., J.Z., and M.Y.; Project administration, Q.Z.; Resources, L.Y. and Q.Z.; Supervision, C.P.; Validation, X.H., Y.H., and Z.K.; Visualization, X.H.; Writing—original draft, X.H.; Writing—review & editing, X.H., J.Z., M.Y., and Q.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Second Tibetan Plateau Scientific Expedition (2019QZKK0304), National Key R&D Program of China (2016YFC0500203), and Fundamental Research Funds for the Central Universities (2019B04714).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We sincerely thank the reviewers for their helpful comments and suggestions about our manuscript.

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

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