

Article

# Impacts of 1.5 °C and 2 °C Global Warming on Net Primary Productivity and Carbon Balance in China's Terrestrial Ecosystems

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**Abstract:** Assessing potential impacts of 1.5 °C and 2 °C global warming and identifying the risks of further 0.5 °C warming are crucial for climate adaptation and disaster risk management. Four earth system models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and a process-based ecosystem model are used in this study to assess the impacts and potential risks of the two warming targets on the carbon cycle of China's terrestrial ecosystems. Results show that warming generally stimulates the increase of net primary productivity (NPP) and net ecosystem productivity (NEP) under both representative concentration pathway (RCP) 4.5 and RCP8.5 scenarios. The projected increments of NPP are higher at 2 °C warming than that at 1.5 °C warming for both RCP4.5 and RCP8.5 scenarios; approximately 13% and 19% under RCP4.5, and 12.5% and 20% under RCP8.5 at 1.5 °C and 2 °C warming, respectively. However, the increasing rate of NPP was projected to decline at 2 °C warming under the RCP4.5 scenario, and the further 0.5 °C temperature rising induces the decreased NPP linear slopes in more than 81% areas of China's ecosystems. The total NEP is projected to be increased by 53% at 1.5 °C, and by 81% at 2 °C warming. NEP was projected to increase approximately by 28% with the additional 0.5 °C warming. Furthermore, the increasing rate of NEP weakens at 2 °C warming, especially under the RCP8.5 scenario. In summary, China's total NPP and NEP were projected to increase under both 1.5 °C and 2 °C warming scenarios, although adverse effects (i.e., the drop of NPP growth and the reduction of carbon sequestration capacity) would occur in some regions such as northern China in the process of global warming.

**Keywords:** 1.5 °C and 2 °C global warming; climate risks; earth system models of CIMIP5; process-based ecosystem model; China

## 1. Introduction

Since the threshold of 2 °C warming was first proposed by Nordhaus [1], it has gradually been accepted as the important greenhouse gas reduction target. Human beings, especially the residents of small island states, are looking for a new long-term target, which is lower than 2 °C warming [2]. The Paris Agreement sets a new global goal that aims at holding the increase of the global average temperature to well below 2 °C above pre-industrial, and pursuing efforts to limit the temperature increase to 1.5 °C [3]. The Intergovernmental Panel on Climate Change (IPCC) special report on 1.5 °C

warming indicated that limiting global warming to 1.5 °C rather than 2 °C would be expected to reduce the risks in terrestrial and wetland ecosystems [4,5]. However, large uncertainties still remain about the responses of the terrestrial carbon cycle to 1.5 °C and 2 °C warming, especially 1.5 °C warming. Previous studies have usually focused on terrestrial carbon cycle change during specific periods, such as the middle or the end of the 21st century [6–9]. Although the enhanced global warming target has been proposed, the assessment of associated impacts on terrestrial ecosystems is very rare in China. Therefore, it is crucial to explore the potential risks of terrestrial ecosystems under the 1.5 °C and 2 °C warming scenarios for accommodating regional and national strategies for climate mitigation and adaptation.

Previous modeling studies have shown that the net primary productivity (NPP) will increase in response to future global warming [9,10]. However, the simulated net ecosystem productivity (NEP) in response to future warming is highly variable [11–14]. Some studies indicated that the land biosphere would turn into a net CO<sub>2</sub> source in the 21st century [6,15,16]. Recent studies using the Coupled Model Intercomparison Project Phase 5 (CMIP5) model projections suggested that the rate of net terrestrial carbon uptake would decrease during the 21st century in most scenarios due to enhanced soil organic matter decomposition, water deficit, climatic extreme events, land use change, etc. [2,17,18].

In China, the mean air temperature has increased by 0.9–1.5 °C during 1909–2011 as compared to the 1971–2000 period; all observations and model estimations showed a higher warming rate in China than the global average [19]. The CMIP5 model simulations showed that the mean air temperature over Asia would increase 2.3 °C in response to 1.5 °C global warming, and 3.0 °C in response to 2 °C global warming, respectively [20]. Most of the research focused on mean and extreme climate change [21,22] and the impacts of future 2 °C warming on the hydrological cycle and water resource in China [22–24]. A few recent studies in China suggested the high ecological risks in the Yangtze River Basin and northern China [25]. Some studies indicated that grassland productivity would increase under the 1.5 °C and 2 °C warming scenarios due to the increased precipitation and atmospheric CO<sub>2</sub> concentration [26]. Changing temperature and precipitation had large temporal and spatial variations because of the vast area and varied terrain in China [21,22], which resulted in diverse responses of terrestrial ecosystems to climate change [8,27,28]. Therefore, future variations in terrestrial ecosystems might be more uncertain under the 1.5 °C and 2 °C global warming scenarios [24]. It is imperative to conduct a comprehensive assessment of the spatial patterns of NPP and NEP responses in China under the threshold of 1.5 °C and 2 °C warming scenarios.

CMIP5 provides the global scale simulations of multiple Earth system models (ESMs), which were widely used in large-scale climate impact analyses [29]. The Carbon Exchange between Vegetation, Soil and Atmosphere model version 2 (CEVSA2) is a process-based ecosystem model, which simulates energy transfer and matter cycles in the vegetation-soil-atmosphere system [6,30]. The model is able to quantify the responses of ecosystem processes to global changes such as atmospheric CO<sub>2</sub>, climate, nitrogen deposition, and land use changes. The CEVSA2 model has been applied to simulate climate impacts on terrestrial ecosystems and to assess the climate vulnerability of terrestrial ecosystems in China [31–34]. The major model parameters and processes have been intensively validated and calibrated in China's ecosystems [30]. In this study, we averaged results of the CEVSA2 model and the ESMs to an ensemble, which was used to provide a comprehensive assessment of impacts and risks of 1.5 °C and 2 °C global warming on the carbon cycle of China's terrestrial ecosystems. Our main objectives include (1) illustrating the impacts of 1.5 °C and 2 °C global warming on NPP and NEP in China; (2) identifying the differences of 1.5 °C and 2 °C global warming effects on China's NPP and NEP, and (3) estimating the probable risks at 1.5 °C compared to 2 °C warming. Our results would be helpful for defining management options for the regional carbon cycle, and also provide evidence for assessing the risks of 1.5 °C and 2 °C warming globally.

## 2. Data and Methodologies

### 2.1. Data

ESMs data. Four ESMs (BNU-ESM, IPSL-CM5A-LR, MPI-ESM-LR, and NorESM1-ME) were used to assess climate change impacts on NPP and NEP in China. The selection was based on the availability of monthly NPP and NEP covering the period of enhanced global warming targets for the representative concentration pathway (RCP) 4.5 and RCP8.5 scenarios, and the approximate classification of vegetation function types to eliminate the effect of land cover as far as possible and to be capable of intercomparison. The RCP4.5 and RCP8.5 describe greenhouse gas concentration trajectories and are the latest generation of scenarios for driving climate models since the Fifth Assessment Report (AR5) of IPCC. They are the products of an innovative collaboration between integrated assessment models, which provide an important approach to study future climate change and its potential effects [35]. In consideration of the transient response of ecosystems to climate change and dynamic simulation, we used RCP4.5 and RCP8.5 scenarios to assess the impact of 1.5 °C and 2 °C warming above the pre-industrial level on terrestrial ecosystems in China. The monthly mean NPP, NEP from 1961–2099 for each ESM were obtained from the program for climate model diagnosis and intercomparison (<https://esgf-node.llnl.gov/projects/cmip5/>). The key features of the ESMs and CEVSA2 model are summarized in Table 1.

**Table 1.** Key features of the four Earth system models (ESMs) and CEVSA2 model used in this study.

Model Name	Initial land Resolution	Land Surface Model	Vegetation Distribution	Plant Function Types	Available Outputs	References
BNU-ESM	2.8° × 2.8°	The Common Land Model	Dynamic	10	NPP and NEP	Ji et al. (2014) [36]
IPSL-CM5A-LR	3.75° × 1.9°	ORCHIDEE	Static	12	NPP and NEP	Dufresne et al. (2013) [37]
MPI-ESM-LR	2.8° × 1.9°	SEIB-DGVM	Dynamic	10	NPP	Giorgetta et al. (2012) [38]
NorESM1-ME	2° × 1°	Community Land Model version 4	Dynamic	12	NPP	Tjiputra et al. (2012) [39]; Oleson et al. (2010) [40]
CEVSA2	0.1° × 0.1°	/	Static	12	NPP and NEP	Cao et al., (1998) [6]; Gu et al. (2017) [30]

Note: Net ecosystem productivity (NEP), net primary productivity (NPP).

Input data for the CEVSA2. The CEVSA2 model is driven by climatic data at the 10-day time step, including temperature, precipitation, cloud cover, and relative humidity. The data sets were obtained from RegCM 4.0 model driven by BCC\_CSM1.1, the latest version of the regional climatic system model developed by the National Climate Center of China [41]. All of these climate data were downscaled to a spatial resolution of 0.1 degrees by 0.1 degrees using the ANUSPLIN software with version 4.3 [42]. Soil types and soil texture were obtained from the 1:14,000,000 digital map of soil texture in China [43]. The vegetation distribution map was reclassified and re-sampled to match with other datasets based on the Global Land Cover 2000 database (GLC2000, European Commission Joint Research Centre, 2003, <https://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php>). All these spatially explicit datasets are at a resolution of 0.1 degrees. Historical and future atmospheric CO<sub>2</sub> concentrations were downloaded from the Data Distribution Centre of IPCC (<http://www.ipcc-data.org>).

## 2.2. Global Warming Scenarios

Jiang et al. (2016) detected the initial year passing through 1.5 °C and 2 °C global warming under RCP2.6, RCP4.5, and RCP8.5 in China's domain [44]. In this study, we adopted the results of Jiang et al. [44] and identified the years 2029 and 2049 as the initial years of 1.5 °C and 2 °C warming under the RCP4.5 scenarios, and the years 2026 and 2039 under the RCP8.5 scenarios, respectively. A total of 10 years before and after the initial year were combined to represent the warming periods; the periods of 2020–2039 and 2040–2059 represent 1.5 °C and 2 °C warming periods under the RCP4.5 scenario. Similarly, 2017–2036 and 2030–2049 represent 1.5 °C and 2 °C warming periods under the RCP8.5 scenario. To compare with the impacts of difference global warming targets, we used the average of the 1986–2005 as a reference period.

The simulated results of ESMs were spatially interpolated to the 0.1° resolution in ArcGIS to be consistent with the CEVSA2 simulations. Although the NPP and NEP magnitudes varied, all of them showed the same change trend during the study period. Therefore, we averaged the annual grid datasets of all models to an ensemble in each respective period for 1.5 °C and 2 °C warming. We defined  $NPP_{RP}/NEP_{RP}$  as the mean NPP/NEP for the reference period of 1986–2005, and we used  $NPP1_{RCP4.5}/NEP1_{RCP4.5}$  as averaged NPP/NEP during 2020–2039 for 1.5 °C warming under the RCP4.5 scenario, respectively, and  $NPP2_{RCP4.5}/NEP2_{RCP4.5}$  during 2040–2059 for 2 °C warming under the RCP4.5 scenario. Similarly,  $NPP1_{RCP8.5}/NEP1_{RCP8.5}$  represents the averaged NPP/NEP during 2017–2036 for 1.5 °C warming under the RCP8.5 scenario, and  $NPP2_{RCP8.5}/NEP2_{RCP8.5}$  represents the averaged NPP/NEP during 2030–2049 for 2 °C warming under the RCP8.5 scenario. The slope was used to indicate the changing trends of NPP and NEP, which smooth the annual fluctuation and capture the characteristic of the indicators in time periods of warming targets.

## 2.3. CEVSA2 Model Simulations

Firstly, the 30-year averaged climatic data (1971–2000) and a fixed CO<sub>2</sub> concentration level of the 30-year mean value were used to drive the CEVSA2 model until the model reached equilibrium status, so that the initial state parameters were obtained. Then, the simulation was conducted using transient climate and atmospheric CO<sub>2</sub> data for the period 1961–2099 in China at a time step of 10-days and a spatial resolution of 0.1 degrees. To eliminate the impact of assumed initial state, the model was run repeatedly with the same transient datasets for dynamic simulation.

## 2.4. Statistics Methods

In this study, we defined some indexes, including linear slope, the differences of linear slopes, the relative increase of NPP, and departure of mean annual NEP, to quantify the effect of different warming scenarios on terrestrial productivity and carbon uptake. We adopted linear fitting to fit the trend of annual NPP and NEP of Chinese terrestrial, and it was also used to fit the trend for each grid during the periods of the 1.5 °C and 2 °C global warming under the two RCP scenarios.

$$\text{Slope} = \frac{n \times \sum_{i=1}^n (i \times NPP_i) - \sum_{i=1}^n i \sum_{i=1}^n NPP_i}{n \times \sum_{i=1}^n i^2 - \left(\sum_{i=1}^n i\right)^2} \quad (1)$$

Here, *Slope* means the changing trend of NPP,  $NPP_i$  is the NPP for  $i$  year,  $n = 1, 2, 3, \dots, 20$  for each year of the reference period and the two periods of global warming targets, respectively.

To indicate the spatial heterogeneity of regional responses of terrestrial ecosystems to global warming and explore the potential risks at different warming levels, the relative increase of NPP ( $RI_{NPP}$ ) is defined as the mean NPP at 1.5 °C and 2 °C warming periods compared to their mean value during the reference period, respectively.  $RI_{NPP}$  calculated as:

$$RI_{NPP} = \frac{NPP_{TP} - NPP_{RP}}{NPP_{RP}} \times 100\% \quad (2)$$

where  $NPP_{TP}$  is the mean NPP during the different period of global warming targets (i.e.,  $NPP1$  and  $NPP2$  for two warming targets), and  $NPP_{RP}$  is the mean NPP during the reference period.

Differences of the linear slopes of NPP between 1.5 °C and 2 °C warming periods were used to estimate the impacts and the probable risks of the additional 0.5 °C warming on terrestrial ecosystems in China, and they were calculated as the slopes over 2 °C warming period minus that over the 1.5 °C warming period.

Departure of mean annual NEP calculated the differences between mean NEP during different warming periods and during the reference period, to represent the impacts of different warming on NEP.

### 3. Results

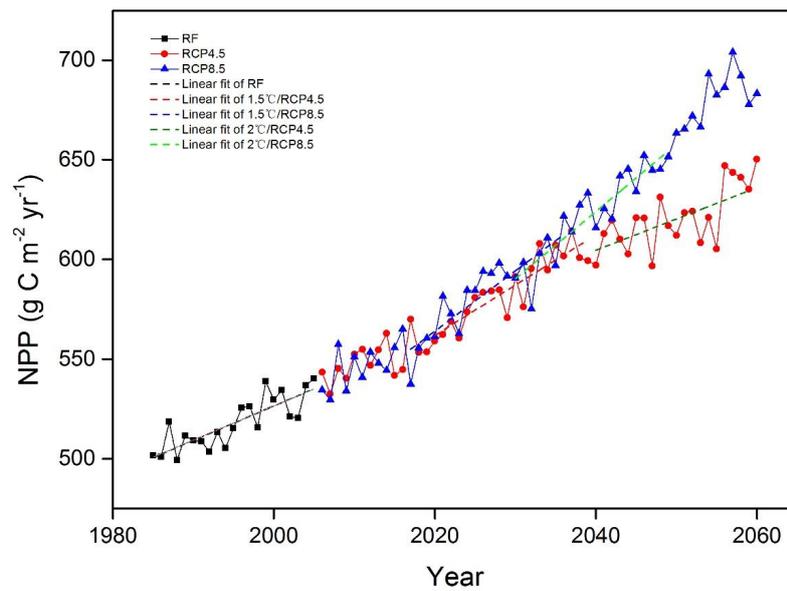
#### 3.1. Responses of NPP to 1.5 °C and 2 °C Warming

Our results indicate the annual NPP averaged over China's terrestrial ecosystem is about  $518.8 \pm 29.0 \text{ g C m}^{-2} \text{ yr}^{-1}$  of the two scenarios during the reference period. The annual NPP is projected to be increased to  $585.9 \pm 16.7 \text{ g C m}^{-2} \text{ yr}^{-1}$  for 1.5 °C warming and  $622.4 \pm 21.8 \text{ g C m}^{-2} \text{ yr}^{-1}$  for 2 °C warming. The increment of NPP is approximately 13% for 1.5 °C warming and 19% for 2 °C warming, compared with the reference period.

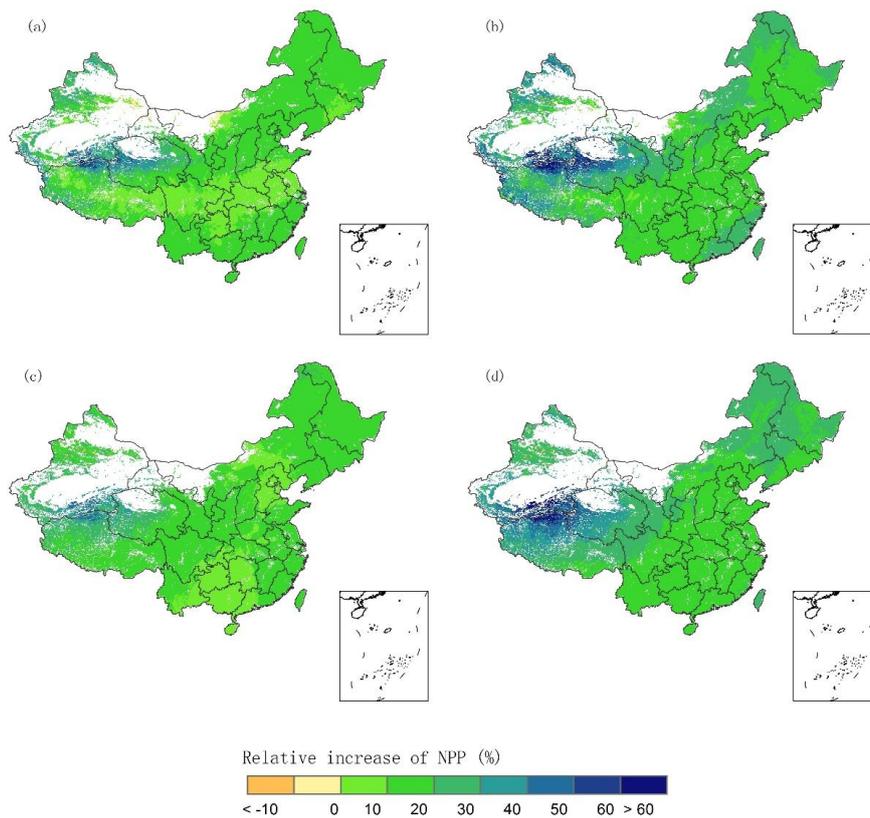
The annual NPP of Chinese terrestrial ecosystems increases significantly ( $p < 0.01$ ) during the 1.5 °C and 2 °C warming periods for both RCP4.5 and RCP8.5 scenarios, but with different slopes in respect to different warming periods and different warming scenarios (Figure 1). On the national scale, the increase of NPP is greater in the 2 °C warming period than that in the 1.5 °C warming period, and the overall relative increase of NPP is about 6% with the additional 0.5 °C warming. Under the RCP4.5 scenario, the growth rate of NPP for the 1.5 °C warming period is the highest among other warming periods, and it slows down obviously in the 2 °C warming period. Conversely, under the RCP8.5 scenario, the increasing rate of NPP is higher in the 2 °C warming period than that in the 1.5 °C warming period. Meanwhile, the fluctuation of annual NPP in the 2 °C warming period is greater under the RCP4.5 scenario than that under the RCP8.5 scenario, and the standard deviation of the former is 1.5 times higher than that of the latter. The results suggest that warming increased to 2 °C under a lower emission scenario would not only decrease the growth rate of terrestrial NPP but also increase the annual fluctuation of NPP.

Both the annual NPP averaged over the 1.5 °C and 2 °C warming periods show clear spatial patterns with obvious gradients decreasing from south to north and from east to west. The annual NPP shows an increase for the extra 0.5 °C warming under both scenarios; the increment of NPP is about  $35.6 \pm 13.4 \text{ g C m}^{-2} \text{ yr}^{-1}$  under RCP4.5 and  $41.1 \pm 12.4 \text{ g C m}^{-2} \text{ yr}^{-1}$  under RCP8.5. The increment of NPP is less in North China under RCP4.5 but higher under RCP8.5. Meanwhile, the increment of NPP is higher under RCP4.5 but less under RCP8.5 in southwest China. The spatial patterns of NPP under different future scenarios are similar to those in the reference period, and also agree with the other model simulations [8].

As shown in Figure 2, overwhelming majority areas in terrestrial ecosystems of China have an increasing trend of NPP responding to temperature rising for both the RCP4.5 and RCP8.5 scenarios under 1.5 °C and 2 °C warming, and only less than 1% of the grids show a decreasing trend of NPP. The relative increase of NPP shows the same spatial patterns under different warming targets or different scenarios, and it is greater in northwestern China than that in southeastern China. The highest increase of NPP occurred in Qinghai-Tibet Plateau and the northwestern arid regions. Comparing to southeastern China, northwestern China and Qinghai-Tibet Plateau have a lower mean annual temperature and are more sensitive to global warming. Moreover, northwestern China has a higher increase in precipitation in the future under the two scenarios. The plant growth is limited by water shortage in northwestern China and will be stimulated by increasing precipitation [45].



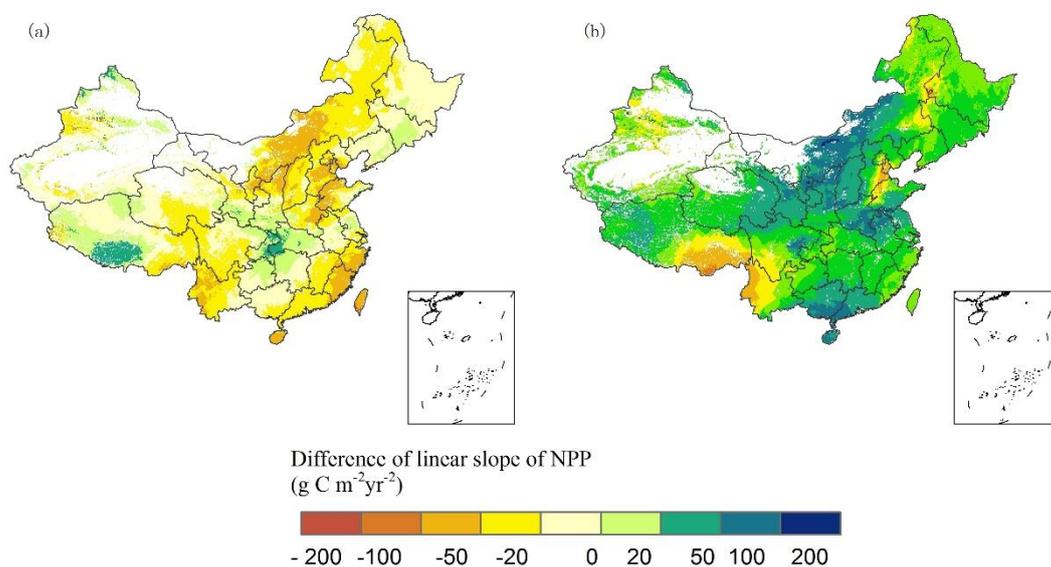
**Figure 1.** Linear fitting of annual NPP during the period of the 1.5 °C and 2 °C global warming for representative concentration pathway (RCP) 4.5 and RCP8.5 scenarios.



**Figure 2.** Spatial patterns of  $RI_{NPP}$  for 1.5 °C and 2 °C warming under RCP4.5 and RCP8.5 scenarios compared with the reference period. (a) 1.5 °C warming for RCP4.5; (b) 2 °C warming for RCP4.5; (c) 1.5 °C warming for RCP8.5; (d) 2 °C warming for RCP8.5. (The blank pixels in the figures mean no vegetation cover, i.e., bare ground, water, urban areas, etc.).

### 3.2. Responses of NPP Increment to Additional 0.5 °C of Global Warming

The additional 0.5 °C of global warming depresses the increase rate of NPP under the RCP4.5 and stimulates the increase of NPP under the RCP8.5 scenario (Figure 3). Although NPP increases in most areas for both 1.5 °C and 2 °C warming (Figure 3), the linear slope of NPP slows down in a 2 °C warming period under the RCP4.5 scenario on a national scale (Figure 1). At the national scale, more than 81% of areas would experience the declined increase rate of NPP with the additional 0.5 °C warming under the RCP4.5 scenario (Figure 3a). Only in some areas of Qinghai-Tibet Plateau, central China, northeastern and northwestern China was NPP was projected to have a higher linear growth rate even with the global temperature rising to 2 °C. On the contrary, the linear growth rate of NPP would still keep increasing in more than 66% of China's areas at 2 °C warming under the RCP8.5 scenario (Figure 3b). Especially, south of southern China and northwest of northern China even have a substantially higher increase rate of NPP at 2 °C warming compared with that at 1.5 °C.

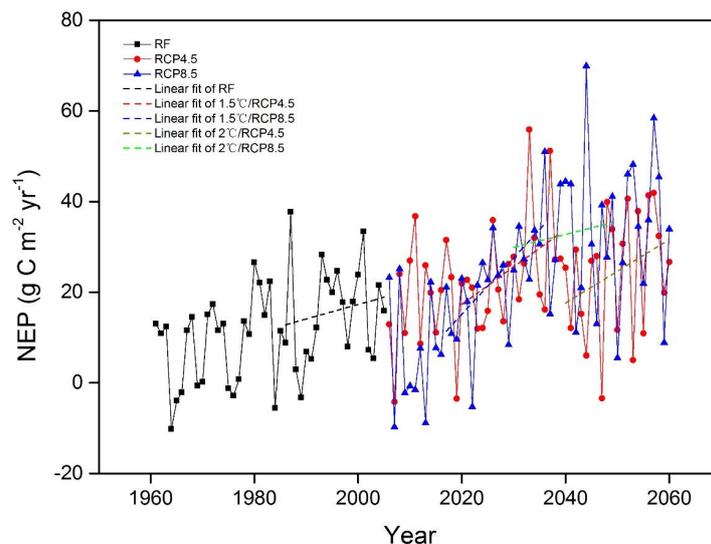


**Figure 3.** Spatial variation of the linear slope of NPP changing in 1.5 °C and 2 °C warming period under RCP4.5 (a) and RCP8.5 (b) scenarios.

### 3.3. Responses of NEP to 1.5 °C and 2 °C Warming

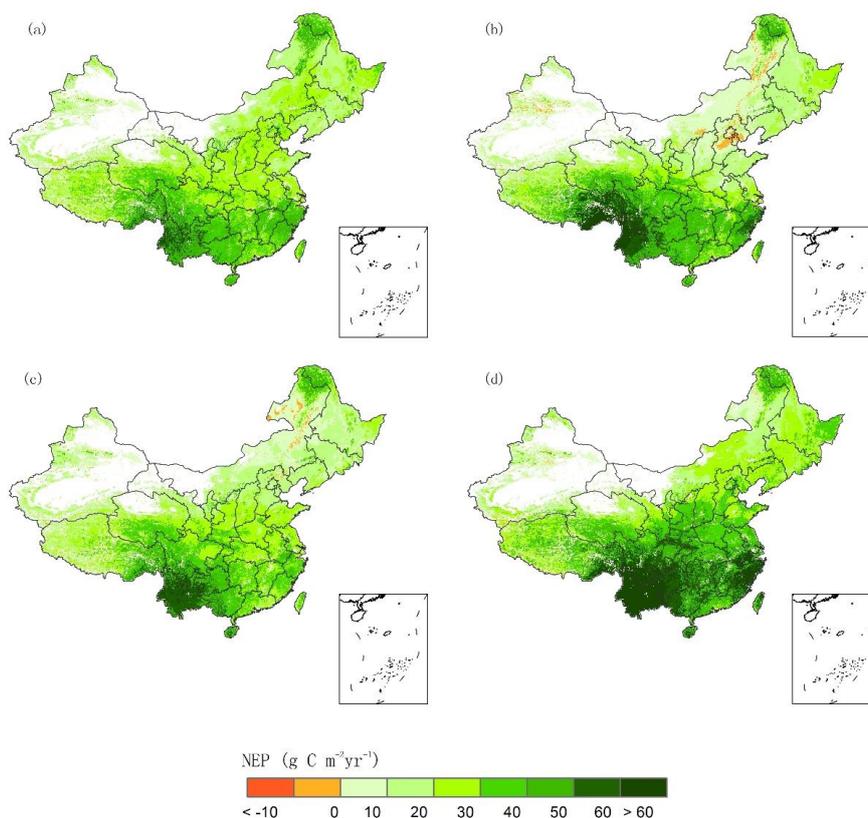
At the national scale, the mean annual NEP was estimated at approximately  $15.9 \pm 10.8 \text{ g C m}^{-2} \text{ yr}^{-1}$  in the reference period, and was projected to increase to  $25.2 \pm 11.7 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $23.3 \pm 11.8 \text{ g C m}^{-2} \text{ yr}^{-1}$  for 1.5 °C,  $24.3 \pm 13.8 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $32.6 \pm 14.1 \text{ g C m}^{-2} \text{ yr}^{-1}$  for 2 °C under the different RCP scenarios, respectively. The total NEP was projected to be increased by 53% at 1.5 °C warming, and by 79% at 2 °C warming (averages of the two scenarios) compared with that in the reference period. NEP was projected to increase approximately by 28% with the additional 0.5 °C warming, which suggests that the terrestrial ecosystems in China were projected to be an increasing carbon sink with the enhanced warming target, and warming together with the elevated CO<sub>2</sub> concentration would promote the net carbon uptake.

However, the total NEP shows a declined growth rate with the additional 0.5 °C under the two scenarios. For the RCP4.5 scenario, both linear trend and mean value of NEP show a slight decrease in 2 °C period compared with those in 1.5 °C period. The linear slope of NEP depresses rapidly at 2 °C warming under the RCP8.5 scenario though the mean value is higher than that at 1.5 °C (Figure 4). During the 2 °C warming period, NEP shows enhanced fluctuations but a declining growth, especially under the RCP8.5 scenario.



**Figure 4.** Linear fitting of annual NEP during the period of the 1.5 °C and 2 °C global warming for different RCP scenarios.

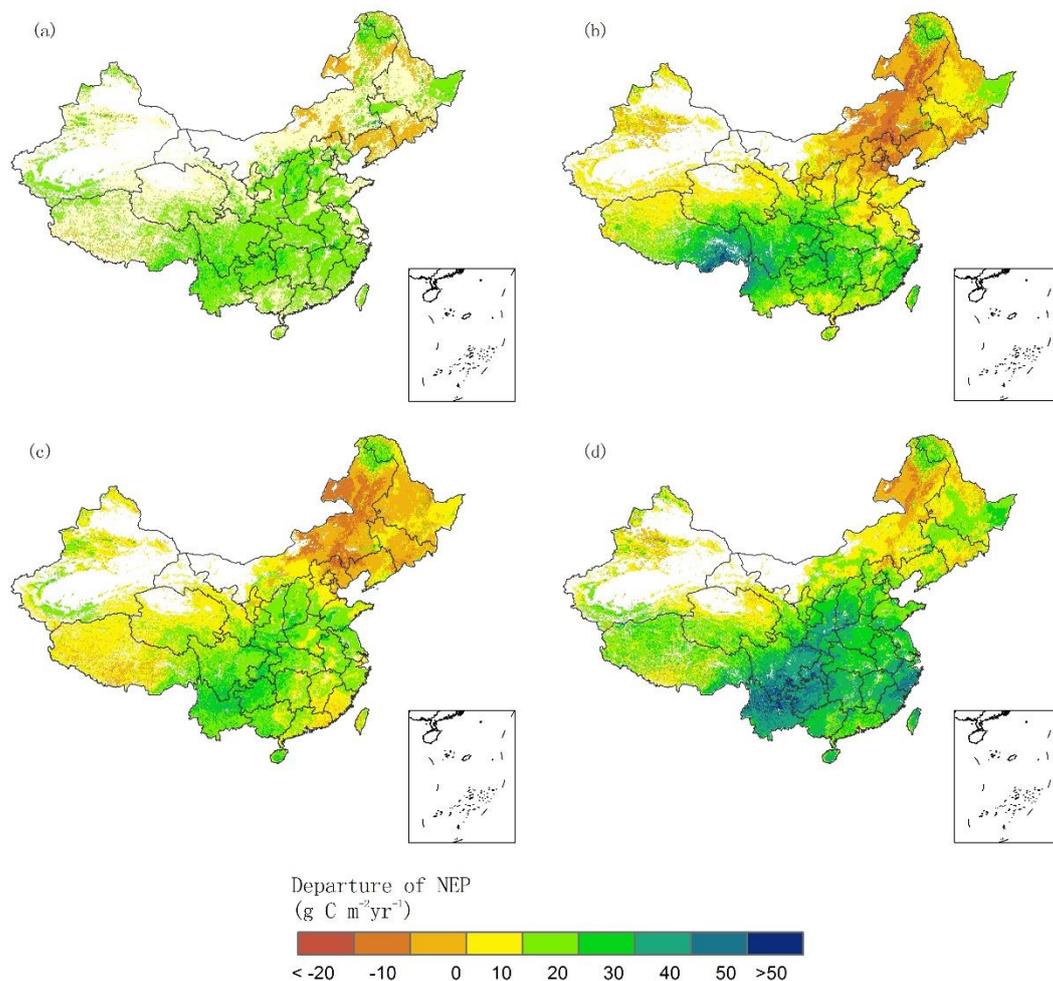
The projections suggest that most Chinese terrestrial ecosystems will act as carbon sinks, and the southern China and mountain areas of northeastern China have the highest NEP (Figure 5). Also, NEP was projected to be higher for the RCP8.5 scenario and at 2 °C warming.



**Figure 5.** Spatial variations of annual NEP in China averaged over 1.5 °C and 2 °C global warming periods under RCP4.5 and RCP8.5 scenarios. (a)  $NEP1_{RCP45}$ ; (b)  $NEP2_{RCP45}$ ; (c)  $NEP1_{RCP85}$ ; (d)  $NEP2_{RCP85_{subst}}$ .

Spatially, the responses of NEP to warming are different from that of NPP substantially. Although Chinese terrestrial ecosystems were estimated to act as carbon sinks overall and NEP was simulated to

increase continually during 1961–2099 under two scenarios, some areas, especially in northeastern China, would experience a decline of carbon uptake capacity. Under the RCP4.5 scenario, the NEP increases in most China's areas at 1.5 °C, especially in the central, southwestern China and mountain areas of northeastern China (Figure 6a). However, the response of NEP to a further 0.5 °C warming has large spatial discrepancies. Warming promotes the increase of NEP further in the regions where NEP increases at 1.5 °C. In contrast, warming accelerates the decrease of NEP in the regions where NEP decreased originally (Figure 6b). Under the RCP8.5 scenario, the response of NEP to 1.5 °C warming would be similar to 2 °C warming under the RCP4.5 scenario. The increase of NEP would occur in central and southwestern China, and northeastern China would experience high decreases in NEP (Figure 6c). However, the additional 0.5 °C warming would induce further increases in NEP over most parts of China, and areas with decreasing NEP would decrease (Figure 6d).



**Figure 6.** Departure of annual NEP at 1.5 °C and the 2 °C warming from values during the reference period under different scenarios. (a) 1.5 °C warming under RCP4.5; (b) 2 °C warming under RCP4.5; (c) 1.5 °C warming under RCP8.5; (d) 2 °C warming under RCP8.5. Positive values represent NEP increase, and vice versa.

#### 4. Conclusions and Discussions

Because of the climatic variability, ecosystem diversity, and topographic complexity, China has large regional discrepancies in response to climate change [31]. It is necessary for the determination of the global warming target to make clear the response of Chinese terrestrial ecosystems to different global warming targets and its regional variations in the future. Our study focused on the potential impacts of 1.5 °C and 2 °C increases in global warming on NPP and NEP of terrestrial ecosystems in

China by using an ensemble of the simulations of four ESMs in CMIP5 and a process-based ecosystem model (CEVSA2 model) under two representative concentration pathways. The main conclusions and discussions are as follows.

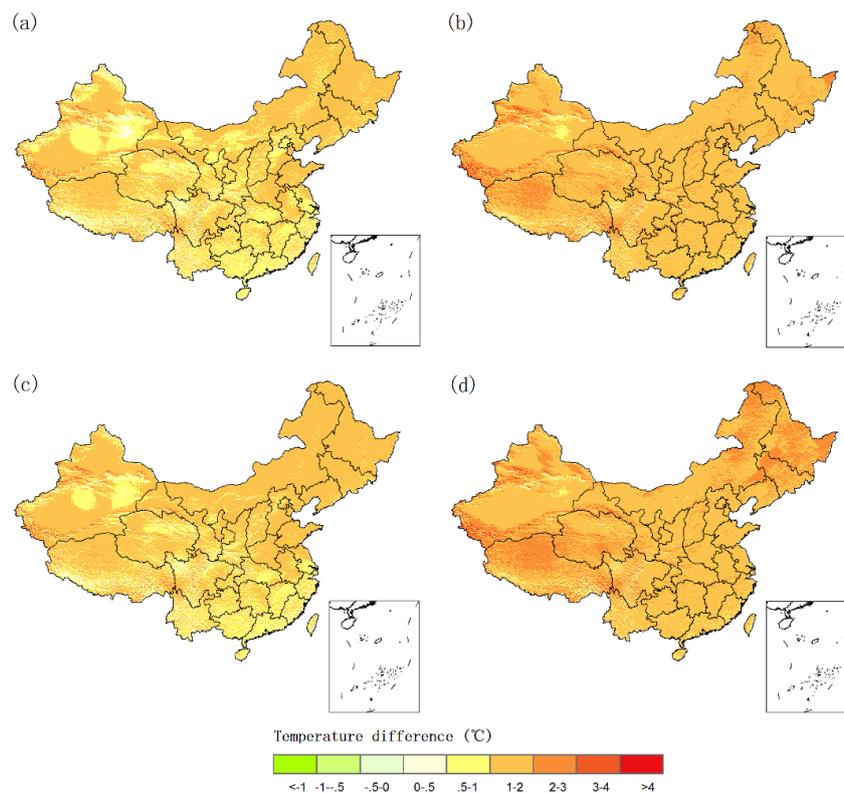
#### *4.1. NPP and NEP in China are Projected to Increase Both at 1.5 °C and 2 °C Global Warming*

Continuous warming was projected to increase both NPP and NEP of terrestrial ecosystems in China at 1.5 °C or 2 °C global warming. Both NPP and NEP were projected to have significant increasing trends ( $p < 0.01$ ). The increment of NPP would be approximately 13% at 1.5 °C and 19% at 2 °C warming. Terrestrial NPP in China is very likely to increase with global warming, and it is projected to increase continuously both at 1.5 °C and 2 °C global warming. This result is consistent with most previous modeling studies of climate change impacts on China's terrestrial ecosystem NPP [8,46,47]. At the global scale, the gross primary productivity (GPP) and NPP were projected to increase or remain unchanged, especially in mid- to high-latitudes [9,10,48]. Overall, the change of NPP would depend on the regions and vegetation types [49]. Other analyses based on CMIP5 models also found that the terrestrial ecosystem NPP would increase globally, and the spatial increment of annual NPP in China is similar to our study [50].

#### *4.2. Additional 0.5 °C Warming Will Depress the Increase Rate of NPP and Carbon Uptake Capacity under the RCP4.5 Scenario*

The model simulations suggest that the increasing rate of NPP would decline at 2 °C compared with that at 1.5 °C under RCP4.5. Both the increasing rates and mean values of NEP would decline under a lower emission scenario, but the increasing rates would decline more significantly under high emission scenarios. About 81% of study areas show a declined increase rate of NPP at 2 °C compared with that at 1.5 °C under the RCP4.5 scenario. Although most areas of China act as carbon sinks in the future under both scenarios, some areas of northern China and Qinghai-Tibet Plateau would show a decline of net carbon uptake. This suggests that continuous global warming under a lower emission scenario should not only influence the increase of NPP but also depress the ecosystem capacity of carbon sequestration in some regions significantly. Rising temperature promotes the growth of plants as well as the respiration of plants and soils [51].

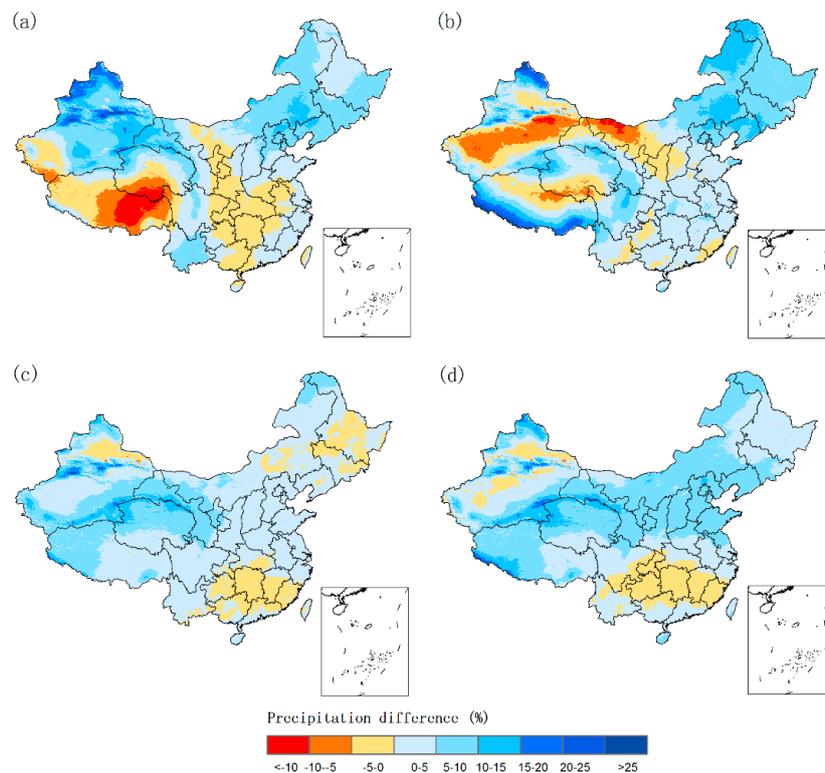
Although the warming trends were projected to be widespread in most parts of China, spatial patterns in precipitation would vary greatly (Figures 7 and 8). The increase of temperature was estimated to be the dominant factor accounting for NPP changes at national scale [20,30,52]. Relatively higher increases in temperature and precipitation would occur in northern China compared to southern China partially because northwestern China and Qinghai-Tibet Plateau have lower mean annual temperature, and higher sensitivity to the global warming [53]. Moreover, northwestern China also has a higher increase of precipitation in the future under the two scenarios. The increase of precipitation would alleviate water deficit on the plant growth over areas where vegetation is limited by water resources during historical periods in spite of counter-effects from climate warming [45]. This suggests that the increase of NPP will be closely associated with variations of temperature and precipitation. However, rising temperature promotes the growth of plants as well as the respiration of plants and soils [51]. Respiration generally tends to be more sensitive to warmer and drier condition than photosynthesis [54,55], so that enhanced respiration would induce the decrease of net carbon uptake capacity in this areas. However, the integrated response of the terrestrial ecosystems to global change also depends on other factors, such as moisture supply status, vegetation types, and climate zones involved [56]. Therefore, how terrestrial ecosystems would respond to future climate change will be diverse in different regions, with interactive effects of multiply influencing factors on NPP and NEP under different climate scenarios [15,57].



**Figure 7.** Spatial pattern of changes in annual mean temperature at 1.5 °C and 2 °C global warming relative to the reference period 1986 to 2005 under RCP4.5 and RCP8.5 scenarios. (a) 1.5 °C warming under RCP4.5; (b) 2 °C warming under RCP4.5; (c) 1.5 °C warming under RCP8.5; (d) 2 °C warming under RCP8.5.

#### 4.3. The Increase of Carbon Sequestration Would Reach a Peak During the Late 2020s

Although NEP shows an increasing trend at both two warming targets, the abnormality of NEP displays more fluctuation in spatial and temporal patterns. Our results suggest that NEP has higher sensitivity and heterogeneity in response to climate change and other driven factors. Model results show obvious differences in impacts on NEP of Chinese terrestrial ecosystems between 1.5 °C and 2 °C warming targets. Most CMIP5 model simulations show that terrestrial ecosystems continue to uptake carbon under all scenarios [16]. However, increases of decomposition could offset or reverse the NEP increase, and the terrestrial ecosystem might become carbon sources [16,58]. Our estimations of NEP responding to global warming suggest a similar trend by Cao et al. [31] and Turner et al. [59]. Some previous studies illustrated various changing trends of NEP under different scenarios with and without CO<sub>2</sub> fertilization. White et al. (2000) suggested that global NEP would reach a peak in the 2030s and then decline to zero by 2100 [60]. Ju et al. (2007) suggested that Chinese forest ecosystems would range from carbon sink to carbon source in the late 21<sup>st</sup> century under different scenarios with or without CO<sub>2</sub> fertilization [46]. However, our projections show that carbon sequestration would reach the peak during the late 2020s and then decline, which is consistent with the simulation of White et al. [60]. All of the differentiations illustrated great uncertainties in estimations of future NEP compared with NPP. More models and regional studies are needed to explore the responses of terrestrial ecosystems to climate change and global warming in the next steps [20].



**Figure 8.** Spatial pattern of changes in annual total precipitation at 1.5 °C and 2 °C global warming relative to the reference period 1986 to 2005 under RCP4.5 and RCP8.5 scenarios.

#### 4.4. Potential Impacts of Land Use and Land Cover Change on Carbon Sequestration of Terrestrial Ecosystems

Land Use and Land Cover (LULC) changes bring large uncertainties to risk analysis of future climate impacts on the terrestrial ecosystem. Human-induced land use change has a significant influence on carbon storage and fluxes in terrestrial ecosystems [61,62]. However, the estimation of carbon sequestration due to land use change still has large uncertainties [15]. Previous studies have controversial conclusions on the effects of land use change on China's terrestrial ecosystem productivities. Li et al. (2018) reported that land cover change has caused over 63% of total carbon losses in terrestrial ecosystems since the 1980s [63]. Some other studies evidenced that the increases in NPP due to climate change were not enough to offset the NPP losses due to LULC change [64,65]. However, the satellite data shows the earth is greening in recent 20 years, which is mostly attributed to the greenness of forests in China and intensive agriculture in India [66]. In addition, recommended agriculture management practices in China during recent 20 years, such as application of organic fertilizer, straw return, non-tillage, etc., enhanced soil carbon sequestration in cropland greatly [67], which would be expected to reduce the risk of carbon emissions of the terrestrial ecosystem.

It is important to consider the effects of human-induced land use changes into the projections of the future terrestrial ecosystem. However, only three out of the five models (BNU-ESM, MPI-ESM-LR and NorESM1-ME) coupled with the dynamic vegetation process, and all models did not consider the effects of human-induced land use change. Considering the importance of this issue, we analyzed China's current policies and their possible impacts on future ecosystems. Since the 1990s, China has launched a series of ecological projects, such as Grain for Green Program, Protection of Natural Forests, Building of Shelterbelts, etc., which have increased vegetation covers in many areas of China, especially in ecologically fragile areas [68], and all the efforts aim to increase  $4.0 \times 10^8$  ha forest areas in 2020. At present, China is promoting policies and actions to mitigate climate change by conducting more ecological projections, such as tree planting programs, intensive agriculture management, etc. These activities imply that future land use changes might have positive impacts on the terrestrial ecosystem

productivities and carbon sequestrations if China's government continues current policies. In this study, the result shows that a further 0.5 °C global warming will not bring more risks of warming on NPP and NEP of Chinese terrestrial ecosystems on the national scale. Therefore, we believe the land use change due to human activities would not influence this conclusion.

#### 4.5. Effect of CO<sub>2</sub> Fertilization

Our results show that NPP and NEP are higher under the RCP8.5 scenario than those under the RCP4.5 scenario, especially at the enhanced global warming target. It is more conducive to China's terrestrial ecosystem under a higher emission scenario with the additional 0.5 °C warming, which is probably due to the effects of CO<sub>2</sub> fertilization to some extent. Our results show obvious interaction between global warming and elevated CO<sub>2</sub> concentration. Other researches also had similar findings of the contribution of climate and CO<sub>2</sub> to ecosystem responses [69–71]. Ju et al. (2007) found that the fertilization effect of CO<sub>2</sub> might change the Chinese forest from a small carbon source to a small carbon sink, and the positive effect of CO<sub>2</sub> fertilization on NPP and NEP would offset the most negative effect of climate change [46]. IPCC AR5 also mentioned that the existing assessments might underestimate the fertilization effect of atmospheric CO<sub>2</sub> concentration [15]. We found that the response of China terrestrial ecosystems also shows a significant CO<sub>2</sub> effect, and it is a critical positive factor to simulate the increase in NPP and NEP with an additional 0.5 °C of global warming. Hence, we believe it is necessary to consider the effects of atmospheric CO<sub>2</sub> concentration in the study of the threshold of global warming of terrestrial ecosystems.

#### 4.6. The Risks of Sensitive or Vulnerable Region to Additional 0.5 °C Warming

Although 2 °C warming will not bring more risks of warming on NPP and NEP of Chinese terrestrial ecosystems on the national scale compared with that at 1.5 °C, we should also notice the decrease of NPP increase rate and carbon sequestration in some regions, especially in northern China. The tipping points of ecosystem security or food production in these regions may occur during the global warming process. IPCC AR5 mentioned that although regional scale or sub-regional scale ecosystem tipping points have not occurred in the recent past, they could occur soon in the future [15]. Furthermore, climate extremes would bring extra risks, which should be taken into consideration in assessing future carbon dynamics. The additional 0.5 °C increase in global mean temperature reveals the substantial differences for heat-related or precipitation-related extremes on both global and regional scales [72]. Northwestern China, northeastern China, and the Tibetan Plateau would be more sensitive to extreme climate events with the additional 0.5 °C [73]. On the other hand, the mean temperature of China increased significantly higher than the global mean [19]. So, under 2 °C global warming scenario, the mean temperature of China would be higher than the warming threshold, which is likely to bring a high risk of extremes in some regions. In this case, appropriate strategies should be taken to enhance climate resilience of terrestrial ecosystems and mitigate the potential risks of warming on productivity and carbon sequestration. Besides, extreme climate events, even under a lower emission scenario, should be considered for ensuring that ecosystems in sensitive areas can deal with the potential risks of 2 °C of global warming.

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