Response of terrestrial net primary production to climate change associated with the quadrupling CO\textsubscript{2} forcing in CMIP6 models

Jiawen Zhu\textsuperscript{1} | Xiaofei Gao\textsuperscript{1,2} | Xiaodong Zeng\textsuperscript{1,2,3}

\textsuperscript{1}International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
\textsuperscript{2}University of Chinese Academy of Sciences, Beijing, China
\textsuperscript{3}Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing, China

Correspondence
Jiawen Zhu, International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, 40 Huayanli, Chaoyang, Beijing 100029, China.
Email: zhujw@mail.iap.ac.cn

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Abstract
Terrestrial net primary production (NPP) has shown remarkable changes in response to increasing atmospheric CO\textsubscript{2} and associated climate change. Many studies have investigated and emphasized the CO\textsubscript{2} fertilization effects, while the climatic effects remain uncertain in magnitude and spatial pattern. This study investigates these climatic effects and underlying causes by using outputs of the simulation abruptly quadrupled CO\textsubscript{2} from 23 CMIP6 models. We find that tropical terrestrial NPP decreases but extratropical terrestrial NPP increases in response to the CO\textsubscript{2}-induced climate change. The decreased tropical terrestrial NPP is significantly correlated with the warmer and drier climate anomalies, while the increased extratropical terrestrial NPP is significantly correlated with the warmer and wetter climate anomalies. These results emphasize the climatic effects on terrestrial NPP and reveal the differences among different terrestrial ecosystems, which is favorable for a better understanding of the terrestrial carbon cycle and its coupling with climate.

KEYWORDS
climatic effects, CMIP6, CO\textsubscript{2} fertilization effects, terrestrial net primary production

1 | INTRODUCTION

During the industrial era, the atmospheric CO\textsubscript{2} concentration has been enhanced rapidly because of anthropogenic emissions (Friedlingstein et al., 2019). This enhancement led to remarkable changes in global climate and has also made marked impacts on the global carbon cycle (Schimel et al., 2015; Wang et al., 2014, 2018). Understanding and quantifying these impacts is a key subject of scientific research in the global climate and environment.

Terrestrial net primary production (NPP), the net carbon uptake by land plants, plays a significant role in regulating the global carbon cycle. Beer et al. (2010) estimated that global terrestrial gross primary production (GPP) is 123 ± 8 PgC year\textsuperscript{-1} during the period from 1998 to 2005. Given the ratio between NPP and GPP is 0.5, about 61.5 Pg carbon or 225 Pg CO\textsubscript{2} is fixed by land...
plants in each year during the period. Many previous studies have reported an increase in terrestrial NPP with rising atmospheric CO₂ concentration because of the CO₂ fertilization effects (Piao et al., 2013; Schimel et al., 2015; Smith et al., 2016). However, the climate change associated with the elevated CO₂ concentration also influences terrestrial NPP. The increasing temperature along with rising CO₂ can attenuate the CO₂ stimulation in photosynthesis by resulting in a condition with a higher vapor pressure deficit and by enhancing plant autotrophic respiration (Dusenge et al., 2019). Changes in water availability and radiative forcing resulted from elevated atmospheric CO₂ may also cause a reduction in vegetation photosynthesis (Zhu et al., 2017). Some studies suggest that nutrient availability, especially nitrogen and phosphorus, may constrain the degree of CO₂ fertilization effects (Du et al., 2020; Terrer et al., 2019). Taken together, these studies indicate that the response of terrestrial NPP to the rising atmospheric CO₂ concentration is a complex balance between CO₂ fertilization effects and associated climatic effects, and this balance remains uncertain in its magnitude and regional pattern (Field et al., 2007).

During the last several decades, coupled climate model has deserved many significant developments in the representation of the terrestrial carbon cycle and has been an important tool to investigate climate-carbon feedbacks (Arora et al., 2013, 2020). The models from different countries participate in the Coupled Model Intercomparison Project (CMIP), which designs many idealized CO₂ experiments (Eyring et al., 2016). One of the experiments is an abrupt quadrupling CO₂ simulation (abrupt-4 × CO₂) in which the atmospheric CO₂ concentration is abruptly four times as much as that in the pre-industrial experiment (piControl). The different values of CO₂ are the only difference between the two experiments, while all other conditions are the same as each other. By doing this, the objective of the experiment is to examine the fundamental climate feedbacks to CO₂ forcing (Eyring et al., 2016).

This study uses the outputs of the simulation abruptly quadrupled CO₂ from the sixth phase of CMIP (CMIP6) and focuses on an investigation of responses of terrestrial NPP to climate change associated with elevated CO₂. We show the changes of NPP in response to the climate change and focus on their relationship with surface air temperature and precipitation.

2 | DATASETS AND METHODS

This study used the abruptly quadrupled CO₂ (abrupt-4 × CO₂) simulation from CMIP6 (Eyring et al., 2016). We downloaded and applied monthly variables of the first 150 years of the simulation, including surface air temperature, precipitation, GPP, plant autotrophic respiration (Ra). Based on data availability, 23 CMIP6 models are selected (Table S1).

This study focuses on annual total NPP and its changes over land areas between latitudes 90°N and 60°S. Terrestrial NPP is derived from differences between GPP and Ra instead of downloading directly from CMIP6 because some models output unreasonable negative values of NPP. The derived NPP are all interpolated into the spatial resolution 64 × 128, the coarsest resolution among the 23 models. Partial correlation is employed to attribute changes in NPP to surface air temperature and precipitation, and the Student’s t-test is used to estimate the significant level.

3 | RESULTS

3.1 | CO₂-induced climate change

In response to the abruptly quadrupled CO₂, the land area shows an overall warm and wet trend (Figure 1).
Globally, the mean rate of the warming trend is 0.14 ± 0.07 K decade\(^{-1}\). The warming trends are seen over all land grids, with a larger magnitude over northern high latitudes (Figure 1a). Meanwhile, the global terrestrial annual mean precipitation shows regional differences in the trend. Wet trends are seen over most of the extratropical land grids, while dry trends mainly occurred over the tropical land grids (Figure 1b).

### 3.2 | NPP response to associated climate change

In abrupt-4 × CO\(_2\), the atmospheric CO\(_2\) concentration is kept constant in the whole simulation, but the climate change stimulated by the elevated CO\(_2\) becomes gradually strong. The changes in annual total terrestrial NPP along with modeling time are thought to partly reflect associated climatic effects. Figure 1c shows the spatial pattern of the NPP trend. It is clear that an overall negative trend is seen in tropical ecosystems (30°S–30°N) while extratropical ecosystems show a broadly positive trend.

The opposite responses of tropical and extratropical terrestrial NPP are seen for most of the 23 models (Figure S1). The differences can be more clearly shown by estimating average NPP differences between the last (NPP\(_{4CO2_L}\)) and the first (NPP\(_{4CO2_F}\)) 30 modeling years, the time spread that is enough to reflect their overall trend. As shown in Figure 2, tropical ensemble NPP\(_{4CO2_L}\) is 4.51 PgC year\(^{-1}\) smaller than ensemble NPP\(_{4CO2_F}\), and 20 of the 23 models reproduced this decreased trend with the largest magnitude of 18.13 PgC year\(^{-1}\) for MRI-ESM2-0. In contrast, extratropical ensemble NPP\(_{4CO2_L}\) is 1.76 PgC year\(^{-1}\) greater than ensemble NPP\(_{4CO2_F}\), and 17 of the 23 models reproduced this increased trend with the largest magnitude of 11.17 PgC year\(^{-1}\) for CanESM5.

### 3.3 | Linkage between changes in NPP and climate

The responses of NPP are tightly connected with the changes in surface air temperature and precipitation. The differences in tropical and extratropical NPP response shown in Figure 2 reflect the different roles of regional surface air temperature and precipitation in regulating terrestrial NPP. To address this regulation over the tropical and extratropical ecosystems, we further analyzed the relationships between NPP and surface air temperature, precipitation.

Over the tropics, NPP is overall significantly and negatively correlated with surface air temperature with a partial correlation coefficient of −0.98 (Figure 3a). The

![Figure 2](image1.png)

**Figure 2** Annual total net primary production differences (PgC year\(^{-1}\)) between the last and the first 30 modeling years in abrupt-4 × CO\(_2\) simulation for (a) tropical and (b) extratropical ecosystems.

![Figure 3](image2.png)

**Figure 3** Scatter plots of annual total net primary production (NPP) (PgC year\(^{-1}\)), surface air temperature (TAS; K), and precipitation (Pr; mm day\(^{-1}\)) over (a) tropical and (b) extratropical ecosystems. The solid dots and red lines represent relationships between NPP and surface air temperature, while the crossed dots and blue lines represent relationships between NPP and precipitation. The red and blue numbers represent their corresponding partial correlation coefficients, respectively, and the asterisks mean the numbers are statistical significance (\(p < 0.001\)). The colors of dots change from cool to warm ones with modeling time.
spatial pattern shows that this significantly negative correlation occurs over 77% of tropical land grids with larger partial correlation coefficients for rainforests (Figure 4a). In contrast, tropical NPP is overall significantly and positively correlated with precipitation with a partial correlation coefficient of 0.55 (Figure 3a), and this significantly positive correlation is seen over 66% of tropical land grids, mainly for arid and semi-arid ecosystems (Figure 4b). The trends show that tropical ecosystems experienced a warmer and drier climate anomaly with modeling time (Figure 1). Thus, the decreased tropical NPP shown in Figure 1 mainly resulted from the combined effects of tropical warmer and drier climate anomalies. Further analysis on trends in GPP and autotrophic respiration (Ra) reveals that the warmer and drier climate anomalies broadly lead to weaker plant photosynthesis and plant respiration over tropics, but the absolute magnitude of GPP trend is larger than that of Ra (Figure S2), reflecting the dominant role of GPP in regulating NPP.

Over extratropical ecosystems, NPP is overall significantly and positively correlated with surface air temperature and precipitation with partial correlation coefficients of 0.34 and 0.51, respectively (Figure 3b). The spatial pattern shows that the significant positive correlation between NPP and surface air temperature is mainly over high latitudes and Tibet Plateau where the temperature is a key limitation for plant photosynthesis (Figure 4a), while the water-limited ecosystems, arid and semi-arid regions over the middle latitudes, are mainly characterized with a significantly positive correlation between NPP and precipitation (Figure 2b). The trends show that extratropical ecosystems experienced a warmer and wetter anomaly with modeling time (Figure 1). Thus, the increased extratropical NPP shown in Figure 1 mainly resulted from the combined effects of extratropical warmer and wetter climate anomalies. Trends in GPP and Ra further reveal that the warmer and wetter climate anomalies broadly enhance plant photosynthesis and plant respiration over extra-tropics, with larger absolute magnitude of GPP than Ra (Figure S2), reflecting the dominant role of GPP in regulating NPP.

4 DISCUSSIONS

This work investigated the effects of CO2-induced climate changes on terrestrial NPP. Using the significant partial correlation coefficients, the work emphasizes the role of surface air temperature and precipitation. To make the results robust, we further calculated the partial correlation coefficients by using de-trended values of NPP, surface air temperature and precipitation. The partial correlation coefficients that based on de-trended values are consistent with ones that based on original values (Table S2), reflecting the significance of the results. Furthermore, quadrupling CO2 induces climate changes in many aspects other than surface air temperature and precipitation. The change in other variables (e.g., solar radiative) may produce uncertainties to our reports in relationships between NPP and temperature, precipitation. Thus, we further analyzed surface solar radiation. Since changes in CO2 mainly force changes in longwave radiation, the changes in surface solar radiation in abrupt-4×CO2 are less than 1.0% and 3.0% for tropics and extra-tropics, respectively (Figure S3). This slight anomaly in surface solar radiation is expected to result in much less effects on NPP than surface air temperature and precipitation.

The results are based on the abruptly quadrupled CO2 simulation. Although CO2 is fixed through the simulation, the CO2 fertilization effects shall have interactions with the CO2-induced climatic effects. CMIP6 has proposed 1% year−1 increasing CO2 experiment (1pcC02) with fully, radiatively and biogeochemically coupled runs to isolate the carbon-concentration feedback (β) and the carbon-climate feedback (γ). In fully coupled simulation,
the increasing CO₂ not only affects land and ocean carbon cycle but also changes atmospheric radiation. In radiatively or biogeochemically coupled simulation, the increasing CO₂ only affects atmospheric radiation or land and ocean carbon cycle, respectively. Using these 1pctCO₂ simulations, previous studies reported the tropical decreased land carbon uptake and the extratropical increased land carbon uptake as a result of the CO₂-induced climate changes, and emphasized the key role of warmer temperature (Arora et al., 2013, 2020; Friedlingstein et al., 2006). Our finding of the opposite responses of tropical and extratropical terrestrial NPP to the CO₂-induced climate changes is significant and consistent with previous reports, even though the analysis did not totally isolate the climatic effects from the CO₂ fertilization effects. Meanwhile, this work further investigates the role of precipitation and radiation on NPP anomalies and discusses the underlying mechanisms, not just the effects of temperature. The investigation of comprehensive effects of climate changes on land carbon cycle favors a better understanding of carbon-climate interactions.

Additionally, the responses of NPP to the CO₂-induced climatic changes are also influenced by different model structures and parameterizations. One important model difference is in a representation of nitrogen limitation. In response to elevated CO₂, models with carbon-nitrogen interactions show relatively weak NPP increase. Over extra-tropical ecosystems, the model ACCESS-ESM1-5 that being with nitrogen limitation on carbon cycle (Arora et al., 2020) simulated the smallest magnitude of NPP increase (−2.81 PgC year⁻¹), while the model CanESM5 that lacking nitrogen limitation show the largest magnitude of NPP increase (11.17 PgC year⁻¹) (Figure 2b). The other important model difference is in a representation of vegetation dynamic. The models with vegetation dynamic can simulate vegetation evolution, and their NPP responses to the associated climate changes are different with those of the models with fixed vegetation distribution. For example, MPI-ESM1-2-LR has a land component that can dynamically simulate vegetation cover. Both its tropical and extra-tropical mean NPP increase with modeling time (Figure 2), and its tropical ecosystems simulated the largest magnitude of NPP increase (7.69 PgC year⁻¹), while 17 of the other 22 models show the negative differences (Figure 2). The increase in tree cover of MPI-ESM1-2-LR is an important contributor to the overall positive NPP trend (Figure S4). Overall, these uncertainties point to the need to further make improvements on model structures and parameterizations, which is crucial for an accurate understanding of terrestrial carbon cycle and its interactions with climate change.

5 | SUMMARY
This study investigated the responses of terrestrial NPP to climate change associated with the abruptly quadrupled CO₂ by using simulated results from the 23 CMIP6 models. We found that tropical terrestrial ecosystems show a decrease in NPP but extratropical terrestrial ecosystems show an increase in NPP, in response to the associated climate change. The decreased tropical terrestrial NPP is significantly correlated with the warmer and drier climatic condition, while the increased extratropical NPP has a significant correlation with the warmer and wetter climate. Our results emphasize the climatic effects on terrestrial NPP and suggest the differences in the climatic effects among different terrestrial ecosystems, which is favorable for a better understanding of the terrestrial carbon cycle and its coupling with climate.

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AUTHOR CONTRIBUTIONS
Jiawen Zhu: Conceptualization; Formal Analysis; Investigation; Methodology; Writing - Original Draft Preparation; Writing - Review & Editing. Xiaofei Gao: Data Curation. Xiaodong Zeng: Funding Acquisition; Resources; Supervision; Validation.

DATA AVAILABILITY STATEMENT
All the model outputs used for this work can be downloaded from the PCMDI (Program for Climate Model Diagnosis & Intercomparison) website at https://esgf-node.llnl.gov/search/cmip6. The model names and their references can be found in Table S1 of the Supporting Information.

ORCID
Jiawen Zhu @ https://orcid.org/0000-0002-6174-7234

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**SUPPORTING INFORMATION**

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