RC2: 'Comment on bg-2023-140', Anonymous Referee #2, 30 Oct 2023

Dear Reviewer and Editor,

We would like to thank the reviewer for his interest in our study, and for the feedback provided. We appreciate these constructive and specific comments, which will help improve the quality of the manuscript. We have carefully inspected all reviewer comments. Below, you will find our responses to the comments (responses in blue). Please find the response to each comment below.

We hope that you will find the result satisfying.

Sincerely,

Tao Chen, Félicien Meunier, Marc Peaucelle, Guoping Tang, Ye Yuan, Hans Verbeeck

Review of "Elevated atmospheric CO_2 and vegetation structural changes contributed to GPP increase more than climate and forest cover changes in subtropical forests of China" by Chen et al.

The manuscript by Chen et al. investigates drivers of subtropical forest GPP trends in China using a process-based model that runs to provide causal attribution. The study concludes that the primary drivers of GPP change are the CO_2 fertilization effect and increased LAI. While the study conducts comprehensive model experiments and maintains a well-organized structure, it lacks a convincing theoretical framework for designing the experiments and conducting the analysis, which is essential for consideration in publication. Additionally, the manuscript requires careful revision for the English language and logical syntax. Please refer to my comments for further details.

Response: Thank you very much for your valuable and thoughtful comments and suggestions. Below we go through point-by-point our answers to the comments, and our responses are in blue. Moreover, we have also streamlined the results, figures and text as suggested. Additionally, we have carefully checked and improved the English writing in the revised manuscript.

General comments:

1. Introduction: In the second paragraph, several relevant drivers are listed, followed by the research question "the relative contributions of these factors…not clear" in the next paragraph. It does not adequately explain to the reader why these factors are crucial to GPP or provide mechanistic expectations. For instance, in Line 60, rather than stating the increased temperature "has also influenced the

forest carbon uptake", it would be beneficial to summarize the specific mechanisms and reasons behind this influence. Is the influence positive or negative? Some clarifications would be helpful.

Response: Thank you very much for the valuable suggestions. To make the possible mechanisms behind the GPP changes clearer, we have added the following sentences to the revised text.

"Previous studies showed that temperature is the major factor influencing GPP variations in the Yangtze River Basin located in southern China (Nie et al., 2023), as well as other southern parts of China (Ma et al., 2019). Li et al., (2022) highlighted that precipitation dominated the interannual changes in the GPP of forest ecosystems in Southwest China, while the GPP changes were more affected by solar radiation than by precipitation and temperature in humid region of China (Chen et al., 2021a). The changes in GPP in response to different climatic factors can be both positive and negative across different regions and periods. For example, properly increasing temperature can promote enzyme activity and CO_2 fixation (Siddik et al., 2019; Moore, et al., 2021). However, when the temperature increases exceed the optimal temperature, the activity of enzymes in plants will decrease, thereby affecting the photosynthesis rate and carbon sequestration. Additionally, climate warming could increase the vapor pressure deficit (VPD), leading to more drought stress on plants (Yuan et al., 2019). Generally, when atmospheric moisture is insufficient, plants tend to inhibit photosynthesis by reducing stomatal conductance, thereby significantly reducing GPP (Yuan et al., 2019; Grossiord et al., 2020). The vegetation productivity response to the precipitation variations shows large spatial heterogeneity (Camberlin et al., 2007), which largely depends on topographic attributes, vegetation types, and even soil texture."

References:

Nie, C., et al., 2023. The Spatio-Temporal Variations of GPP and Its Climatic Driving Factors in the Yangtze River Basin during 2000–2018. Forests, 14(9):1898.

Li, Y., et al., 2022. Interannual variations in GPP in forest ecosystems in Southwest China and regional differences in the climatic contributions. Ecological Informatics, 69: 101591.

Ma et al., 2019. Trends and controls of terrestrial gross primary productivity of China during 2000–2016. Environmental Research Letters, 14, 8.

Chen, S. et al., 2021a. Vegetation structural change and CO_2 fertilization more than offset gross primary production decline caused by reduced solar radiation in China. Agricultural and Forest Meteorology, 296: 108207.

Siddik, M.A., et al., 2019. Responses of indica rice yield and quality to extreme high and low temperatures during the reproductive period. European Journal of Agronomy, 106, 30-38.

Moore, C.E., et al., 2021. The effect of increasing temperature on crop photosynthesis: from enzymes to ecosystems. Journal of Experimental Botany, 72 (8), 2822-2844.

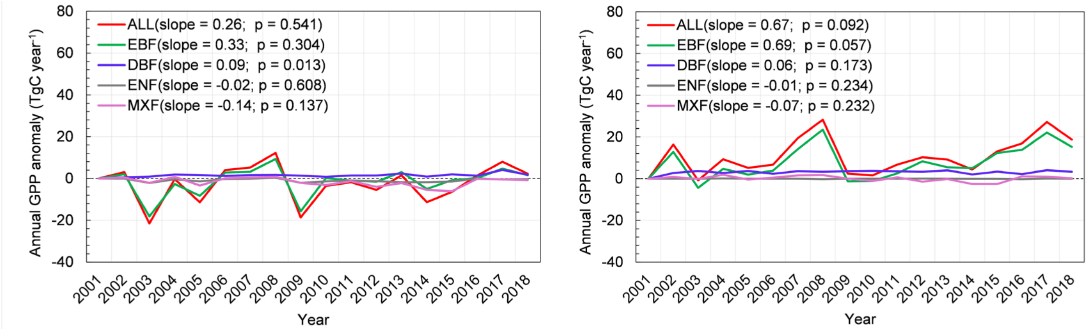
Yuan, W. P., et al., 2019. Increased atmospheric vapor pressure deficit reduces global vegetation growth. Science Advances, 5, eaax1396.

Grossiord, C., et al., 2020. Plant responses to rising vapor pressure deficit. New Phytologist, 226(6), 1550–1566.

Camberlin, P., et al., 20007. Determinants of the interannual relationships between remote sensed photosynthetic activity and rainfall in tropical Africa. Remote sensing of environment, 106, 199–216.

2. Experiment design: I have two main concerns concerning the experiment design in Table 1. A) When assessing the effect of climate variables on GPP, one of the climate variables (e.g., precipitation) is fixed as the value in 2001 in the forcing for the S2 scenario. As I understand it, that means in the S2 scenario there is no climatological cycle at all. The difference in GPP between S2 and the control run should include the effect of both the long-term trend and short-term variabilities of climate. This means, by design, the trend of GPP driven by climate is overshadowed by the shorter-term variabilities (Figure 6). However, when designing the CO_2 and LAI scenarios, the difference of CO_2 or LAI forcings are less variable (Figure S10, S11), thus a “clear” trend of GPP can be observed in both Figure 7 (a) and 8 (a). There is no surprise when the authors find that CO_2 and LAI are the most prominent drivers, when they are comparing the effect of “trend” (e.g., CO_2) and “trend + variabilities” (e.g., precipitation). One may need to test to which extent the way of prescribing climate forcings influences the conclusion, e.g., by removing the trend of climate variables but keeping variabilities. B) Is the GLASS LAI also sensitive to climate change and increasing CO_2? With an increased carbon uptake due to increasing CO_2, more carbon can be allocated to leaf growth. I wonder if the authors have some thoughts about the causal link when discussing the effect of LAI on GPP.

Response: Thank you very much for the comment and suggestion. As suggested, we used the mean of each climate variable, including the precipitation, temperature, and solar radiation rather than the initial (2001) value for the different variables to redo the simulation. Here, taking the precipitation as an example, we compared the simulated results based on the mean value of the precipitation over the study periods (see below right figure) with the simulations in the first year (2001) (see below left figure), and found that there are no significant differences between them. Although there are relative differences in the magnitude of the slopes (i.e., compared the present simulations with previous simulations) under the effect of precipitation changes on GPP, they are not significant and show a similar effect, suggesting that the effect of precipitation on changes in GPP in different forests is less influenced by trends. As shown in Fig. S9, our results also indicated that the annual variations of the climate variables have insignificant trends from 2001 to 2018. From Fig. 6 and Fig. S9, the results also suggested that the year 2001 was not an extreme year for any of those variables. Therefore, the initial year (2001) used in this study may be reasonable. The same experiment designs were also adopted in previous studies (Chen et al., 2021a; Sun et al., 2022). Overall, considering that there are no obvious trends in these climate variables and the low effects of these variables when compared to the CO_2 and LAI, whatever the experimental design it wouldn't change our findings.



For question B, we acknowledge that LAI may be affected by climatic factors and CO_2 fertilization. We added the following discussion to the revised manuscript as suggested.

Revised text to:

"Changes in LAI could be influenced by climatic factors and elevated atmospheric CO_2 concentration (Chen et al., 2019; Chen et al., 2021a; Sun et al., 2022). For example, previous studies reported that the elevated atmospheric CO_2 concentration was the dominant driver of global LAI increase, and there are regional differences in the impact mechanism of climate factors on LAI changes (Zhu et al., 2016; Zhu et al., 2017), thereby influencing the GPP dynamics. Moreover, the interactions between these driving factors can also influence the LAI, and even the interactive impacts of these factors on LAI may offset each other. For instance, rising in CO_2 concentration and solar radiation can affect temperature and VPD (Chen et al., 2021a). High VPD leads to plants to close their stomata, resulting in lower intercellular CO_2 concentrations in the leaves, which reduces the rate of photosynthesis (Yuan et al., 2019). Additionally, changes in LAI can feed back to the climate through biogeochemical and biogeophysical processes (Li et al., 2023). In short, there is a bidirectional interaction between vegetation and the atmosphere, and the relationship between vegetation dynamics and driving factors is complicated. The current methods used in this study cannot eliminate the complex interactions of the climate factors and elevated CO_2 concentration on LAI changes, which may bring some uncertainties to our results."

References:

Chen, S. et al., 2021a. Vegetation structural change and CO_2 fertilization more than offset gross primary production decline caused by reduced solar radiation in China. Agricultural and Forest Meteorology, 296: 108207.

Sun et al., 2022. Causes for the increases in both evapotranspiration and water yield over vegetated mainland China during the last two decades. Agricultural and Forest Meteorology, 324, 109118.

Chen, C., et al., 2019. China and India Lead in Greening of the World through Land-Use Management. Nature Sustainability, 2 (2), 122–129.

Zhu, et al., 2016. Greening of the Earth and Its Drivers. Nature Climate Change, 6 (8), 791–795.

Zhu et al., 2017. Attribution of seasonal leaf area index trends in the northern latitudes with “optimally” integrated ecosystem models. Global Change Biology, 23, 4798–4813.

Yuan, W. P., et al., 2019. Increased atmospheric vapor pressure deficit reduces global vegetation growth. Science Advances, 5, eaax1396.

Li, Y., et al., 2023. Biophysical impacts of earth greening can substantially mitigate regional land surface temperature warming. Nature Communications,14, 121.

3. Results: This study compares the contribution of different drivers to GPP in the unit of TgC/year (e.g., Figure 9). It is not introduced in the method section how the total GPP is calculated. If I assume GPP in TgC/year is the sum of GPP from all regions or the sum for each PFT, then it is highly related to the specific regions. Figure 1 shows the study region is mostly occupied by EBF and ENF, there is no wonder GPP is higher in TgC/year in EBF. In addition to that, the title indicates that CO_2 and LAI contribute more to GPP than forest cover changes. However, only very few regions are affected by forest cover change (Figure 5c), by contrast, all of the regions are under increasing CO_2 in the model experiment. It is unfair to compare the relative impact between these two drivers when looking at the total GPP. Or one has to make it clear in the beginning, that only total GPP in this specific region is considered.

   Response: Thanks. The total GPP (TgC/year) for the entire forest area or a specific forest area (e.g., EBF, ENF, etc.) was calculated based on the regional mean value of GPP (gC/m^2/year) multiplied by the total area (m^2) of a certain forest type (1TgC = 1×10^{12} gC). Then, the trends of the total GPP for different forests were computed from 2001 to 2018 based on the linear regression method, and the magnitude of the trends were used to measure the effect of different factors on GPP. For example, when we calculated the impact of factors such as LAI, climate change, and CO_2 concentration on the GPP of EBF, the area of EBF remained the same in the corresponding year. The same method was also used when calculating other forest types or the entire forest of the study area. Therefore, the results are only affected by the magnitude of the mean value of the EBF area, and thus the effects of different factors on the GPP of a given forest type are comparable. In the revised version, we also added the statement of the method for calculating the total GPP for a given forest as follows:

"In this study, the total GPP (TgC/year and $1TgC=1x10^{12}$ gC) was only applicable to a specific forest region, namely the entire subtropical forest region or the regions of EBF, DBF, ENF, and MXF, and it was calculated based on the regional mean of GPP ($gC/m^2/year$) multiplied by the total area (m^2) of a certain forest type."

4. Discussion: I like they discuss the model uncertainties. Most of the model discussion is about the input data, though it is important, the inherent model structure and underlying assumptions and how would these possibly affect the attribution is not so well discussed. For instance, it is not clear how the model simulates plants' response to CO_2. It would greatly enhance the understanding of the contribution results if the authors included more discussion on these elements.

Response: Thanks. As suggested, we added the following discussion about the BEPS model to the revised manuscript.

"In the BEPS model, the LAI is separated into two parts including the LAI of sunlit and shaded leaves, which are adopted to calculate the photosynthesis at leaf level (sunlit and shaded leaves) based on the FvCB photosynthesis model (Farquhar et al., 1980), and further compute the GPP at canopy level by adding the photosynthesis rates of sunlit and shaded leaves. Moreover, the Ball-Berry equation (Ball et al., 1987) was used in the model to calculate the stomatal conductance of sunlit and shaded leaves, which influenced the intercellular CO_2, the photosynthesis rate, and evapotranspiration (ET). Therefore, the LAI directly determined the allocation of energy and water availability and influenced the gross photosynthesis rate of the sunlit and shaded leaves. The accuracy of the LAI may impact its contribution to GPP variations through these processes. The atmospheric CO_2 concentration affects the intercellular CO_2 through the stomatal conductance, which, together with temperature and maximum carboxylation rate (V_{cmax}), determines the Rubisco-limited (A_c) and RuBP-limited (A_j) gross photosynthesis rate in the model. Over the past few decades, the CO_2 concentrations continuously increased and reached the current level of over 400 ppm. Elevated atmospheric CO_2 concentration can increase photosynthesis by accelerating the rate of carboxylation, thereby influencing the GPP changes. Additionally, solar radiation variability would directly influence the potential electron transport rate and thus regulate the RuBP-limited (A_j) gross photosynthesis rate. The temperature in the model directly impacts the V_{cmax} and the CO_2 compensation point without dark respiration (Γ), thereby determining the gross photosynthesis rate. Moreover, the temperature positively affects the V_{cmax} when it is below the optimal temperature. However, when the temperature exceeds the optimal temperature, V_{cmax} will not continue to increase with the temperature. Therefore, changes in temperature in the model may have a positive or negative impact on GPP."

References:

Farquhar, et al., 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C3 species. Planta 149, 78–90.

Ball, J.T., et., 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. J. Biggins (Ed.). Progress in Photosynthesis Research: Volume 4 Proceedings of the VIIth International Congress On Photosynthesis Providence, Rhode Island, USA, August 10–15, 1986. Springer Netherlands, Dordrecht, pp. 221–224.

Specific comments:

1. L16: If you only use LAI to represent vegetation structural change, it might not be necessary to mention "VSC" explicitly.

   Response: Thanks for the suggestion. Yes, LAI does not represent all vegetation structure changes. As suggested, we use LAI directly in the revised version instead of VSC.

2. L29: Please be consistent with abbreviations.

   Response: Thanks. As suggested, the LAI and FCC were adopted here to be consistent with the abbreviations mentioned above.

3. L30: What do you mean by “overlooked”?

   Response: We are sorry for the confusion. Here we are trying to emphasize the importance of LAI. For clear understanding, the “overlooked” was changed to “essential”.

4. L32: How might these findings inform climate change mitigation efforts or forest management strategies?

   Response: Thank you for the comment. GPP is a crucial indicator for estimating the carbon sequestration capacity of ecosystems (Chen et al., 2021b; Ma et al., 2019). Firstly, estimation of the GPP in the subtropical forests is important for people to understand how much carbon sequestration capacity it offers. For example, in this study, we have estimated the GPP of different forests, thus providing forest managers with basic data on the carbon sequestration potential of different Chinese subtropical forests. Secondly, we investigated the dynamics of GPP and their dominant driving factors in the study area. This information is crucial for decision-makers to adjust and optimize forest management policies promptly, so as to ensure that forests can provide the best ecological services for humans (Fang et al., 2010).

Additionally, China is still one of the world's top emitters of greenhouse gases that directly contribute to global warming (Chen al et., 2021). In September 2020, China announced the plan to achieve carbon neutrality by 2060 (Dong et al., 2021). This target closely aligns with the Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5 °C (SR15), which states that global CO_2 emissions must decline well before 2050 to curb the anticipated 1.5 °C global warming. Vegetation carbon uptake could significantly regulate the inter-annual variability of atmospheric CO_2 concentration and mitigate climate change. Developing forest carbon sinks is very important for China to achieve carbon neutrality. The Chinese government implemented several large-scale forestation programs since the 2000s, especially in the subtropical regions. Therefore, quantification of China's subtropical forest GPP and understanding of its driving mechanisms in this study can provide policy makers with a basic reference to answer the question: (1) How has the carbon sequestration potential of subtropical forests changed over the past decades? (2) Does the region have the potential to achieve carbon neutrality and mitigate climate change?

References:

Chen, Y. et al., 2021. Accelerated increase in vegetation carbon sequestration in China after 2010: A turning point resulting from climate and human interaction. Global Change Biology, 27(22), 5848-5864.

Ma, J., 2019. Trends and controls of terrestrial gross primary productivity of China during 2000–2016. Environmental Research Letters, 14, 084032.

Zhao et al., 2023. Toward the carbon neutrality: Forest carbon sinks and its spatial spillover effect in China. Ecological Economics, 209, 107837.

Dong, L., et al., 2021.China's carbon neutrality policy: objectives, impacts and paths. East Asian Policy, 13, 5-18.

Beer, C., et al., 2010. Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. Science, 329 (5993), 834–838.

Fang, J., et al, 2010. Why are East Asian ecosystems important for carbon cycle research? Science China Life Sciences, 53(7): 753–756.

5. L37: Carbon emissions?

Response: Sorry for the confusion. We have reworded the sentence as follows:

"Terrestrial ecosystems can capture carbon dioxide (CO_2) from the atmosphere through photosynthesis, which was regarded as a potential solution for slowing down the increase in global CO_2 concentration (Keenan et al., 2016) and mitigating global warming (Fang et al., 2018; Shevliakova et al., 2013)."

References:

Keenan, T.F., et al., 2016. Recent pause in the growth rate of atmospheric CO_2 due to enhanced terrestrial carbon uptake. Nature Communications, 7, 13428.

Fang, J., Yu, G., Liu, L., Hu, S. and Chapin, F.S., 2018. Climate change, human impacts, and carbon sequestration in China. Proceedings of the National Academy of Sciences, 115(16): 4015-4020.

Shevliakova E., et al., 2013. Historical warming reduced due to enhanced land carbon uptake. Proceedings of the National Academy of Sciences, 110,16730–16735.

6. L66-68: Which regions are they looking at? The major drivers on GPP vary a lot depending on regions and even seasons. Please be precise here.

   Response: Thanks. As suggested, we added the specific regions to the revised text as follows:

   "Previous studies showed that temperature is the major factor influencing GPP variations in the Yangtze River Basin located in southern China (Nie et al., 2023), as well as other southern parts of China (Ma et al., 2019). Li et al., (2022) highlighted that precipitation dominated the interannual changes in the GPP of forest ecosystem in Southwest China, while the GPP changes were more affected by solar radiation than by precipitation and temperature in humid region of China (Chen et al., 2021a). Therefore, the dominant factors affecting GPP vary a lot depending on regions and different time scales."

   References:

Nie, C., et al., 2023. The Spatio-Temporal Variations of GPP and Its Climatic Driving Factors in the Yangtze River Basin during 2000–2018. Forests, 14(9):1898.

Li, Y., et al., 2022. Interannual variations in GPP in forest ecosystems in Southwest China and regional differences in the climatic contributions. Ecological Informatics, 69: 101591.

Ma et al., 2019. Trends and controls of terrestrial gross primary productivity of China during 2000–2016. Environmental Research Letters, 14, 8.

Chen, S. et al., 2021a. Vegetation structural change and CO_2 fertilization more than offset gross primary production decline caused by reduced solar radiation in China. Agricultural and Forest Meteorology, 296: 108207.

7. L70-71: The term "CO_2 fertilization" has not been introduced. Do you mean the CO_2 fertilization effect is stronger in China than in other regions, or the CO_2 effect is stronger in forest ecosystems than in other ecosystems?

Response: Thank you. As suggested, we have added a brief introduction to CO_2 fertilization as follows.

"Elevated CO_2 concentrations may enhance the plant productivity, i.e., GPP, at the ecosystem scale (Wenzel et al 2016), which is known as the CO_2 fertilization effect."

Here, we mean that the southern region of China is more affected by the carbon dioxide fertilization effect than other regions of China. Revised text to:

"CO_2 fertilization was the pivotal driver for enhancing carbon sink in terrestrial vegetation, and the southern region of China also being more affected by the CO_2 effect than other regions of China (Chen et al., 2019b; Zhu et al., 2019b)."

References:

Wenzel, S., et al., 2016. Projected land photosynthesis constrained by changes in the seasonal cycle of atmospheric CO_2. Nature, 538, 499–501.

Chen et al., 2019b. Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink. Nature Communications, 10(1): 4259.

Zhu et al., 2016. Greening of the Earth and its drivers. Nature Climate Change, 6, 791–795.

8. L73-74: "…most of the current studies…", really? At least different PFTs are represented in land surface or earth system models.

   Response: We agree that different PFTs are represented in land surface or earth system models. Although some studies set different parameters based on PFTs during the simulation (e.g., simulating GPP), they often consider different forests (e.g., EBF, ENF, MXF, etc.) as a single forest type (i.e., forest) when analyzing the results, especially in large-scale research (Chen et al., 2021a). We apologize for the misleading description. We have changed the statement "most of the current studies" to "some of the current studies".

   References:

Chen, S. et al., 2021a. Vegetation structural change and CO_2 fertilization more than offset gross primary production decline caused by reduced solar radiation in China. Agricultural and Forest Meteorology, 296: 108207.

9. L86: How "better-performed" is BEPS? It seems unusual to encounter the conclusion without having reviewed the results, where the performance of the BEPS model has been tested.

   Response: Thanks. Yes, the BEPS model has been tested and validated at the regional and global scales. Considering the statement "better-performed" is not necessary, we have removed the confusing sentence from the revised text.

Revised text to: "Recently, the BEPS model has been widely used to simulate carbon fluxes at the regional and global scales (Chen et al., 2019b; Chen et al., 2012; Liu et al., 1997; Luo et al., 2019; Wang et al., 2021a), especially it has been well evaluated and validated in China (Feng et al., 2007; Liu et al., 2018; Peng et al., 2021; Wang et al., 2018)"

References:

Chen, J.M., 2019b. Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink. Nature Communications, 10(1): 4259.

Chen, J.M. et al., 2012. Effects of foliage clumping on the estimation of global terrestrial gross primary productivity. Global Biogeochemical Cycles, 26(1): GB1019.

Liu, J., et al., 1997. A process-based boreal ecosystem productivity simulator using remote sensing inputs. Remote Sensing of Environment, 62(2): 158-175.

Luo, X., et al., 2019. Improved estimates of global terrestrial photosynthesis using information on leaf chlorophyll content. Global Change Biology, 25(7): 2499-2514.

Wang, M., Wang, S., Zhao, J., Ju, W. and Hao, Z., 2021a. Global positive gross primary productivity extremes and climate contributions during 1982-2016. Science of the Total Environment, 774: 145703.

Feng, X. et al., 2007. Net primary productivity of China's terrestrial ecosystems from a process model driven by remote sensing. Journal of Environmental Management, 85(3): 563-573.

Liu, Y. et al., 2018. Satellite-derived LAI products exhibit large discrepancies and can lead to substantial uncertainty in simulated carbon and water fluxes. Remote Sensing of Environment, 206: 174-188.

Peng, J. et al., 2021. Incorporating water availability into autumn phenological model improved China's terrestrial gross primary productivity (GPP) simulation. Environmental Research Letters, 16(9): 094012.

Wang, M. et al., 2018. Detection of Positive Gross Primary Production Extremes in Terrestrial Ecosystems of China During 1982-2015 and Analysis of Climate Contribution. Journal of Geophysical Research: Biogeosciences, 123(9): 2807-2823.

10. L93: Do you mean different GPP products?

Response: Thanks for catching the error in the description. Here are the GPP of different forest types. We reworded the sentence as follows:

"to quantify the spatiotemporal trends in GPP of different forests across the subtropics."

11. L95-96: I find this statement not specific. Also, see my comment before.

    Response: To make it clearer, we have added the following sentences to the revised manuscript.

    "The results of this study can provide forest managers with basic data on the carbon sequestration potential of different Chinese subtropical forests. Moreover, investigating the dynamics of GPP and their dominant driving factors in the study area is crucial for decision-makers to adjust and optimize forest management policies promptly, so as to ensure that forests can provide the best ecological services for humans."

12. L139: What are "the other parameters"?

    Response: The other important parameters include the clumping index, maximum stomatal conductance, specific leaf area, respiration coefficient for leaf, stem, coarse root, and fine root, as well as the Q10 for leaf, stem, and root. We have added this information to the revised text. Revised text to:

    "The other important parameters, including the clumping index, maximum stomatal conductance, specific leaf area, respiration coefficient for leaf, stem, coarse root, and fine root, and Q10 for leaf, stem, and root, used in the BEPS model for each plant functional type can be found in Liu et al. (2018)"

    References:

    Liu, Y. et al., 2018. Satellite-derived LAI products exhibit large discrepancies and can lead to substantial uncertainty in simulated carbon and water fluxes. Remote Sensing of Environment, 206: 174-188.

13. L147-149: How is the "nighttime flux correction" done? Gap filling and flux partitioning are not data quality control.

    Response: According to the flux dataset processing standards developed by ChinaFLUX (Zhang et al.), the nighttime flux correction mainly includes removing outliers when there is precipitation, CO_2 concentration exceeds the instrument's measurement range, insufficient turbulence (e.g., u* <0.2 m/s), and less than 15,000 valid samples. We have added this information to the revised text. As suggested, we also removed the statement "gap filling and flux partitioning" from the revised text.

    References:

Zhang et al., 2019. Carbon and water fluxes observed by the Chinese Flux Observation and Research Network (2003–2005). China Scientific Data, 4(1), DOI: 10.11922/csdata.2018.0028.zh.

14. L150: Which u* is used for each site?

Response: Thanks. We have added the specific values of u* for each site, namely the threshold of u* < 0.2 m s^{-1} was used for the QYZ and ALS stations, while the threshold of u* < 0.05 m s^{-1} was used for DHS station.

15. L167: Vague statement. What does "robust enough" mean?

Response: We apologize for this error in the description. Revised text to:

"It has been shown that this can effectively reduce the uncertainty in the simulations of the BEPS model."

16. L195: You mean "original vegetation classes"?

Response: Yes, the "original classes" changed to "original vegetation classes".

17. L210-213: The sentence is not clear.

Response: Sorry for the inappropriate description. To avoid confusion, we have removed the statement from the revised text where there are unnecessary.

18. L244: "reasonably well" is not an accurate phrasing, notably considering that all R^2 values are below 0.5. Why is NEP only used for testing model performance? Why is NEP exclusively used for testing the model's performance? There seems to be a lack of additional results or discussion regarding NEP thereafter.

Response: Thank you very much for the comment. As suggested, we have removed the "reasonably" from the revised text. Yes, we also used the NEP for testing the model performance, because NEP (i.e., -NEE) is a direct measurement of carbon fluxes between the atmosphere and ecosystems, while the ecosystem GPP cannot be measured directly and is derived from the partitioning of NEE from flux measurements. Therefore, we not only used the observed GPP from the flux sites to validate our model, but also the NEP. We recognized that the validation of model performance based on measured NEP was relatively lower than that of GPP. One reason for this is that the simulation of NEP in the model is affected not only by the accuracy of simulated GPP, but also by the accuracy of simulated heterotrophic respiration (R_h) and autotrophic respiration (R_a). Therefore, a relatively poor performance of the simulated NEP was observed in this study.

However, the purpose of this is to disentangle how different drivers affect GPP changes in China's subtropical forests. Therefore, we mainly focus on the GPP in our study area. Our findings also showed that the validation of the simulated GPP at three flux sites performed well. We have added the explanations to the discussion section in the revised manuscript. Revised text to:

"In this study, we also used the NEP for testing the model performance, because NEP (i.e., -NEE (net ecosystem exchange)) is a direct measurement of carbon fluxes between the atmosphere and ecosystems, while the ecosystem GPP cannot be measured directly and is derived from the partitioning of NEE from flux measurements. Therefore, we not only used the observed GPP from the flux sites to validate our model, but also the NEP. The validation of model performance based on measured NEP was relatively lower than that of GPP. One cause is that the simulation of NEP in the model is influenced not only by the accuracy of simulated GPP, but also by the accuracy of simulated heterotrophic respiration (R_h) and autotrophic respiration (R_a). Therefore, a relatively poor performance of the simulated NEP was observed in this study."

19. What do the green lines and circles represent in Figure 2?

Response: Thanks. The green lines represent the simulated GPP, and the dark circles represent the observations. We added the description of the green lines and dark circles in the Figure caption (see below).

"Figure 2 Comparison of simulated GPP with measured GPP from three flux tower stations at daily (a-c) and annual (d-f) scales. The green lines and dark circles represent the simulated GPP and observed GPP, respectively."

20. L254-255: It is not clear how the spatial correlation is calculated.

Response: Thanks. Here the spatial correlation is calculated pixel by pixel at the annual scale. For example, we obtained the MODIS GPP from a certain pixel, and our simulated GPP was also derived from the same pixel during the same period. Then, the correlation between the two GPPs was computed. Similarly, we can calculate the correlation coefficients of different pixels to obtain their spatial distribution. We added the following description of the methodology for calculating spatial correlation to Section 2.5 of the revised manuscript. Revised text to:

"spatial correlation is calculated pixel by pixel at the annual scale. First, we should obtain two GPP time series for a certain pixel in the same period, and then calculate the correlation between the two GPPs. By analogy, the correlation coefficients of different pixels can be calculated to obtain the spatial distribution of the correlation coefficients."

21. L261-264: The number does not align within the range of all five GPP products as mentioned. Additionally, the reference to 'another BEPS' requires clarification. How to interpret the difference between "another BEPS" and "this BEPS" in Figure S7d?

Response: Thanks. We acknowledge that our simulated GPP is slightly higher than other products. Although our estimated GPP is slightly higher for the entire study area, our modeled GPP is very close to other GPP products for a specific forest type, such as the DBF and MXF (Fig. S8). In fact, other GPP products (e.g., MODIS GPP, EC-LUE GPP, NIRv GPP, and VPM GPP) also have large differences when they are compared with each other (Fig. S8). These results indicate that there are still significant differences in simulating GPP to date. The possible reasons are:

(1) there are some substantial differences in the simulated GPP from various ecosystem models due to many differences in model structure, parameterization, and driving data (Cai et al., 2014; Lin et al., 2023).
(2) our simulated GPP is compared with other GPP products mainly generated by the LUE model-based and remote sensing-based models. However, previous studies (Zhu et al., 2018; O'Sullivan et al., 2020; Wang et al., 2023) also reported that LUE-based models, remote sensing-based models, and machine-learning-based models may underestimate the GPP at an annual scale. For example, the GPP estimates by the LUE models mainly depend on a few important factors, including solar radiation, air temperature, water availability, and vegetation indexes (e.g., EVI or NDVI). Current LUE-based models do not completely integrate the other key environmental regulations to vegetation productivity, such as the effect of atmospheric CO_2 concentration, canopy structure (e.g., LAI), diffuse radiation, etc. on GPP.
(3) the underestimation in other GPP products is possibly due to failure to assess the CO_2 fertilizer effects, because almost no apparent response to the rising atmospheric CO_2 concentration in the LUE models leads to an underestimated trend (Anav et al., 2015). In our study, the GPP was estimated by a process-based model (i.e., BEPS) that considers the effects of these important factors on GPP, especially the CO_2 fertilization effect, which may lead to a higher GPP compared to all the other products.

For what it's worth, the results of our comparisons showed that the interannual trends of our simulated results were in line with other GPP products (Fig. S8). Despite possible overestimation, the purpose of this study mainly focuses on the trends and explains the driving mechanism behind them, thus it may not affect our results and conclusions.

We added the above discussion to the revised version. We also changed the statement "…, which falled in the range of the five GPP products… " to "…, which was closed to the magnitudes of the five GPP products… ".

In order to distinguish it from the GPP we simulated, the reference ($BEPS_g$ GPP) to 'another BEPS' has been added to Table S3. Actually, another BEPS GPP product was also produced by a similar BEPS model. However, this model is driven by the global datasets, and the parameters in the model are also calibrated for the GPP mapping. Therefore, it can be used for comparison with our simulated GPP.

References

Cai, W., et al., 2014. Large differences in terrestrial vegetation production derived from satellite-based light use efficiency models. Remote Sensing, 6(9), 8945–8965.

Lin et al., 2023. Underestimated Interannual Variability of Terrestrial Vegetation Production by Terrestrial Ecosystem Models. Global Biogeochemical Cycles, 34(4), e2023GB007696.

Zhu et al., 2018. Underestimates of Grassland Gross Primary Production in MODIS Standard Products. Remote Sensing, 2018, 10(11), 1771.

Wang et al., 2023. Assessment of Six Machine Learning Methods for Predicting Gross Primary Productivity in Grassland. Remote sensing, 15(14), 3475.

O'Sullivan, M., et al. 2020. Climate-driven variability and trends in plant productivity over recent decades based on three global products. Global Biogeochemical Cycles, 34(12), e2020GB006613.

Anav, A., et al., 2015. Spatiotemporal patterns of terrestrial gross primary production: a review. Reviews of Geophysics, 53(3), 785-818.

22. L268-269: Rather than a simple conclusion that BEPS-GPP aligns well with other GPP products, it would be more informative to delineate areas of agreement and disagreement between the models.

    Response: Thank you for the constructive suggestion. We added the following sentences to the revised text:

    "Overall, our simulated GPP is slightly higher for the entire study area than other products. For specific forest types such as DBF and MXF, our modeled GPP is very close to other GPP products, but has some differences compared to EBF and ENF (Fig. S8). Similarly, these commonly used GPP products also have large differences when compared to each other (Fig. S8). These results indicate that there is still a large discrepancy in modelling GPP to date, due to many differences in model structure, parameterization, and driving data."

23. L277: Please explain what is the "interactive effect".

    Response: Here the "interactive effect" represents the effect of different drivers together, namely, GPP is simultaneously influenced by different driving factors, such as changes in the climatic factors, vegetation status, etc. It is worth noting that these effects may be non-linear and cannot be simply added together.

24. L281: "…of the forest GPP", do you mean forest areas showed increased and decreased GPP?

Response: Yes, we mean that 90.4% of the forest areas in the study area exhibited an increasing trend in GPP, while 9.6% of the forest areas showed a decreasing trend in GPP. Sorry for the confusion. We have updated the sentence as follows:

"Spatially, 90.4% of forest areas in the study area showed an increasing trend in GPP, while 9.6% of forest areas exhibited a decreasing trend in GPP."

25. L297: What is "stable state"? No forest cover change? Or no significant effect of forest cover change?

    Response: Thanks for the comment. True, here the stable state indicates no forest cover change.

26. In Figure 5 (b), the time series of GPP in MXF seems to be very symmetric with GPP in ENF, any explanations for that?

    Response: Thanks. Such results are mainly due to the inter-annual variability of the area of each forest type and the conversion between them. This is because in this section we only investigated the effect of changes in the area of each forest type on the GPP.

27. L307: Is the increasing trend significant?

    Response: Thanks. As shown in Fig. S9, the trends in annual precipitation and temperature of the entire study area showed increasing trends, but are not significant. However, the trends in annual precipitation and temperature varied spatially (Fig. S9b and Fig. S9d), with some areas showing significant increasing trends.

28. L334: "…58.2% of the…", but quite a lot of white spaces are shown up on the map. How is the 58.2% derived? Are you referring to Fig. 6h in this statement?

    Response: Thank you for the comment. The 58.2% was computed as the ratio of the pixels with a decreasing trend to the total number of pixels in the study area. This statement refers to Fig. 6f. A lot of white spaces mainly arise from the results of masking non-forested areas. To avoid confusion, we have updated the color of the mask area in the revised manuscript.

29. In Figure 6a, most of the variabilities are from EBF, any explanations?

    Response: Thanks. As shown in Fig. S9b and Fig. 1, the predominant forest type in areas with significant variability in precipitation is EBF, especially in some parts of the West. However, precipitation is relatively stable in other forest regions (e.g., ENF, MXF, etc.). Therefore, changes in precipitation have a greater impact on EBF, leading to most of the variabilities being from EBF.

30. L381-383: Where does the conclusion "…EBF…has the highest carbon uptake potential" come from?

Response: We are sorry for the confusion. We also reworded the sentence as follows:

"Overall, the GPP of EBF in the subtropical region of China showed the fastest growth rate when compared with other forest types (Fig. 9b)."

31. L423-424: But in Table S6, the majority of the ENF has been observed to transition into MXF (19040 km^2).

    Response: Thank you for the comment. Yes, there were 19,040 km^2 of MXF was converted from ENF, however, this is a conversion between different forest types. The conversion between different forest types just leads to changes in the internal structure of the forests, such as increasing or decreasing LAI. Therefore, this conversion was also considered in this study. As shown in Table S6, when ENF converts to non-forests, the ENF mainly converts to cropland (13,100 km^2). We are sorry for the confusion. We have reworded the sentence as follows:

    "The total area of the ENF was lost obviously during the study period in eastern and southern regions, and the ENF was mainly converted to cropland (13,100 km^2) (Table S6), causing large parts of GPP to decrease."

32. L450: Could you explain how climate warming negatively influences GPP in your study?

    Response: Thanks. Our findings found that temperature induced the GPP decrease and mainly located in large parts of the eastern and the southwest (see Fig. 6d). In these areas, the temperature showed significant increasing trends (see Fig. S9d). The results indicated that increased temperature led to GPP reduction. Climate warming could increase the vapor pressure deficit (VPD), leading to more drought stress on plants (Yuan et al., 2019). Generally, when atmospheric moisture is insufficient, plants tend to inhibit photosynthesis by reducing stomatal conductance, thereby significantly reducing GPP (Yuan et al., 2019; Grossiord et al., 2020). Additionally, when the temperature increases exceed the optimal temperature, the activity of enzymes in plants will decrease, thereby affecting the photosynthesis rate and carbon sequestration. As suggested, we have added these discussions to the revised manuscript.

    References:

    Yuan, W. P., et al., 2019. Increased atmospheric vapor pressure deficit reduces global vegetation growth. Science Advances, 5, eaax1396.

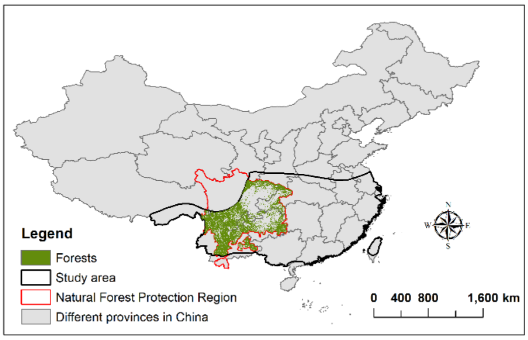
    Grossiord, C., et al., 2020. Plant responses to rising vapor pressure deficit. New Phytologist, 226(6), 1550–1566.

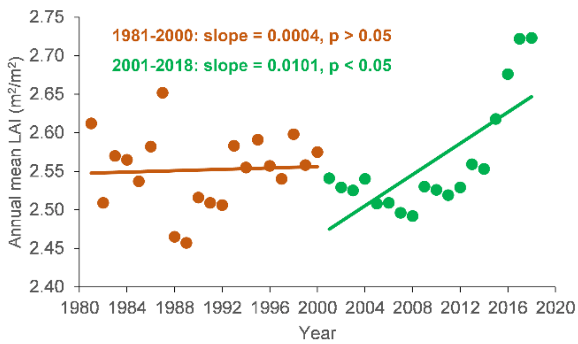
33. L460-462: Why do you observe different behaviors between EBF and ENF? Any hypothesis for that?

Response: Thanks for the comment. The cause of the observed different behaviors between EBF and ENF is that different forest types have different geographical distributions and are subject to different influences of climatic factors. As shown in Fig. 1, ENF is mainly distributed in the eastern and western regions of the subtropics. Our results showed that climatic factors (e.g., temperature, precipitation, and solar radiation) in these regions have negative effects on the GPP of ENF (Fig. 6), particularly the solar radiation declined significantly in the eastern region, which led to a decrease in the GPP of ENF in the east. For EBF, it is mainly distributed in the central and some western regions where climate change mainly contributes to the increase of GPP of EBF, especially the precipitation and temperature in the small area of the west (see Fig. 6h) contribute significantly to EBF GPP increase.

34. L486-L488: How much increase in LAI is related to the forest protection projects?

Response: Thanks for the comment. The Chinese Natural Forest Protection Project (NFPP) has been implemented around 2000 and completed by the end of 2020. Therefore, we first obtained the natural forest protection region in our study area (see below left figure) from the National Ecosystem Science Data Center (http://www.nesdc.org.cn/). Further, we calculated the annual average LAI for the region to compare the LAI changes over two phases (i.e., 1981-2000 and 2001-2018) (see right figure). Before 2000, the annual mean LAI showed a relatively stable state (slope = 0.0004 m^2/m^2/year, $p > 0.05$), and in the second phase (our study period), the annual mean LAI displayed a significant increasing trend (slope = 0.0101 m^2/m^2/year, $p < 0.05$), indicating that the implementation of NFPP may contribute to the increase in LAI.





35. L495: Chen et al. attribute drivers to GPP in gC/m2/year, which is not comparable with the GPP attribution in this study because of different regions and units as I mentioned in the general comments. The results in Zhan et al. stem from a land surface model instead of eddy covariance records.

Response: Thanks for the comment! As suggested, we first removed the reference of Chen et al.,2022a from the revised text. Besides, we also reworded the sentence in the revised version as follows:

"This was also confirmed by the results of a previous study using a terrestrial biosphere model (i.e., the QUINCY model) (Zhan et al., 2022)."

References:

Chen, C., 2022a. CO_2 fertilization of terrestrial photosynthesis inferred from site to global scales. Proceedings of the National Academy of Sciences, 119(10): e2115627119.

Zhan, C., et al., 2022. Emergence of the physiological effects of elevated CO_2 on land-atmosphere exchange of carbon and water. Global Change Biology, 28(24): 7313-7326.

36. L515-517: "…still in the early developing stage…" Could you specify the limitations of using this V_{cmax25} product? Is the limitation about the theory or data quality?

Response: Thanks. It is possible that the limitation may derive from the data quality and the key parameters in the model. Following your suggestion, we added the following sentences to the revised text to specify the limitations of using this V_{cmax25} product.

"The V_{cmax25} product was mainly generated by the MODIS surface reflectance, thus the data quality of the surface reflectance may cause the uncertainty in V_{cmax25} product. The uncertainties in MODIS reflectance datasets can arise from sensor calibration issues, cloud contamination, atmospheric correction errors, etc. Changes in the reflectance could result in large changes in the modelled chlorophyll values, thereby affecting the V_{cmax25} product. Additionally, the V_{cmax25} was produced by a semi-mechanistic model (Friend., 1995), and the key parameter K_{cat}^{25} in the model (the Rub turnover rate at 25 °C) would bring uncertainties in modeling V_{cmax25}, because current ground-based data are still rarely used for calibration of this parameter and validation of the V_{cmax25} products (Lu et al., 2022; Chen et al., 2022b)."

References:

Friend, A., 1995. PGEN: an integrated model of leaf photosynthesis, transpiration, and conductance Ecol. Modell. 77 233–55.

Lu, X., et al., 2022. Estimating photosynthetic capacity from optimized Rubisco–chlorophyll relationships among vegetation types and under global change. Environmental Research Letters, 17(1): 014028.

Chen, J.M. et al., 2022b. Global datasets of leaf photosynthetic capacity for ecological and earth system research. Earth System Science Data, 14(9): 4077-4093.

37. Kindly utilize diverging color schemes with the midpoint at 0 for clarity.

Response: Thanks for the suggestion. Yes, a diverging color scheme with the midpoint at 0 was adopted in this study. We also revised Fig. S9 using the diverging color scheme.

38. I suggest minimizing the use of abbreviations in the conclusion for better clarity. If necessary, they can be reintroduced.

    Response: Thank you for the suggestion. The full name of different abbreviations was added to the conclusion section of the revised manuscript, as suggested.

Technical corrections:

1. L164: “yearly” means “from year to year”.

   Response: We changed the “yearly” to “annual”.

2. L470: “increase” instead of “improve”.

   Response: Thanks again! The “increase” has been changed to “improve”.