Author's response to the Reviewers' comments

Please refer to the detailed itemized responses below. Our responses are indicated in blue text and the edits are highlighted in red text.

Reviewer #2

[Comment #1] In this study, Yao et al. used a well-established ecosystem model equipped with plant physiology, demography, and hydraulic processes to simulate the carbon sink response to CO2 fertilization in the Amazon rainforest. The results in the figure and texts are well presented, and the experiment simulations are reasonable. While I enjoy reading this work, I found that the paper needs to extract more clear messages especially in the Abstract and Conclusion. For example, what do we learn from this advanced improvement of the model process related to mortality and hydraulic resistance to droughts, and what does this imply for the carbon cycling in Amazonia? The message is not totally clear to me though detailed results have been reported.

Response #1:

There has been less emphasis on understanding carbon loss compared to productivity changes in response to rising CO_2, making it crucial to comprehend how carbon loss varies with changing environmental conditions. Our study distinguishes between carbon losses induced by competition and those induced by drought, as these two types of tree mortality respond differently to their respective drivers. The refinement of our model processes related to mortality and hydraulic resistance to drought will contribute to understanding how the carbon balance changes in response to eCO_2, including productivity enhancement as well as changes in carbon loss induced by tree mortality from two distinct schemes.

Following the reviewer's suggestions, we have carefully revised the abstract and conclusion part. Compared to the previous version, we highlight the implications of model advancement.

Abstract:

The Amazon rainforest plays a crucial role in global carbon storage, but a minor destabilization of these forests could result in considerable carbon loss. Among the external factors affecting vegetation, elevated CO_2 (eCO_2) levels have long been anticipated to have positive impacts on vegetation, including direct photosynthesis / productivity enhancement and increasing water use efficiency. However, the overall impact of eCO_2 on the net carbon balance, especially concerning tree mortality-induced carbon loss and recovery following extreme drought events, has remained elusive. Here, we use a process-based model that couples physiological CO_2 effects with demography and drought mortality / resistance processes. The model was previously calibrated to reproduce observed drought responses of Amazon forest sites. The model results, based on factorial simulations with and without eCO_2, reveal that eCO_2 enhances forest growth and promotes competition between trees, leading to more natural self-thinning of the forest stands, following a growth-mortality trade-off response although the growth outweighs the tree loss. Additionally, eCO_2 provides water-saving benefits, reducing the risk of tree mortality during drought episodes, although extra carbon losses still could occur due to eCO_2 induced increase in background biomass density, thus 'more carbon available to lose' when severe droughts happen. Furthermore, we found that eCO_2 accelerates the drought recovery and enhances drought resistance and resilience. By delving into the less-explored aspect of tree mortality response to eCO_2, the model improvements advance our understanding of how the carbon balance responds to eCO_2 particularly concerning competition-induced continuous carbon loss vs. drought-induced pulse carbon loss mechanisms. These findings provide valuable insights into the intricate ways in which rising CO_2 influences forest carbon dynamics and vulnerability, offering critical understanding of the Amazon rainforest's evolution amidst more frequent and intense extreme climate events.

Conclusion:

In summary, this work offers a comprehensive basin-scale quantitative assessment of how eCO_2 influences aboveground biomass carbon gain and carbon loss in a warming and increasingly water-stressed climate. We systematically disentangle the effect of eCO_2 in this complex ecosystem. Our findings not only underscore the role of eCO_2 in shaping the 'high gain high loss' pattern but also highlight its water saving benefits. Additionally, we identify an enhancement in drought resistance and resilience attributed to eCO_2, as it accelerates drought recovery. Our improved model, which separates tree mortality schemes into competition-driven and drought-driven mechanisms, offers a more comprehensive understanding of carbon fluxes in response to eCO_2, a perspective that cannot be solely attained through field experiments. With the likelihood of more frequent and intense drought events in the near future, these findings serve as a compelling impetus for further modeling and observational efforts aimed at deeper insights into the role of eCO_2 in predicting the forest biomass carbon budget and ecosystem vulnerability within the Amazon rainforest.

[Comment #2] My other minor comments are mainly about clarification issues. In Lines 145-150, since the carbon gain and loss time series are from Brienen et al. (2015), why do you say in the first paragraph of the results that the model simulates these two? How do you get carbon gain and carbon loss from the model output? What are the output variables?

Response #2:

In our model, we are able to simulate both carbon gain and carbon loss, where carbon gain refers to the woody NPP for trees cohorts with a diameter above 10 cm, following the standards established by inventory protocols. Carbon loss corresponds to the reduction in woody biomass for cohorts with a diameter above 10 cm. We conducted a comparison of the time series of carbon gain and loss between model simulations and inventory observations (for undisturbed plots). To enhance clarity, we have revised the methods section to provide a clearer description of the model outputs as follows.

As ORCHIDEE is a cohort-based model, we obtain woody carbon gain, woody carbon loss and biomass carbon pools for 20 cohorts, associated with increasing circumference / diameter classes from small trees to large trees. Carbon gain in our model refers to the woody NPP, specifically for cohorts with a diameter above 10 cm, aligning with inventory protocols. Carbon loss represents the amount of live biomass (with diameter >10 cm) that is transferred to the woody litter pool due to tree mortality, from continuous competition induced mortality (killing small trees) and drought induced pulse mortality events (killing large trees). Then we aggregate the grid-level carbon gain and carbon loss to the basin-level, following the approach used by Brienen et al (2015).

[Comment #3] The definitions of drought resistance and resilience are not entirely clear to me. The equations are clear, as in Equations (5) and (6). But what do these metrics imply for drought resistance and resilience? More explanations are needed.

Response #3:

We give more explanation on the meaning of these two metrics. Section 2.4 has been revised as follows.

> For each drought event, drought *resistance* is defined as the change in the net biomass carbon sink during the drought disturbance relative to the pre-drought state. A positive value indicates that drought conditions lead to an increase in the net carbon sink relative to non-stressed conditions, while negative values indicate a decrease in the net biomass carbon sink. A more negative value indicates higher vulnerability. Drought *resilience* refers to the ability of the net carbon sink to recover to the pre-drought state. It is computed as the difference in the net carbon sink between the post-drought period and the pre-drought state relative to the pre-drought period. Positive values indicate full recovery, where the net carbon sink after drought stress surpasses the pre-drought state, while negative values indicate incomplete recovery. A more negative ratio represents a more limited capacity for recovery. The calculation of drought resistance and resilience of net biomass carbon change followed the definitions proposed by Tao et al (2022). We also used the net biomass carbon balance 2 years before, and 2 years after a drought event to represent forest pre- and post-drought conditions, respectively (Tao et al., 2022).

[Comment #4] Overall, I think this work is very novel and represents our newest process understanding of the Amazonian carbon sink from CO2 forcing from the perspective of models. But the messages need to be clearer.

Response #4:

We have enhanced the clarity of our results in response to the comments. We believe we have effectively addressed their concerns.