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 #1

[Comment #1] The study uses a new version of the ORCHIDEE model to study elevated CO2 impact on forest growth and mortality in the Amazon in the past decades. The model was previously calibrated at several Amazon sites and was applied at regional scale with and without historical CO2 increase. The simulations with elevated CO2 can better reproduce the temporal trend of C gain and C loss estimated from long-term field plots. Comparison between the simulations with and without CO2 effects show that elevated CO2 increased both growth and mortality while the latter is caused by increased competition and elevated CO2 reduced drought-induced mortality. Further spatial analysis reveals that the CO2 effect is stronger in drier regions.

Overall, it is neat to use a model to separate the processes (CIM and DIM) over the Amazon. The manuscript is clear and well written. I feel the mortality response makes sense but I am not sure how much we should trust simulated growth responses to eCO2 as outlined below.

Response #1:

We thank the Reviewer for the time and effort to thoroughly evaluate our study and appreciate the Reviewer's constructive comments. We have added comparisons to existing studies on eCO_2 and expanded the discussion on the uncertainties associated with eCO_2. We believe we have effectively addressed the concerns raised by the Reviewer.

[Comment #2] I am concerned that models overestimated average carbon gain and carbon loss by ~30% or more (3.0-3.5 Mg/ha/yr vs observed 2-2.5 Mg/ha/yr, Fig.3) in simulation A2 but not in A1. To me, this means simulations with elevated CO2 greatly overestimated baseline growth (and thus mortality), suggesting the CO2 fertilization effect might be overestimated. It would be important to explain this difference in baseline values.

Response #2:

The overestimated baseline growth (and mortality) likely results from nutrient limitations that are not modeled or other model structural errors. In particular, uncertainties in carbon allocation may contribute to differences in baseline values compared to inventory. In the ORCHIDEE model, carbon allocation among biomass components follows the 'pipe model' theory, which determines the relationship between leaf area, sapwood area and fine root area (Sitch et al., 2003). However, the carbon allocation process is relatively unconstrained and requires further observation for benchmarking. Given that nutrient availability influences productivity and carbon allocation adjustments, a nutrient-enabled version of the model would help better elucidate ecosystem responses to eCO_2.

The explanation on the possible overestimation of baseline growth rates can be found in lines 431-436 in the clean version.

> In addition to the absence of downregulation due to nutrient availability, uncertainties in carbon allocation could also contribute to differences in baseline values compared

to inventory data. In the ORCHIDEE model, carbon allocation among biomass components adheres to the 'pipe model' theory, which dictates the relationship between leaf area, sapwood area and fine root area (Sitch et al., 2003). However, the carbon allocation process remains relatively unconstrained and requires further observation data for benchmarking purposes. Given that nutrient availability influences productivity and adjustments in carbon allocation, a nutrient-enabled version of the model would help elucidate ecosystem responses to eCO_2. Therefore, estimating the strength and persistence of the CO_2 fertilization effect under future climate scenarios remains challenging (Nolte et al., 2023). Additional observations are imperative, and the AmazonFACE project will be a robust observational constraint on our knowledge of the rainforest's response to eCO_2 (Lapola and Norby, 2014).

[Comment #3] In addition, the positive trend of carbon gains in observation is mainly due to increase from 1980s to early 1990s. I believe the trend is much weaker after 1990s and in the same Hubau et al. study, there was not growth trend in Africa, suggesting CO2 fertilization effect on growth is quite uncertain. For instance, van der Sleen et al. 2014 reported no growth simulation by CO2 from tropical tree rings. More recently, Jiang et al. 2020 reported eCO2 increased GPP but not woody NPP in an Eucalyptus woodland. Such allocation changes are briefly mentioned in Discussion (line 415 - 425) while I think it should be highlighted as one of the major limitation/uncertainty of the study. For example, how would your conclusion change if the CO2 effect on growth is overestimated by 50% - 100%?

Response #3:

In Hubau et al (2020), the observed positive trend of carbon gains is indeed higher in the earlier period of inventory (before 1993: 0.029 MgC ha^{-1} yr^{-1}) compared to the later stage (after 1993: 0.009 MgC ha^{-1} yr^{-1}), although the relatively smaller number of monitored plots in the earlier period may also contribute to this difference. We acknowledge that the eCO_2 fertilization effect remains subject to large uncertainties. Particularly, the impact of eCO_2 on woody NPP is influenced by both nutrient limitation and carbon allocation strategies.

For growth response to eCO_2, we summarized existing studies on the eCO_2 effects below (Table R1), including process-based model approaches, analytical solutions and ecological optimality theory. In our simulations, the effect of eCO_2 on carbon gains (AGB gains before mortality) is estimated to be approximately 5% per decade. The increasing trend in carbon gains derived from inventory data is calculated to be 0.014 MgC ha^{-1} yr^{-1}, which equates to an increase of almost 6.2% per decade. This trend reflects contributions from various factors, including the effects of eCO_2, climate change, nutrient limitation and other factors. Disturbance recovery is probably not important for the plot data as they are undisturbed forests. Therefore, if negative climate effects are assumed, the 'intrinsic' eCO_2 effect should be slightly higher than the 6.2% value derived from inventory data. Hence, our model estimate of 5% per decade, falling within the upper range of the existing trend distribution, is not unreasonable.

We made revisions in the Results to describe the comparison with other existing eCO_2 studies. Please see lines 214-217 in the clean version.

> Our model simulation thus implies that the CO_2 fertilization effect plays a dominant role in augmenting forest aboveground productivity (carbon gains) and to a lesser extent biomass loss rates from mortality. Our estimate falls within the upper range of trend distribution, which is consistent with existing studies on the effects of eCO_2, including those employing process-based models, analytical solutions and ecological optimality theory (Table S1).

We made revisions in the Discussion to highlight that the eCO_2 effects embedding in our model could be subject to overestimation given the non-explicit consideration of nutrient limitations and uncertainties associated with biomass carbon allocation (please see lines 431-436).

> The lack of downregulation on fertilization in the model could lead to an overestimation of eCO_2 effects. In addition to the absence of downregulation due to nutrient availability, uncertainties in carbon allocation could also contribute to differences in baseline values compared to inventory data. In the ORCHIDEE model, carbon allocation among biomass components adheres to the 'pipe model' theory, which dictates the relationship between leaf area, sapwood area and fine root area (Sitch et al., 2003). However, the carbon allocation process remains relatively unconstrained and requires further observation data for benchmarking purposes. Given that nutrient availability influences productivity and adjustments in carbon allocation, a nutrient-enabled version of the model would help elucidate ecosystem responses to eCO_2. Therefore, estimating the strength and persistence of the CO_2 fertilization effect under future climate scenarios remains challenging (Nolte et al., 2023). Additional observations are imperative, and the AmazonFACE project will be a robust observational constraint on our knowledge of the rainforest's response to eCO_2 (Lapola and Norby, 2014).

Table R1 Summary of eCO_2 fertilization effects.

Time period	Term	Magnitude	Method	Reference
1980-2019	AGB gain (DBH>10cm)	Amazon rainforest: 5% per decade	ORCHIDEE model with climate impacts on growth and mortality, CO_2, stand level demography	This study
2001-2016	GPP	Global 4.1% per decade EBF: 4.8% per decade	Analytical approach	Chen et al (2022)
2001-2016	GPP	EBF: 1.61-5.78% per decade	TRENDY models (S1)	Chen et al (2022)

1981-2020	GPP	Global: 3.4% per decade	Remote sensing + ecological optimality theory	Keenan et al (2023)
1982-2011	NPP	Tropical: 2.7% per decade	CMIP5	Kolby Smith et al (2016)
1980-2016	GPP	Tropical: 3.7% per decade	CABLE model	Haverd et al (2020)

[Comment #4] Finally, since AmazonFACE is mentioned, it would be interesting to provide results from some short-term (e.g. 5-10 years, single site) simulation results using similar magnitude of CO2 increase. This can serve as a priori estimate of AmazonFACE results (not necessarily correct).

Response #4

Thanks for your suggestions. We agree with the importance of having a prior estimate for such a FACE experiment. The AmazonFACE experiment is situated in the Amazon rainforest near Manaus, Brazil. We conducted a short-term simulation focusing on the Manaus site, where CO_2 will be artificially elevated by 200 ppm above ambient levels. The simulations were conducted for the period from 2010 to 2020, considering two scenarios: one forced by ambient CO_2 concentration and the other forced by elevated CO_2 concentration (ambient + 200 ppm).

The discussion section has been revised as follows (please see lines 439-445 in the clean version).

> Additional observations are imperative, and the AmazonFACE project will be a robust observational constraint on our knowledge of the rainforest's response to eCO_2 (Lapola and Norby, 2014). We have also provided estimates of carbon gain and carbon loss in response to the planned CO_2 increase (i.e. 200 ppm above ambient levels) at this forest for the period from 2010 to 2020. Our simulations indicate an enhancement of ~34% in GPP and ~55% in woody NPP (DBH>10cm) throughout the simulation period. These values are higher compared to simulations conducted with nutrient cycle-enabled models as reported by Fleischer et al (2019). Obtaining more experimental data to illustrate the interactions between water and nutrient availability and their impacts on the CO_2 fertilization effect would aid in constraining model responses, thus enabling more accurate predictions of the Amazon rainforest's response to future climate change.

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:
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> 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.
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> Conclusion:
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> 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. Please see lines 145-151 in the clean version.

> 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. Please see lines 183-190 in the clean version.

> 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.

References

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