nature portfolio

Peer Review File

Synthesis of the land carbon fluxes of the Amazon region between 2010 and 2020

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

Decision letter and referee reports: first round

8th Aug 23

Dear Dr Rosan,

We are sorry that the review process took much longer time than expected. Now your manuscript titled "Amazon forests a net carbon source during drought and under high rates of human-disturbance" has been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file or provide a list of the changes to the manuscript with your responses to the reviewers. We expect the revision to meet the following editorial thresholds:

1) Clearly communicate the new analyses and findings that are presented and their distinction from those already presented in the literature.
2) Further analyse and explore the impact of drought disturbances.
3) Provide a clear but brief overview of bottom-up and top-down techniques and other background information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Yongqiang Liu, PhD
Editorial Board Member
Communications Earth & Environment

Clare Davis, PhD

Senior Editor
Communications Earth & Environment

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If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The research entitle " Amazon forests a net carbon source during drought and under high rates of human-disturbance" by Rosan et al is a timely piece of work that can improve the understanding of the stresses and impacts currently facing the Amazon Forest. The authors have done considerable amount of work in creating an ensemble of models to tackle the problem of integrating multiple stressors. However, very limited information if presented on the key findings ie research on drought. Throughout the article, drought is treated as a single finding while the title emphasises that the research is mainly about drought. More background is needed on top down and bottom up methodologies. These have been introduced in the abstract without prior information and continued in the introduction without paving the way for the research. The article can be restructured so that a clear picture is given about drought, and human disturbances. I also recommend that a timeseries analysis of climate data be used to support the finds on droughts-shoudl this still remain the m ain focus of the research. Additionally, more effort is needed to improve the grammar and style of writing. This will definitely be an important piece of research!

Reviewer #2 (Remarks to the Author):

Review for "Amazon forest a net carbon source during drought and under high rates of human-disturbance" from Rosan et al.

The Amazon, renowned as the world's largest continuous tropical forest, holds immense significance in the global carbon cycle and is threatened by anthropogenic impact. In an extensive study, Rosan et al. undertook a comprehensive analysis of contemporary land carbon flux estimates in the Amazon, employing both bottom-up methodologies and top-down inversions. They include deforestation, forest degradation, and regrowth using regional and global spatially explicit bookkeeping models.
The bottom-up methodologies suggested a modest average carbon sink over the time span 2010-2020, while the top-down inversions pointed to a carbon source during 2010-2018. After factoring in the substantial individual uncertainties associated with these estimates, the differences between the two methodologies lost, however, statistical significance, underscoring the presence of considerable knowledge gaps that demand immediate attention to enhance accuracy.

Nevertheless, amidst the discord, both methodologies yielded a consensus on one critical aspect: the Amazon acted as a net carbon source during recent periods of climatic extremes. The southeastern Amazon, in particular, displayed consistent net carbon emissions throughout the study period (2010-2020).
Their findings underscore the escalating impact of human-induced disturbances, including deforestation and forest degradation due to wildfires, on the carbon balance of the Amazon. Furthermore, the carbon sequestration capacity of mature forests suffered a decline during drought conditions.

The paper reads very interesting and is well-written. Because of its large carbon pool and climate impact potential, the estimation of Amazon's carbon fluxes is very important and significant. I struggle however to separate the part of an own analysis of the authors or modeling exclusively performed for this paper and where just publicly available model results and datasets have been quoted. For example the net carbon sink of Amazon forests according to the used methods is certainly published somewhere but probably for individual methods and not a comprehensive analysis as done in this paper. Also e.g. in the Abstract, it is not entirely clear, which methods have been employed in the study. While it is a useful work to collect different results and methods, associated with the carbon balance in the Amazon rainforest, I would suggest to stronger highlight analysis and data creation exclusively for this paper, compared to results already published somewhere else.
To better depict this and have a better overview of the different methods, datasets, and models used, I would suggest a comprehensive conceptional figure. Such an overview would enhance the capability of the reader to easily follow the different approaches to analyze the carbon balance in the Amazon forest.

Furthermore, I have a few minor remarks:

The term old-growth forest is used extensively throughout the paper. Could the authors maybe give a clear definition in the paper? What exactly is understood as old in this context? I guess this is also related to the term primary forest.

P6 L10: Why does GFED only show fires from deforestation and degradation? To my knowledge, all different fires can be obtained in the GFED database.

P6 L24: Uncertainty in models is usually given by ensemble runs with either different models (e.g. in Trendy) or by changing parameters or conditions in the model. Therefore I would not write the sentence as it is and maybe highlight that the uncertainty here is the difference between the two models used.

It would be interesting to have a little bit more discussion about the spatial pattern of the carbon fluxes. Why, for example in Figure 2d, is an area in northwest Amazon a strong source, while almost all of the other area is a carbon sink?

Could the authors give an estimation of future Amazon carbon fluxes based on their results? Maybe they can detect a trend (or no trend) in the data?

Author responses: round 1

Message to reviewers from authors:
We would like to thank the reviewers for providing feedback on our manuscript. We have taken on board all comments, making the required adjustments in the text to improve the communication of our findings and techniques used. We also added a further figure in the supplementary material to show the relationship between drought events driven by El Niño in the Amazon and the old-growth carbon sink variation. Below we respond to each point raised by the reviewers, in blue.

Many thanks,
Thais Rosan on behalf of all co-authors.

REVIEWER COMMENTS:

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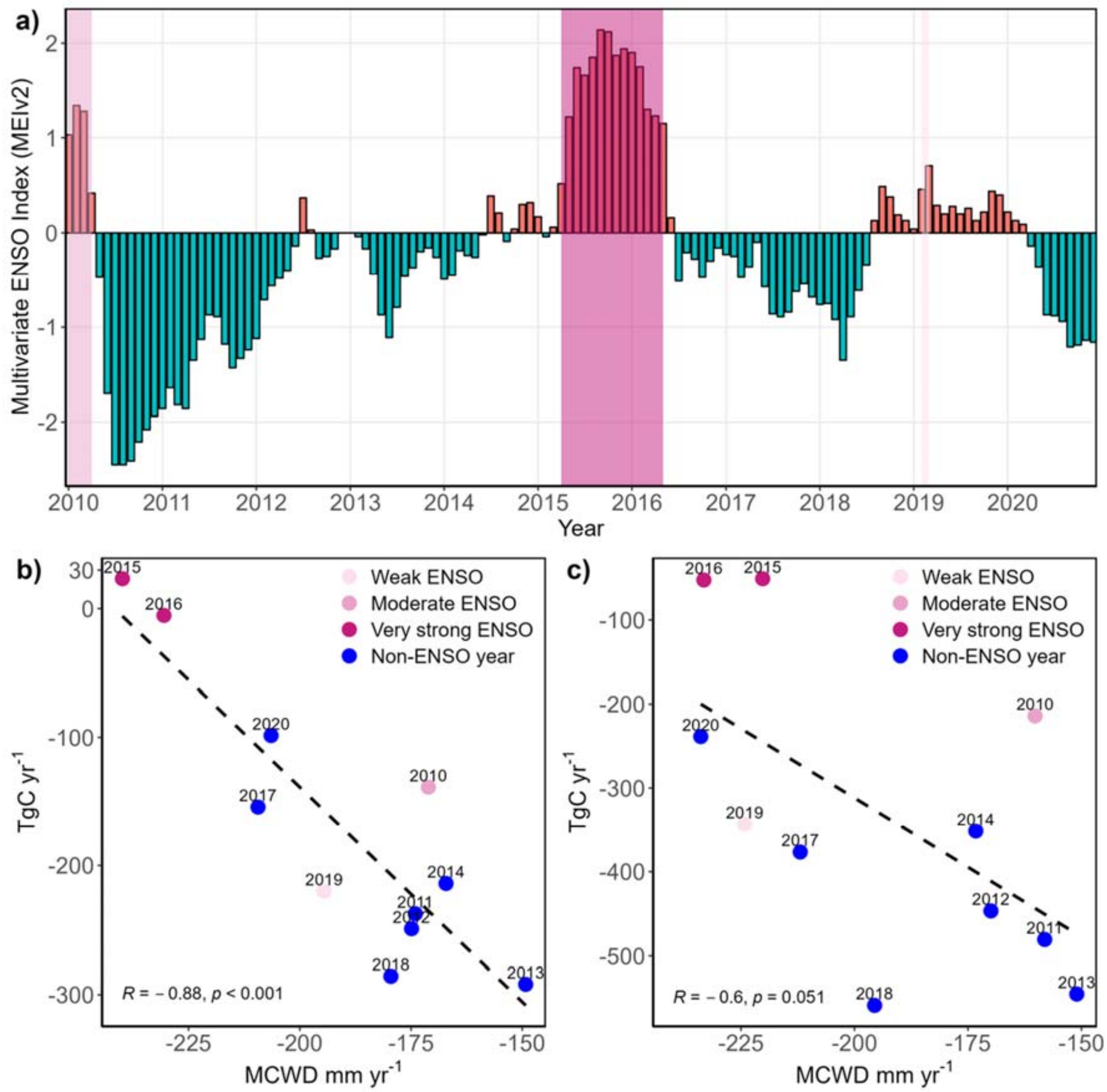
The research entitle ”Amazon forests a net carbon source during drought and under high rates of human-disturbance” by Rosan et al is a timely piece of work that can improve the understanding of the stresses and impacts currently facing the Amazon Forest. The authors have done considerable amount of work in creating an ensemble of models to tackle the problem of integrating multiple stressors. However, very limited information if presented on the key findings ie research on drought. Throughout the article, drought is treated as a single finding while the title emphasises that the research is mainly about drought. More background is needed on top down and bottom up methodologies. These have been introduced in the abstract without prior information and continued in the introduction without paving the way for the research. The article can be restructured so that a clear picture is given about drought, and human disturbances. I also recommend that a timeseries analysis of climate data be used to support the finds on droughts-shoudl this still remain the m ain focus of the research. Additionally, more effort is needed to improve the grammar and style of writing. This will definitely be an important piece of research!

We would like to thank reviewer time for their assessment of our manuscript.
We changed the title to highlight this is a synthesis paper of the Amazon carbon balance using a set of modelling approaches for a common period and region. The new title is **“Synthesis of the land carbon fluxes of the Amazon region between 2010 and 2020”.**

We edited the abstract to include more information about top-down and bottom-up methodologies, however, given the limited space of the abstract, we opted to expand the background on these methodologies in the introduction section (page 5, lines 1 – 9) and include other minor editions throughout the introduction. Further details of each model can be found in the methods section.

> *“There are multiple approaches to estimate the land carbon fluxes. Bottom-up approaches comprise the use of process-based Dynamic Global Vegetation Models (DGVMs)[29] and bookkeeping models[30–32], as well as remote sensing-based estimates[24]. Top-down approaches are based on atmospheric inversion models, which combine in situ CO_2 measurements, aircraft measurements of CO_2 concentration and atmospheric transport model simulations[33]. There are discrepancies between bottom-up and top-down estimates for the South America carbon budget, with the top-down inversions estimating a net land source and bottom-up a net land sink[34].”* (page 4, lines 27– 32)

Concerning the drought analysis, we added a supplementary figure (SI Fig 2) with a time series of the Multivariate ENSO Index (MEIv2) over the study period, as well as a figure showing the correlation between the old-growth forest sink and the maximum cumulative water deficit (an annual drought index) for both the Brazilian Amazon (SI Fig 2b) and the whole biogeographical Amazon (SI Fig 2c). This analysis shows that there is a reduction in the old-growth forest sink in the ENSO years, driven by the higher water deficit (MCWD). We also edited the main paper figures to highlight the years affected by ENSO.



SI Figure 2 El Niño–Southern Oscillation (ENSO) events between 2010 and 2020. a) Bimonthly Multivariate ENSO index (MEIv2) from the National Oceanic and Atmospheric Administration (NOAA); shaded pink areas highlight the ENSO occurrence between 2010 and 2020. b) Correlation between old-growth forest sink simulated by the TRENDY-v11 DGVMs (Tg C yr^{-1}) and the Annual Maximum Cumulative Water Deficit (MCWD mm yr^{-1}) for the Brazilian Amazon. c) Correlation between old-growth forest sink simulated by the TRENDY-v11 DGVMs (Tg C yr^{-1}) and the Annual Maximum Cumulative Water Deficit (MCWD mm yr^{-1}) for the whole Biogeographical Amazon. Dashed line represents the correlation between the old-growth forest sink and the MCWD and the Pearson's correlation, the Pearson correlation coefficient (R) and p-value at 95% confidence level are in the bottom-right of plots b and c, respectively.

Reviewer #2 (Remarks to the Author):

Review for "Amazon forest a net carbon source during drought and under high rates of human-disturbance" from Rosan et al.

The Amazon, renowned as the world's largest continuous tropical forest, holds immense significance in the global carbon cycle and is threatened by anthropogenic impact. In an extensive study, Rosan et al. undertook a comprehensive analysis of contemporary land carbon flux estimates in the Amazon, employing both bottom-up methodologies and top-down inversions. They include deforestation, forest degradation, and regrowth using regional and global spatially explicit bookkeeping models.
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Their findings underscore the escalating impact of human-induced disturbances, including deforestation and forest degradation due to wildfires, on the carbon balance of the Amazon. Furthermore, the carbon sequestration capacity of mature forests suffered a decline during drought conditions.

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To better depict this and have a better overview of the different methods, datasets, and models used, I would suggest a comprehensive conceptional figure. Such an overview would enhance the capability of the reader to easily follow the different approaches to analyze the carbon balance in the Amazon forest.

We would like to thank the reviewer for the detailed revision and positive comments about our manuscript.

Our manuscript is a <u>synthesis study standardizing existing state-of-the-art estimates</u> of the Amazon carbon fluxes over <u>common domains and time-period</u>. For clarity, we further edited the abstract accordingly to state it is a synthesis of existing estimates. Additionally, we highlight in the abstract we have used a set of bottom-up and top-down methodologies and give further detail on these in the Introduction page 5 (lines 6 – 13). Due to the limited word count in the abstract we opted to not specify each model combination that was used to estimate the individual terms (i.e., sources and sinks) and added the following sentence in the abstract:

> "Here we conduct a comprehensive synthesis of existing state-of-the-art estimates of the contemporary land carbon fluxes in the Amazon using a set of bottom-up methods (i.e., dynamic vegetation models and bookkeeping models) and a top-down inversion (atmospheric inversion model) over the Brazilian Amazon and the whole Biogeographical Amazon domain."

We also added some sentences in the introduction to clarify it is a comprehensive synthesis study of existing estimates. The individual methods for disturbance fluxes are published and their respective references are available in table 2. For clarity, we also added the reference of the DGVMs, CARDAMON and TOMCAT in Table 3.
Additionally, to better provide an overview of the different methods and models used to estimate the net land carbon fluxes in both Brazilian Amazon and whole Biogeographical Amazon, we made a conceptional figure (Figure 1) as requested, which was added at the end of Introduction section and attached below this response.

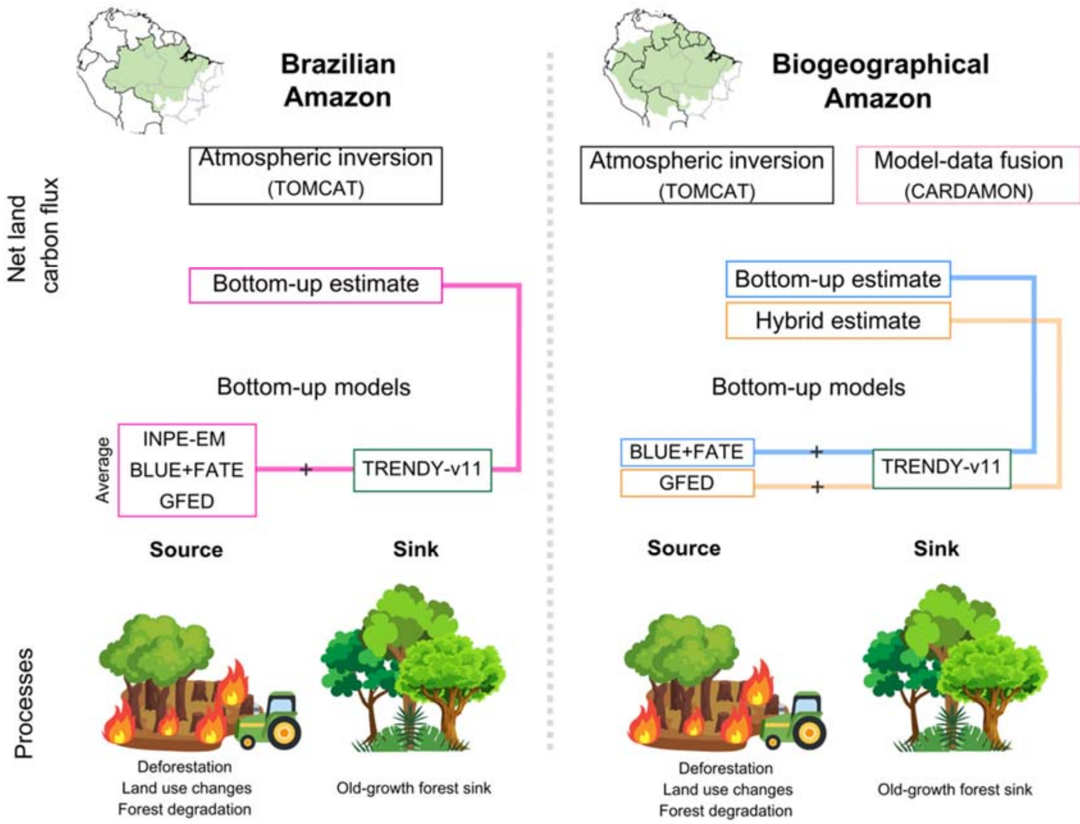

Figure 1 Overview of the existing methodologies applied to estimate the carbon fluxes in the Brazilian Amazon and Biogeographical Amazon according to data availability. Details of each bookkeeping models (INPE-EM, BLUE, FATE and GFED), TRENDY-v11 DGVMs, TOMCAT atmospheric inversion (called top-down inversion in the results section) and CARDAMON can be found in the methods section and their combinations in Table 3. Further detailed information about the processes included in each source/disturbance model can be found in Table 2 and SI Table 3 for the TRENDY-v11 DGVMs.

Furthermore, I have a few minor remarks:

The term old-growth forest is used extensively throughout the paper. Could the authors maybe give a clear definition in the paper? What exactly is understood as old in this context? I guess this is also related to the term primary forest.

There is a consensus in the ecology community that given the ancient history of the Amazon rainforest and the presence of pre-Columbian communities managing these forests, they cannot be considered pristine (primary forest definition). Therefore, we prefer to call the forests that were not impacted by recent mapped disturbances as old-growth instead of primary forest. We added the following sentence in the introduction “The carbon sink contribution of the **old-growth forests (i.e., forests not impacted by contemporary human-induced disturbances)** in the Amazon has been estimated to be undergoing a persistent decline, driven by an increase in tree mortality, associated with environmental change[8–11]."

P6 L10: Why does GFED only show fires from deforestation and degradation? To my knowledge, all different fires can be obtained in the GFED database.

Indeed, other fire types such as savannas, agriculture and pasture (i.e., non-forest fires) can be obtained from GFED database. However, we used only disturbance estimates that account for forest related fires, such as the net carbon balance of deforestation and degradation fires (INPE-EM model) and wildfires (FATE model) which have a higher impact on the annual carbon balance.
There is a high turnover of carbon fluxes from fires in savannas, agricultural and pasture areas (i.e., with rapid vegetation regrowth, it tends to be net carbon neutral on the long-term; ~ decadal scale), therefore, we assume it does not have a large impact on the long-term carbon balance of the Amazon, compared to disturbances in forests which have been shown not to recover even 30 years of fire occurrence (i.e., in Silva et al, 2020).

Silva, C. V. J. *et al.* Estimating the multi-decadal carbon deficit of burned Amazonian forests. *Environmental Research Letters* **15**, (2020).

P6 L24: Uncertainty in models is usually given by ensemble runs with either different models (e.g. in Trendy) or by changing parameters or conditions in the model. Therefore I would not write the sentence as it is and maybe highlight that the uncertainty here is the difference between the two models used.

Thank you for pointing this out. This sentence refers to the combination of BLUE+FATE and GFED models used to estimate the disturbance flux for the whole biogeographical Amazon. These models do not provide uncertainty estimates. Therefore, we are unable to quantify the uncertainty for the disturbance flux for the whole biogeographical Amazon.
We edited this sentence for clarity: "The models used to estimate the disturbance flux for the whole Biogeographical Amazon do not provide regional uncertainty estimates, therefore, we are unable to quantify the uncertainty for the disturbance term."

It would be interesting to have a little bit more discussion about the spatial pattern of the carbon fluxes. Why, for example in Figure 2d, is an area in northwest Amazon a strong source, while almost all of the other area is a carbon sink?

The strong old-growth forest source pattern (pink grid-cells) in the TRENDY-v11 simulated carbon sink in Figure 1e and Figure 2d (now Figure 2e and Figure 3d) in the northwest Amazon is driven by a response of the DGVMs to the precipitation driving data, which shows lower precipitation for Amazon (<1000mm) during the 2015/16 El Niño. This highlights the importance of the climate data, and the sparsity of meteorological ground data across this region used for interpolation in climate reanalysis. We added further supplementary figures showing the annual precipitation driving data (SI Figure 3) and the average old-growth forest sink by each DGVM (SI Figure 4). As well, we added the following sentences in the manuscript.

> "Stronger patterns in the old-growth forest sink, such as the pink grid-cells in Figure 2e, are driven by lower annual precipitation (<1000mm) during the 2015/2016 ENSO in the precipitation data used as input in the TRENDY-v11 DGVMs (SI Figure 3). Several DGVMs simulate a stronger transition of the old-growth forest from sink to source in this region in 2015/2016, which dominates the decadal mean flux (SI Figure 4). This localized pattern points to the general sparsity of climate datasets across this important region for

interpolation in reanalysis datasets, which are used as in input for the DGVMs simulations. (pages 8-9, lines 31-33 and 1-5)

"Likewise, as was explained in the Biogeographical Amazon section, the strong pink pattern in the old-growth forest sink (Figure 3d) is driven by lower annual precipitation during the 2015/2016 ENSO (SI Figure 3) and the simulated response from DGVMs to this lower precipitation in the decadal mean flux (SI Figure 4)." (page 12, lines 17-20)

Could the authors give an estimation of future Amazon carbon fluxes based on their results? Maybe they can detect a trend (or no trend) in the data?

As this study focuses on modelled carbon fluxes for the contemporary period, making future predictions is not within our scope. There are several studies using Earth System Models in IPCC CMIP6 investigating the fate of the Amazon under climate change, and we refer the reader to these publications.

"Current studies investigating the fate of the Amazon under climate change using seven Earth System Models from Phase 6 of Coupled Model Intercomparison Project, CMIP6, indicate localised future reductions in vegetation carbon across Amazon by 2100[55–57]. The inclusion of long-term drought induced tree mortality in current model developments is a priority, and will likely improve Earth System model representation of carbon stocks and fluxes[58], thus providing a better quantification of the future evolution of the Amazon in response to climate change." (page 20, lines 10-17)

The 11-yrs time-series from bottom-up approaches and 9-yrs from atmospheric inversion are relatively short and does not show any significant temporal trend (Bottom-up: $R2 = 0.007$, $p = 0.74$; Atmospheric inversion: $R2 = 0.07$, $p = 0.5$, respectively for whole biogeographical Amazon). Therefore, we prefer to be conservative and not provide the trend and an estimation of the future Amazon carbon fluxes given the large uncertainty and no significant trend over the study period. Future developments towards reducing the uncertainty within and between top-down and bottom-up approaches, as well the availability of field data to better parametrize DGVMs tree-mortality response, will likely improve the estimates to be able to provide longer constrained estimates of the Amazon carbon fluxes.

Decision letter and referee reports: second round

13th Nov 23

Dear Professor Sitch,

Your manuscript titled "Synthesis of the land carbon fluxes of the Amazon region between 2010 and 2020" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

Please note that it may still be possible for your paper to be published before the end of 2023, but in order to do this we will need you to address these points as quickly as possible so that we can move forward with your paper.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Yongqiang Liu, PhD
Editorial Board Member
Communications Earth & Environment

Clare Davis, PhD
Senior Editor
Communications Earth & Environment

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@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

Thank you for the revised manuscript. I am satisfied with the authors' response and the paper can be published as is.