nature portfolio

Peer Review File

Observed shifts in regional climate linked to Amazon deforestation

Corresponding Author: Mr Marcus Silveira

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Mr Silveira,

Your manuscript titled "Observed shifts in regional climate due to Amazon deforestation" has now 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 outline the essential criteria that must be addressed for your manuscript to be considered for publication as follows:

a) Fully incorporate long-range moisture transport and assess controls by accounting for non-local moisture sources, ensuring control areas are unaffected, and addressing ENSO-related biases in precipitation analysis.

b) Justify the chosen spatial resolutions and explain how they impact the detectability of deforestation effects on temperature and evapotranspiration, including whether the feedback is resolution-dependent and the extent of deforestation visible at different resolutions.

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.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary 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:

Link Redacted

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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,

Rodolfo Nobrega, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-9858-8222

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

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:

Editorial Policy Policy requirements (Download the link to your computer as a PDF.)

For Manuscripts that fall into the following fields:
• Behavioural and social science
• Ecological, evolutionary & environmental sciences
• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.zip

For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript submitted by Silveira and co-authors presents an analysis of shifts in the Amazon climate as result of deforestation. The first finding is that forest loss induced regional changes on climate in the Amazon (ET, land surface temperature and precipitation), mainly during the dry period. This work also quantifies the impact of deforestation, using different ranges of remaining forest on climate using the same variables. They also indicate that areas with below 50% remaining forest cover, regional levels of ET and rainfall start to substantially deviate from the observed climate state in highly forested regions. I carefully read the manuscript, and I have a few concerns with the analyses and with the form that results and conclusions are presented.

1. The findings that forest loss induce climate change in the Amazon are not new, especially in the dry season. Thus, the main findings of the work are not novel, nor is the method employed. The mechanisms that are presented in the literature to explain the deforestation-induced changes in the Amazon climate are the same discussed, and early presented in the introduction (L56-65).

2. A fundamental problem with their analysis is the evaluation of change in precipitation in response to deforestation. It is well known that the majority of dry-season precipitation in the Amazonia is a result of forest transpiration; but the source is not locally recycled and in fact feeds other regions (Staal et al., 2018); Therefore, how can one evaluate the impact of deforestation on precipitation when not taking into account the travelled distances of moisture? Or simply put, the deforestation impact is likely not reflected at the scale evaluated by the analysis, and control areas can also be affected by deforestation.

3. Additionally, precipitation is quite heterogeneous in the landscape, even when trying to minimize by selecting neighboring ‘control’ and different percentages of forest changes (l110-112). To tie the change to deforestation, and associated magnitude to the forest loss, one needs to first prove that there are no changes in the control itself and if there are, the

magnitude changes in the deforested areas are significantly larger. This is not shown.

4. Additional concern is with the split period of evaluation (which is not “decadal” - the text should avoid calling it decadal changes). When comparing 2003-2012 (9 years) with 2013-2021 (8 years), there are two ENSO years in the last 8 years, which brought more extreme effects (Mattar et al. 2016). How does analysis count for the extreme events without introducing bias in the “decadal” changes?

5. Another major concern comes from the statements presented both in the abstract (L32-33), and the conclusions of the work (L458-461). The statistical analysis used doesn’t support pinpointing thresholds, and such is only presented at the end of the manuscript. It is dangerous to present such without clear and strongly supported evidence. One could interpret (as stated) that keeping 50% of forest is already enough to not trigger deforestation-driven climate change, and this work cannot support it. To what extent temporally? To what extent spatially (as the text also switches back and forth between local and regional)?

6. Regarding the analysis of “wet and dry season”. Was the three consecutive months with the highest rainfall volume consistent year-to-year? Were the dry months also consistent year-to-year? (L556-558). And across the spatial scale? This is important to state since those periods can change year to year and the onset of dry and wet season is spatially distinct across the Amazon.

7. Lastly, the manuscript itself is not easy to read and comprehensive. Because several analyses were done using similar approaches, but splitting periods, without splitting periods, between control and deforestation, and across distinct scales (0.5 and 1.5), I would highly recommend that the authors combine results and discussions, and clearly state which results they are referring to and analysis. Additionally, there are several sentences that are unclear. For example:

L356-361: Unclear whether they discuss their own observations or others.
L362-364, “during 2003 to 2021” is it a "decadal" split evaluation or a continuous analysis?
L373-375, “increase in driest period rainfall during the past two decades”, increase in relation to what if the two “decades” are referred to?
L444-447: Unclear – check the sentence structure.
L458-459: What are “optimal levels of ET”? Defined based on what?

Staal, A., Tuinenburg, O. A., Bosmans, J. H., Holmgren, M., Van Nes, E. H., Scheffer, M., Zemp, D. C., & Dekker, S. C. (2018). Forest-rainfall cascades buffer against drought across the Amazon. Nature Climate Change, 8(6), 539-543. https://doi.org/10.1038/s41558-018-0177-y

C., J., Mattar, C., Barichivich, J., Takahashi, K., Malhi, Y., Sobrino, J. A., & Schrier, G. V. (2016). Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016. Scientific Reports, 6(1), 1-7. https://doi.org/10.1038/srep33130

Reviewer #2 (Remarks to the Author):

Review on “Observed shifts in regional climate due to Amazon deforestation” by Silveira et al.
General considerations
The manuscript is very interesting. Despite the large number of studies focused on the Amazon deforestation, the authors were able to evaluate deforestation-LST relationships with a novel approach.
I find the manuscript generally well written, though the methods were difficult to understand. As the manuscript analyses the feedback at two spatial resolutions (scale is composed of resolution and extension, thus in my opinion the use of “scale” should be exchange by “resolution”), I missed the evaluation of how the response to deforestation changes due to a change in resolution. On its current version, the manuscript does not discuss the implications of resolution on the temperature and ET response. Is the feedback dependent on the resolution? And if it is, which extend of deforestation is “visible” at a coarse resolution?
Below I provide comments for each section.
Methods
I find the methods section very hard to understand. A flux diagram summarizing the section would be very helpful. I strongly recommend re-writing this section to make it clearer to the reader, as on its current structure, it does not provide enough information to reproduce the experiment.
The reference for Andrade et al., (2024) is absent from the Refence section. As this is a key input in methodology, it is not possible to evaluate the manuscript’s robustness.
Line 520-539: Why not use the MSWEB dataset for precipitation?. On this set biases due to lack of weather stations have been complemented by IMERG and ERA5.
Line 509 states that the data from Andrade et al., (2024) yielded the highest accuracies but it is not clear if the statement comes from Andrade et al., or the current manuscript. Please clarify. If the second case is true then authors must demonstrate the statement.
The treatment of CHIRPS data is appropriate, and the uncertainty well assessed. As a comment, the authors could have used MSWEP since also is as accurate as CHIRPS for the Amazon (Sapucci et al., 2022).

Cordeiro and Blanco (2021) not in references Section. Please add.
Lines 479-492 It is not clear to me the use of two grid sizes. Authors need to provide more methodological information on the approach to study the impacts on temperature and precipitation. The citation of the studies of Cohn et al., (2019) and Smith et al., (2023) is necessary but it is not clearly justified. Authors needs to expand on the mechanisms behind the use of the 0.5 and 1.5° grid size for temperature and precipitation, respectively.
Line 591-592 Can you please provide evidence of the minimum number of grid cells for statistical comparisons?. Please provide evidence of the minimum number of samples and confidence level. Authors do not provide the number of samples in the 1.5° resolution.
Line 660 Add a sentence at the beginning of the subsection explaining the purpose of “Climate characteristics of biomes”. On its current form, it is not clear the objective of this particular analysis in the Methods section.
Abstract
Lines 24-25 As the abstract does not explain previously what 0.5° and 1.5° scale means, this confuses the reading. Please remove or explain what these scales mean.
Introduction
Line 49 Need a citation at the end of the paragraph
The research has some level of novelty in addressing combining the effects of deforestation at two different scales, seasonality and heterogeneity in the Amazon.
The results are very interesting and well presented. It is interesting that results are presented based on how LST relates to percentage of forest cover and seasonality.
Discussion
Line 335. In this line there is a very important sentence about the increase in LST not directly related to deforestation fall below 0.5°C. However, I do not see any evidence supporting this sentence. Please justify.
It is very interesting that highly deforested areas still share climatic similarities with both moist forests and savannas.

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Mr Silveira,

Your revised manuscript titled "Observed shifts in regional climate linked to Amazon deforestation" has now been seen by our original reviewers 2 and 3 and a new reviewer 4 who replaces the original reviewers 1 (reviewers 1 was not available for further comments). All 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, provided you tone down claims about precipitation reduction mechanisms, and fully acknowledge and clarify the limitations of the current approach, particularly with regard to tracing moisture sources, along the lines recommended by our reviewers 3 and 4.

If you can address this request, we therefore invite you to revise your paper 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.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication. For further information about article processing charges, open access funding, and advice and support from Nature Portfolio, please visit https://www.nature.com/commsenv/open-access

At acceptance, you will be provided with instructions for completing the open access licence agreement on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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

Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

Rodolfo Nobrega, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-9858-8222

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

Details of appropriateness and validity of statistical analysis and other aspects of the review can be found in the report.

Reviewer #3 (Remarks to the Author):

As a second-round reviewer invited to evaluate the authors’ response to Reviewer 1’s concerns—particularly regarding moisture recycling—I found the manuscript interesting, and I believe the results are publishable.

The authors have made commendable efforts to revise their analysis in response to earlier critiques. Notably, they replaced the broad grouping of forested and non-forested areas with a more localized, paired comparison of adjacent cells within a moving window. This is a meaningful improvement, and the results are compelling.

However, spatial heterogeneity and scale effects remain only partially addressed. There is a key difference between selecting a few cells from a large, homogeneous deforested area and selecting cells that are part of a heterogeneous, small deforestation patch. This issue was highlighted in the review by D'Almeida et al. (2007). Introducing some form of scale grouping could provide additional insight. Additionally, scale itself is critical: how sensitive are the results to the size of the window used for pairing? A sensitivity analysis exploring the effect of varying window size would help assess the robustness of the patterns observed.

Another important aspect is the relative position of forested and deforested patches with respect to prevailing wind direction, which would be relevant for moisture recycling. For instance, is the forested patch located upwind or downwind of the deforested area? This distinction is crucial for interpreting fluxes, and previous studies—such as those by Spracklen et al. (2012), Poveda et al. (2014), and Molina et al. (2019)—may provide useful context for this discussion.

To be clear, I do not believe that new analyses are strictly required, as the current results are already of interest. However, I encourage the authors to address these scale and directional effects—whether through additional analyses, expanded discussion, or suggestions for future work.

Finally, a structural note: the manuscript places the full Methods section after the Discussion, with each Results subsection containing a brief methodological summary. However, I found these summaries insufficient to fully understand the analyses as I was reading. The structure made it difficult to follow the reasoning behind some choices until much later in the manuscript. While this format may be allowed by the journal, I encourage the authors to reconsider it. The IMRD structure—Introduction, Methods, Results, and Discussion—remains widely used for good reason, and adopting it, or at least including a clearer overview of the methods earlier on, could significantly improve readability.

References

D'Almeida, C., et al. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. International Journal of Climatology, 27(5), 633–647.

Molina, R. D., Salazar, J. F., Martínez, J. A., Villegas, J. C., & Arias, P. A. (2019). Forest-induced exponential growth of precipitation along climatological wind streamlines over the Amazon. Journal of Geophysical Research: Atmospheres, 124(5), 2589–2599.

Poveda, G., Jaramillo, L., & Vallejo, L. F. (2014). Seasonal precipitation patterns along pathways of South American low-level jets and aerial rivers. Water Resources Research, 50(1), 98–118.

Spracklen, D. V., Arnold, S. R., & Taylor, C. M. (2012). Observations of increased tropical rainfall preceded by air passage over forests. Nature, 489(7415), 282–285.

Reviewer #4 (Remarks to the Author):

Manuscript Title: Observed shifts in regional climate linked to Amazon deforestation
Manuscript ID: COMMSENV-24-3350
Date of Review: 30/07/2025

In their reviewed manuscript, authors have used observational data (0.5deg pixels) to estimate seasonal impacts of deforestation on climate variables over the Amazon lowland biome forest. These climate variables come mainly from MODIS/CHIRPS as forest data comes from MapBiomas Amazonia Collection 4. Authors have claimed to find an explicit cause-effect relationship between extensive deforestation and regional trends of key hydroclimatic variables as LST, ET, and P with most pronounced effect during dry seasons. Similar findings have been previously reported by other studies (Nobre et al., 1990; Khanna et al, 2017; Baker and Spracklen, 2019; Silva et al., 2022; Longo et al., 2025 among others) but authors have claimed their novelty is based on their methodological approaches. Particularly, they conclude similar features of transitional moist forest-savannas correspond to highly deforested areas.

Among the most remarkable changes of their reviewed version, the authors have improved the manuscript by excluding 1.5deg data and focusing on 0.5deg data, reordering and renaming sections according to previous reviewer's comments, providing most robust statistical analysis of the differences as suggested by reviewer #1, and enhancing general readability of the manuscript. However, the core of the paper is still hard to understand necessitating repeated readings for comprehension.

First, I have focused on the novelties authors have claimed to include in this new version regarding the assessment of deforestation-climate relationships in the study region:

i.Comparing two scenarios: deforested surrounded by forested vs forested surrounded by forested (Methodological advance?). Authors claim not clearly made in previous studies
i.Including more variables than previous studies (Methodological advance?)
ii.Observational approach vs modelling approach of previous studies (Methodological advance?)
iii.Analysis based on comparative assessments of deforested surrounded by forested regions vs forested surrounded by forested regions (Methodological advance?)

I find them very relevant and, evidently, there is an enormous effort in this sense; neverthless, my main concern is that they appear novelties directly connected to methodological approaches respect to previous studies leading to the same results.

Can authors more explicitly connect how the methodological approaches increase our understanding of deforestation-climate relationships in the Amazon lowland biome?

Second, another relevant point: the response to reviewer #1 in his/her comment #2, "how can one evaluate the impact of deforestation on precipitation when not taking into account the travelled distances of moisture?" Authors argue that the 0.5deg pixel resolution allows a better representation of local moisture recycling processes respect to the original 1.5deg, initially presented. This is true; however, reviewer #1 has also suggested that Amazon's rainfall in dry seasons comes from transpiration which is also connected with moisture transport and recycling. Precisely, it has been proven interconnected effects of deforestation and regional climate trends through the dynamics of moisture cascades (see Zemp et al. 2014, 2017 and Staal. et al, 2018).

So the controversial issue here is the spatial scale and maybe what reviewer #1 asked authors was to analyze the possible role of moisture recycling and transport in the overall hydroclimate scenario of the Amazon lowland biome and in the context of their observational approach. Staal et al. (2018) provides evidence of transpiration recycling ratios up to 50% in northern and southwestern Amazon where the median geographic distances are shorter (see their figures 1b,c); instead, the authors declare: "…less than 10% of regional evapotranspiration in the Amazon is suggested to be locally recycled (Theeuwen et al., 2023)". Notably, as remarked again by Theeuwen et al. (2023) : "…spatial scale at which moisture recycling is the dominant process for precipitation is unknown.", and also in this sense: "…with increasing distance from the Andes Mountains, the median travelling distance of transpired moisture from the Amazon forest increases (Staal et al., 2018),…". I think this is the point of reviewer #1. Since the proved connection between moisture recycling and deforestation which involves both local and regional mechanisms as moisture cascades: How your findings reconcile the interaction among deforestation, your on multiple space scales?

Specific Comment: Please include in-line cites references of Staal et al (2010, 2018) and exclude Staal et al. (2020) from the reference list. Also, please revise again the coherence between in line and reference list.

References

Baker, J., & Spracklen, D. (2019). Climate Benefits of Intact Amazon Forests and the Biophysical Consequences of Disturbance. Frontiers in Forests and Global Change. https://doi.org/10.3389/ffgc.2019.00047.

Khanna, J., Medvigy, D., Fueglistaler, S., & Walko, R. (2017). Regional dry-season climate changes due to three decades of Amazonian deforestation. Nature Climate Change, 7, 200-204. https://doi.org/10.1038/NCLIMATE3226.

Longo, M., Keller, M., Kueppers, L., Bowman, K., Csillik, O., Ferraz, A., Moorcroft, P., Ometto, J., Soares-Filho, B., Xu, X., De Assis, M., Görgens, E., Larson, E., Needham, J., Ordway, E., Pereira, F., Pinagé, E., Sato, L., Xu, L., & Saatchi, S. (2025). Degradation and deforestation increase the sensitivity of the Amazon Forest to climate extremes. Environmental Research Letters, 20. https://doi.org/10.1088/1748-9326/adc58c.

Silva, R., Lopes, A., & Santos, C. (2022). Deforestation and fires in the Brazilian Amazon from 2001 to 2020: Impacts on rainfall variability and land surface temperature. Journal of environmental management, 326 Pt A, 116664 . https://doi.org/10.1016/j.jenvman.2022.116664.

Staal, A., Tuinenburg, O. A., Bosmans, J. H., Holmgren, M., van Nes, E. H., Scheffer, M., ... & Dekker, S. C. (2018). Forest-rainfall cascades buffer against drought across the Amazon. Nature Climate Change, 8(6), 539-543.

Zemp, D. C., et al. On the importance of cascading moisture recycling in South America. Atmospheric Chemistry and Physics 14.23 (2014): 13337-13359.

Zemp, D. C., Schleussner, C. F., Barbosa, H. M., Hirota, M., Montade, V., Sampaio, G., ... & Rammig, A. (2017). Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. Nature communications, 8(1), 14681.

Note: I truthfully declare I have not used AI to produce this report

Review on “Observed shifts in regional climate due to Amazon deforestation” by Silveira et al.

General considerations

The manuscript is very interesting. Despite the large number of studies focused on the Amazon deforestation, the authors were able to evaluate deforestation-LST relationships with a novel approach.

I find the manuscript generally well written, though the methods were difficult to understand. As the manuscript analyses the feedback at two spatial resolutions (scale is composed of resolution and extension, thus in my opinion the use of “scale” should be exchange by “resolution”), I missed the evaluation of how the response to deforestation changes due to a change in resolution. On its current version, the manuscript does not discuss the implications of resolution on the temperature and ET response. Is the feedback dependent on the resolution? And if it is, which extend of deforestation is “visible” at a coarse resolution?

Below I provide comments for each section.

Methods

I find the methods section very hard to understand. A flux diagram summarizing the section would be very helpful. I strongly recommend re-writing this section to make it clearer to the reader, as on its current structure, it does not provide enough information to reproduce the experiment.

The reference for Andrade et al., (2024) is absent from the Refence section. As this is a key input in methodology, it is not possible to evaluate the manuscript’s robustness.

Line 520-539: Why not use the MSWEB dataset for precipitation?. On this set biases due to lack of weather stations have been complemented by IMERG and ERA5.

Line 509 states that the data from Andrade et al., (2024) yielded the highest accuracies but it is not clear if the statement comes from Andrade et al., or the current manuscript. Please clarify. If the second case is true then authors must demonstrate the statement.

The treatment of CHIRPS data is appropriate, and the uncertainty well assessed. As a comment, the authors could have used MSWEP since also is as accurate as CHIRPS for the Amazon (Sapucci et al., 2022).

Cordeiro and Blanco (2021) not in references Section. Please add.

Lines 479-492 It is not clear to me the use of two grid sizes. Authors need to provide more methodological information on the approach to study the impacts on temperature and precipitation. The citation of the studies of Cohn et al., (2019) and Smith et al., (2023) is necessary but it is not clearly justified. Authors needs to expand on the mechanisms behind the use of the 0.5 and 1.5° grid size for temperature and precipitation, respectively.

Line 591-592 Can you please provide evidence of the minimum number of grid cells for statistical comparisons?. Please provide evidence of the minimum number of samples and confidence level. Authors do not provide the number of samples in the 1.5° resolution.

Line 660 Add a sentence at the beginning of the subsection explaining the purpose of “Climate characteristics of biomes”. On its current form, it is not clear the objective of this particular analysis in the Methods section.

Abstract

Lines 24-25 As the abstract does not explain previously what 0.5° and 1.5° scale means, this confuses the reading. Please remove or explain what these scales mean.

Introduction

Line 49 Need a citation at the end of the paragraph

The research has some level of novelty in addressing combining the effects of deforestation at two different scales, seasonality and heterogeneity in the Amazon.

The results are very interesting and well presented. It is interesting that results are presented based on how LST relates to percentage of forest cover and seasonality.

Discussion

Line 335. In this line there is a very important sentence about the increase in LST not directly related to deforestation fall below 0.5°C. However, I do not see any evidence supporting this sentence. Please justify.

It is very interesting that highly deforested areas still share climatic similarities with both moist forests and savannas.

Review #2

Title: Observed shifts in regional climate linked to Amazon deforestation

Authors: Marcus V. F. Silveira; Patrick W. Keys; Anderson Ruhoff, Paulo Artaxo, Marcos H. Costa, Liana O. Anderson, Marcos Adami, Celso von Randow, Luiz E. O. C. Aragão

Recommendation: For the reasons explained below, I recommend the manuscript for publication only after the authors share the datasets, codes and all relevant information to make the study replicable.

Report

Using satellite-based observational data, the study investigated how deforestation contribute to shifting the Amazon climate conditions away from those in highly forested and intact areas. The findings show compelling evidence that forest loss has contributed to climate shifts, particularly in regions with less than 60% remaining forest cover. The climate shift linked to deforestation include warmer LST, lower evapotranspiration, lower dry-season rainfall and fewer rainy days. Thy study that rain metrics (annual rainfall and the number of rainy days) in highly deforested regions still share similarities with highly forested regions, but LST, ET, and rainfall in the driest period of the year are like transitional regions.

The methodology involved analyzing satellite-based data for LST, ET, and rainfall variables across grid cells grouped by remaining forest cover in 2021. Grid cells with over 80% forest cover served as a reference for conditions under negligible deforestation influence. Control methods were applied to minimize the influence of factors other than deforestation, such as ensuring neighboring deforested and reference regions shared similar climatic backgrounds and were entirely within the moist forest biome (this is correct). Statistical tests confirmed that the magnitude of observed climate differences in deforested regions was significantly larger than differences related to background factors. These findings included analysis of drought years.

The authors emphasize the need to identify and quantify deforestation's impacts on regional climate to inform mitigation and adaptation strategies. They cite other studies and highlight that large-scale observational studies remain limited. The study addresses this gap with an observational approach that includes key atmospheric variables across different seasons. The study objective is clearly stated: to analyze the potential impact of deforestation on the change of essential climate variables at different seasonal periods and according to the regional extent of remaining forest cover.

Methods rely on satellite observation aggregated to 0.5° (they addressed my observation from my previous review) grid cells, and analyzed LST, evapotranspiration from the validated geeSEBAL-MODIS model, and rainfall (CHIRPS). The authors implemented multiple controls to isolated deforestation effects and chose representative cells for deforested cells.

A key limitation is the small sample size meeting all controls applied: 9 cells for ≤ 40%, 20 for 40-60%, and 100 for 60-80%. The authors acknowledge this aspect constrains the precision of their estimates that are also scale-dependent. Despite limited sample size in some categories, the experimental design and the use of good set of satellite products render the methodology allows to appropriately justify their results and conclusions.

The authors applied suitable statistical tests to compare climate variable distribution (Ks and Welch-s t-test) and report the confidence intervals for p-values from bootstrapping.

The authors demonstrate that deforestation drives climate shifts toward higher LST, lower ET, reduced dry season rainfall, and fewer rainy days in areas with less than 60% forest cover. These results support the conclusions and respond to the main study's question.

Peer Review - COMMSENV-24-3350

Response to reviewers regarding the manuscript "Observed shifts in regional climate linked to Amazon deforestation"

We thank the reviewers for carefully reading our manuscript and providing thoughtful comments. Thanks to the reviewers' comments, we were able to identify pathways to make our analyses more robust and to make the text more cohesive and clear. We have made substantial modifications in our manuscript and we believe this new version demonstrates in a more assertive and clear manner the impacts of Amazon deforestation on regional climate. We provide below a summary of the major changes performed in the manuscript, followed by a point-by-point response to the reviewers.

Summary of changes

We made a slight modification in the previous title by replacing the term "due to" to "linked to". We believe the word "linked" is more representative of the different assessments we performed to evaluate the influence of deforestation on regional climate shifts. To make all Results' sections more aligned to each other and part of an integrated story, we decided to remove the sections "Changes in climate during the past two decades across the Amazon" and "The effect of forest loss over 2003-2021 on decadal changes in climate variables". The "Changes in climate during the past two decades across the Amazon" section was the first shown in the text but the least aligned directly to the study objectives, which could confuse the reader. The section "The effect of forest loss over 2003-2021 on decadal changes in climate variables" was conveying similar messages with the "Effect of regional forest cover on climate variables in the last decade" section, but in a higher level of complexity, with different terminologies and time scales, which was making this part of the text difficult to understand. These modifications helped to make the text more cohesive and clear, addressing both reviewers' recommendations to improve readability in our text.

Alternatively, we expanded the analyses for the previous sections "Effect of regional forest cover on climate variables in the last decade" and "Similarities and differences in the observed climate of highly deforested compared to moist forests and savanna patterns" to make them more robust, as these two sections were conveying the main messages of the manuscript. These sections were renamed respectively to "The impact of Amazon forest cover on regional climate" and "The observed climate in highly deforested areas shares similarities with transitional regions between moist forests and savannas".

For the "The impact of Amazon forest cover on regional climate" section, we improved our approach to control the effect of drivers other than deforestation by directly comparing climate averages between deforested grid cells and their highly forested neighbors. To better understand if climate differences in deforested regions had larger magnitudes compared to background factors, we additionally compared the overall climate difference distributions of deforested vs. forested neighbors across our study area against the forested vs. forested neighbors. These modifications addressed reviewer #1 recommendations to better demonstrate that deforestation-related climate impacts are significantly larger than those driven by other factors that can include external moisture sources. To assess the consistency of patterns found by statistical tests, we further tested these comparisons 1000 times with a subsampling approach for the distribution of forested vs. forested neighbor across our entire study area, retrieving the 95% confidence intervals for p-values. This evaluation addressed reviewer #2 recommendations to better demonstrate the validity of our statistical comparisons. We also provided comparisons for extreme drought and non-drought years to evaluate if climate differences in deforested regions were influenced by interannual climate variability, such as due to ENSO events, as recommended by reviewer #1. Lastly, we attempted to estimate the isolated contribution of deforestation to climate differences in deforested regions through a novel approach.

For the "The observed climate in highly deforested areas shares similarities with transitional regions between moist forests and savannas", we provided a map showing the spatial distribution of regions in the moist forest biome that have more climate similarities with savannas, highlighting the location of deforested regions, which can help to identify priority areas for climate intervention. For this section we used part of the moist forest samples also used in the previous analysis, making both sections more cohesive.

Lastly, we decided to only work with grid cells of 0.5° spatial resolution, instead of 0.5° and 1.5°. The 0.5° resolution provides a good compromise between the number of samples and the necessary scale to start detecting deforestation impacts. As we increased the controlling approaches for our analyses, few samples in the 1.5° spatial resolution would meet controlling criteria, which could compromise the robustness of our assessments for deforestation impacts on climate and the comparison with patterns found for the 0.5° resolution. We therefore decided to focus on a robust identification of deforestation impacts on climate, rather than differences across scales. These modifications address the point raised by reviewer #2 that we had not discussed how deforestation impacts on climate change according to the spatial resolution. In addition, we included a contextualization in the introduction for the different deforestation-induced effects on climate according to different spatial resolutions, and a better justification for the use of 0.5° in the Methods section.

Point-by-point response

Reviewer #1

0. The manuscript submitted by Silveira and co-authors presents an analysis of shifts in the Amazon climate as result of deforestation. The first finding is that forest loss induced regional changes on climate in the Amazon (ET, land surface temperature and precipitation), mainly during the dry period. This work also quantifies the impact of deforestation, using different ranges of remaining forest on climate using the same variables. They also indicate that areas with below 50% remaining forest cover, regional levels of ET and rainfall start to substantially deviate from the observed climate state in highly forested regions. I carefully read the manuscript, and I have a few concerns with the analyses and with the form that results and conclusions are presented.

Response: We thank reviewer #1 for carefully reading our manuscript and providing comments that helped to improve the quality of our work.

1. The findings that forest loss induce climate change in the Amazon are not new, especially in the dry season. Thus, the main findings of the work are not novel, nor is the method employed. The mechanisms that are presented in the literature to explain the deforestation-induced changes in the Amazon climate are the same discussed, and early presented in the introduction (L56-65).

Response:

The new version of our manuscript includes four novelties in the assessment of deforestation-climate relationships, which we outline as follows: (i) We compared climate differences between deforested vs.

forested (control) regions against climate differences between control vs. control regions, which has not been performed in this exact way in the literature as far as we know. For instance, previous studies have compared changes of climate variables over time in deforested areas and contrasted with changes in neighboring forested areas (Baker et al., 2019; Smith et al., 2023). In our study we compared climate averages between deforested and neighboring forested regions, and compared these differences with those found between forested regions neighboring each other, as a way to understand if climate differences in deforested regions are larger than those driven by factors other than deforestation. (ii) Another novelty in our approach is the evaluation of five climate variables, three of these variables assessed in three in different seasonal periods (11 climate variables in total), into a single study; this comprehensive approach has not been performed in the literature yet with observational data. (iii) Moreover, we used all these variables to compare climate envelopes of different biomes in the Amazon against climate envelopes in deforested regions through an observational approach. This practice is usually performed by modelling studies, and the few more recent observational studies have mostly focused on annual rainfall to compare biome differences (Flores et al., 2024; Staver et al., 2011). (iv) Lastly, we developed an approach to estimate the magnitude of deforestation-induced impacts on climate by using the magnitude of climate differences between neighboring control regions to offset the effect of background factors on climate differences between deforested and neighboring control regions, as a way to isolate the magnitude of climate differences that are related to deforestation.

We acknowledge that previous studies have found deforestation-induced impacts on climate during the dry season (Baker & Spracken, 2019; Khanna et al., 2017; Maeda et al., 2021; Negri et al., 2004; Smith et al., 2023; Xu et al., 2022), but observational studies on this matter are still limited in number and have used different methodologies. Findings for land surface temperature (LST) and evapotranspiration (ET) have been more consistent on the few observational studies analyzing this matter (Baker et al., 2019; Maeda et al., 2021; Xu et al., 2022), but there is less consistency with respect to deforestation impacts on rainfall during the dry season leading to either increases (Khanna et al., 2004; Negri et al. 2004), decreases (Smith et al., 2023; Xu et al., 2022), or even no significant relationship at all (Baker et al., 2019; Maeda et al., 2021). Evidence from additional studies is therefore very important to assess whether previous evidence is reinforced by different approaches and to provide more insight into uncertainties that still remain in the literature.

We agree with reviewer #1 that repeating some information in the introduction and discussion about deforestation-induced mechanisms of climate change was introducing some degree of redundancy to the text. We have extended the explanation of mechanisms in the introduction and kept for the discussion only information of mechanisms that have not been explained before in the text.

2. A fundamental problem with their analysis is the evaluation of change in precipitation in response to deforestation. It is well known that the majority of dry-season precipitation in the Amazonia is a result of forest transpiration; but the source is not locally recycled and in fact feeds other regions (Staal et al., 2018); Therefore, how can one evaluate the impact of deforestation on precipitation when not taking into account the travelled distances of moisture? Or simply put, the deforestation impact is likely not reflected at the scale evaluated by the analysis, and control areas can also be affected by deforestation.

Response:
We highlight that analyzing deforestation-rainfall relationships at regional scales, with no explicit assessments of travelled distances of moisture, is a consolidated practice in the literature (Baker & Spracklen, 2019; Maeda et al., 2021; Smith et al., 2023). The usual method employed by these studies to address external moisture sources, in addition to other confounding factors on the deforestation-rainfall relationship, is by comparing climate in deforested regions with that of controlled neighbors. These

neighbors usually represent highly forested and intact areas where the influence of deforestation is small. It is assumed therefore that both deforested and control regions, due to their proximity, share a similar influence of factors other than deforestation, such as external moisture sources. As a result, the effect of deforestation can be put into evidence by comparing deforested regions with control neighbors to offset the influence of background factors. This same rationale was employed in this new version of our manuscript, as explained in more detail in the following topics. Similarities between neighboring regions in terms of external moisture sources are even more expected at finer scales such as the one we worked with (0.5°). Although differences in external moisture could influence climate differences in deforested vs. forested neighbors, they also could influence those between forested vs. forested neighbors. By comparing climate differences between deforested vs. forested and forested vs. forested neighbors, we investigate if the magnitude of climate differences under the contribution of deforestation is larger than the ones driven by background factors such as external moisture sources.

With respect to the role of local moisture recycling on changes in precipitation, indeed, less than 10% of regional evapotranspiration in the Amazon is suggested to be locally recycled (Theeuwen et al., 2023) and this mechanism thus might not completely explain the observed reductions in driest-period rainfall we found in our study. However, previous studies have demonstrated other mechanisms that can lead to deforestation-induced reductions in rainfall at the 0.5° spatial resolution. For example, Xu et al. (2022) observed that hotter and drier atmospheric conditions in 0.5° deforested regions extended further into the middle troposphere during the dry season, which can enhance updraft winds and thus weaken the inflow of external moisture supplies, such as those from the Atlantic Ocean, that could moisten the lower troposphere and contribute to rainfall in that region. Changes in mesoscale circulation due to deforestation, such as vegetation-breezes, can also occur at the 0.5° resolution, with some studies suggesting a reduction of rainfall into the interior of larger-scale deforested regions during the dry season, whereas rainfall increases could occur in the downwind edges with forested regions (Khanna et al., 2018; Knox et al., 2011). Even after improving our controlling approaches, we still found lower rainfall values in deforested regions during the driest period of the year in relation to forested and intact regions. Although previous studies have also been able to link rainfall reductions to deforestation based on observations (Smith et al., 2023; Leite-Filho et al., 2021), the explanation of mechanisms behind this process is still largely open for investigation, with no clear answers from the literature so far. To address these points, we updated and added the following sentences to the text:

<u>In the third paragraph of introduction:</u>

"However, deforestation-induced effects on climate may depend on several factors that remain open for investigation, including the scale of observation, seasonality, and the intensity of forest loss in terms of extent or rate. For instance, studies point to different effects of deforestation on rainfall at scales smaller than 200 km. Increased cloudiness and rainfall over deforested areas is suggested to occur in the dry season due to changes in mesoscale circulations, such as the vegetation breeze process (Khanna et al., 2017; Negri et al., 2004; Roy, 2009; Saad et al., 2010). As the extent of deforested area increases, rainfall can be redistributed to decrease in the interior of deforested regions and increase near forest edges in the prevailing wind direction (Khanna et al., 2018; Knox et al., 2011). However, rainfall decreases due to deforestation have also been suggested for scales as small as 0.05° for all seasonal periods, with larger reductions as the scale increases (Leite-Filho et al., 2021; Reygadas et al., 2023; Smith et al., 2024), or even no significant relationships at all (Baker & Spracklen, 2019). Moreover, deforestation has been suggested to negatively impact rainfall seasonality, such as by delaying wet season onset and increasing the occurrence of longer dry spells (Xu et al., 2022; Leite-Filho et al., 2019; Wright et al., 2017). "

<u>In the third paragraph of discussion:</u>

"In contrast to Smith et al. (2023), who found significant deforestation impacts on rainfall for all seasonal periods, our findings only showed clear evidence for deforestation-induced reductions in rainfall during the driest period of

the year. The largest increases in land surface temperature and reductions in evapotranspiration are also observed during this period, which can promote higher vapor pressure deficit in the atmosphere and less moisture available to be locally recycled back as rainfall. However, local moisture recycling might not fully explain the intensity of rainfall reductions found here, as less than 10% of local evapotranspiration is suggested to return as rainfall within scales lower than 170 km in the Amazon (Theeuwen et al., 2023). As another potential mechanism, Xu et al. (2022) suggests that deforestation enhances hot-dry updrafts in the troposphere during the dry season, which could reduce the inflow of external moisture sources that contribute to rainfall in that region.

Alternatively, perhaps the landscape configuration of our deforested regions and their surroundings may fall into the rationale of vegetation-breezes driving reductions in rainfall in the interior of extensively deforested regions, as suggested by some studies (Khanna et al., 2018; Knox et al., 2011). Future observational and modelling studies will be important to validate and clarify our understanding of mechanisms behind deforestation-induced reductions in rainfall. In addition to reductions in rainfall volume, our findings also indicate reductions in the number of rainy days. Although we did not explore the seasonal period in which this reduction has occurred, previous studies have linked deforestation to delays in wet season onset and wet season duration (Leite-Filho et al., 2019; Leite-Filho et al., 2020; Wright et al., 2017). "

3. Additionally, precipitation is quite heterogeneous in the landscape, even when trying to minimize by selecting neighboring 'control' and different percentages of forest changes (l110-112). To tie the change to deforestation, and associated magnitude to the forest loss, one needs to first prove that there are no changes in the control itself and if there are, the magnitude changes in the deforested areas are significantly larger. This is not shown.

Response: We thank reviewer #1 for raising a pathway for improvement in our analysis. In the first submitted version of the manuscript, we had only selected grid cells with different ranges of forest cover that were neighboring each other, but our comparisons of climate variables between these grid cells considered their entire distribution across the study area, not pairwise differences between neighbors. In this new version, we modified the analysis to explicitly define a reference group of grid cells (regions with forest cover>80%) from which our deforested grid cells (groups with forest cover ≤40%, 40-60%, and 60-80%) had their climate averages compared against. We ensured our selection of 0.5° grid cells was restricted to deforested regions and reference regions neighboring each other. We then computed pairwise climate differences between deforested vs. reference neighboring regions and compared their distribution with that of pairwise differences between reference vs. reference neighboring regions that were also neighboring deforested regions.

This approach allowed us to assess if the magnitude of climate differences between deforested vs. reference neighboring regions was significantly larger than climate differences majorly driven by factors other than deforestation from the reference vs. reference neighboring regions. We used the Two-Sample Kolmogorov Smirnov test to assess significant differences in these distributions at the 0.05 level, and Welch's t-test to assess significant differences in the mean of distributions at the 0.05 level. With this approach we also attempted to quantify the contribution of deforestation to the climate differences observed between deforested vs. reference regions, using climate differences between reference vs. reference regions to offset the contribution of factors other than deforestation. These analyses are presented in the Results section "The impact of Amazon forest cover on regional climate", illustrated in Figure 1, and further explained in the Methods section.

4. Additional concern is with the split period of evaluation (which is not "decadal" - the text should avoid calling it decadal changes). When comparing 2003-2012 (9 years) with 2013-2021 (8 years), there are *two ENSO years in the last 8 years, which brought more extreme effects (Mattar et al. 2016). How does analysis count for the extreme events without introducing bias in the "decadal" changes?*

Response: In this new version of the manuscript, we did not include the analyses from the section "The effect of forest loss over 2003-2021 on decadal changes in climate variables", which presented comparisons across split periods (2003-2012 and 2013-2021). This modification avoids confusion in the text related to terminologies and improves the clarity of our analyses throughout the text, thus addressing the need for better readability in the text as raised by both reviewer #1 and #2. Our analyses now are focused on comparisons of climate averages over 2013-2021 among regions with different extent of forest cover, as previously presented in the "Effect of regional forest cover on climate variables in the last decade" section. We also avoided the terminology "decadal" in this new version of the manuscript.

To account for the potential influence of interannual climate variability such as ENSO in our comparison of climate averages over 2013-2021, we selected two extreme drought years and two non-drought years within the 2013-2021 period to perform the same comparisons done for the whole time series. We selected the 2015 and 2016 years as representatives of extreme drought conditions in the Amazon influenced by the El Niño and anomalous warming in the North Atlantic Ocean, while the 2013 and 2018 years were selected as representatives of non-drought conditions in the Amazon (Aragão et al., 2018; Silveira et al., 2022; Tian et al., 2021). We calculated the average of climate variables in the extreme drought years, non-drought years, and the whole time series, and computed pairwise differences in these averages between deforested vs. reference regions and between reference vs. reference regions. We then compared the deforested vs. reference and reference vs. reference distributions of climate differences with the Two-Sample Kolmogorov test and Welch's t-test, for each time period and climate variable (tables with p-values are shown in the Supplementary Table 2).

This analysis revealed that differences in deforested vs. reference regions for driest-period ET and rainfall remained significantly more negative compared to differences in reference vs. reference regions during extreme drought years and non-drought years. In other words, deforested regions continued to present lower ET and rainfall than reference regions during extreme drought years in a magnitude that is significantly larger than the one driven by factors other than deforestation. In addition, the mean magnitude of climate differences between deforested vs. reference regions among the whole time series, extreme drought years, and non-drought years, was not significantly different at the 0.05 level based on Welch's t-test. In summary, these analyses provide evidence that patterns found for climate shifts in deforested regions have not been biased by interannual climate variability, such as the one driven by ENSO. Findings and explanations for this analysis can be found in "The impact of Amazon forest cover on regional climate" section of Results, Supplementary Table 2, Supplementary Figure 1, and Methods.

5. Another major concern comes from the statements presented both in the abstract (L32-33), and the conclusions of the work (L458-461). The statistical analysis used doesn't support pinpointing thresholds, and such is only presented at the end of the manuscript. It is dangerous to present such without clear and strongly supported evidence. One could interpret (as stated) that keeping 50% of forest is already enough to not trigger deforestation-driven climate change, and this work cannot support it. To what extent temporally? To what extent spatially (as the text also switches back and forth between local and regional)?

Response: We acknowledge the reviewer's concern that we did not present enough evidence to pinpoint precisely the threshold of forest cover in which deforestation-driven climate change is not significantly triggered. This approach would require a larger number of samples than the ones we found suitable for working with forest cover ranges. In this new version of the manuscript, we did not include statements pinpointing specific thresholds and focused our discussion and conclusion on the ranges of forest cover that we worked with (≤40%, 40-60%, 60-80%, and >80% - reference). For these ranges, our findings provide different lines of evidence supporting the idea of larger climate impacts of deforestation for regions with forest cover <60% (as shown in Figures 2 and 3). But even for our deforested regions with 60-80% forest cover, our findings still indicate significant climate impacts of deforestation. Our new findings brought more comprehensive insights on the impacts of deforestation that changed our interpretation of thresholds in the first submitted version. In this new version, our findings provide scientific support to Brazil's Forest Code requirement of keeping farmlands in the Amazon with 80% of their area protected by forests. Statements about forest cover ranges are now presented in the text as follows:

In the Abstract:

"Our findings show compelling evidence that forest loss has contributed with climate shifts towards warmer land surface temperatures (LST), lower evapotranspiration (ET), lower driest-period rainfall, and less rainy days, especially in regions with forest cover <60%."

In the Discussion:

"After controlling the role of deforestation from other factors such as differences in topography, external moisture sources, and natural climate variability, our findings consistently show negative impacts of deforestation on climate, mainly in our mostly deforested regions (<60% forest cover)."

"Recently, bills have been proposed in Brazil (PL No. 3334/2023 at the federal level and PLC No. 18/2024 from Mato Grosso State) with the potential to reduce the 80% forest cover threshold to 50% or even 35% in some regions of the Amazon. We demonstrated in our study that deforestation impacts on climate are already evident in regions with 60-80% of forest cover, but these impacts increase in intensity as the range of forest cover decreases. Thus, maintaining the 80% threshold of forest cover as originally stated by law is crucial to minimally sustain climate benefits from forests at the regional level. Under highly deforested regions, climate-based economic activities such as agriculture can face higher risks and climate impacts, as the long-term effects of climate change are exacerbated by deforestation."

6. Regarding the analysis of "wet and dry season". Was the three consecutive months with the highest rainfall volume consistent year-to-year? Were the dry months also consistent year-to-year? (L556-558). And across the spatial scale? This is important to state since those periods can change year to year and the onset of dry and wet season is spatially distinct across the Amazon.

Response: We computed the wettest and driest periods in each grid cell according to their corresponding rainfall climatology over 1990-2020 based on CHIRPS data. First we computed the monthly mean rainfall over 1990-2020 in each grid cell and then identified their three consecutive driest months and wettest months. Thus, these months varied across grid cells.

We now provide maps showing the spatial variation of wettest and driest periods in Supplementary Figure 2. We decided to identify these months based on the rainfall climatology, rather than year-to-year, to reduce the degree of complexity in this analysis. The chosen months for each grid cell provide a general representation of wetter and drier periods of the year in each grid cell. The use of different months year-to-year could introduce additional bias in our comparisons due to additional confounding factors from year-to-year variations.

For the 204 grid cells used in our comparison of climate averages between deforested vs. reference neighboring regions, we assessed the percentage of grid cells in which there is a match of at least two months between their three consecutive wettest and driest months defined year-to-year and those defined by the rainfall averages of 1990-2020 (Figure 1). This assessment was performed for each year of our time series, which covered 2013 to 2021. We found that, for any year of our time series, at least 80% of grid cells have two or three of their three consecutive wettest and driest months matching the wettest and driest periods defined by the 1990-2020 rainfall climatology. This indicates that our approach for defining fixed wettest and driest periods for each grid cell based on their climatology provides a good representation of year-to-year wet and dry periods in most of the grid cells.

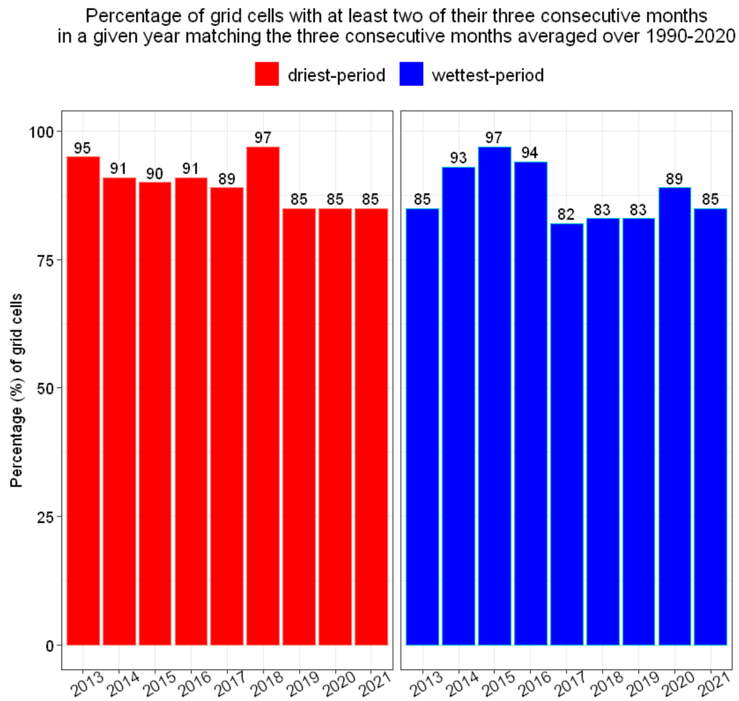

Figure 1. Percentage of grid cells (out of a 204 total) having at least two of their three consecutive wettest and driest months, for each year during 2013 to 2021, matching the wettest and driest months defined for each grid cell based on their rainfall climatology from 1990-2020.

We now present a clearer explanation in the Methods section for the computation of wettest and driest periods, as follows:

"Wettest and driest periods were computed for each 0.5° grid cell according to their corresponding rainfall climatology from 1990-2020 derived from CHIRPS. We computed the monthly mean rainfall over 1990-2020 in each grid cell and then identified their three consecutive wettest and driest months. Supplementary Figure 2 shows the spatial variation in wettest and driest periods across the Amazon. Our definition of fixed wettest and driest periods over time, based on rainfall climatology, also shows a good correspondence with year-to-year variations in wettest and driest periods during 2013 to 2021 for the majority of grid cells (Supplementary Figure 3), providing a good representation of wet and dry periods in general."

7. Lastly, the manuscript itself is not easy to read and comprehensive. Because several analyses were done using similar approaches, but splitting periods, without splitting periods, between control and deforestation, and across distinct scales (0.5 and 1.5), I would highly recommend that the authors combine results and discussions, and clearly state which results they are referring to and analysis.

Response: We acknowledge the reviewer's point that using different splitting periods across sections of Results, different approaches to address the role of deforestation, different filtering approaches to select control neighbors, and different scales, were making the text difficult to read. In this new version of the manuscript, we brought modifications that greatly improved the cohesion of our approach and clarity of the text. First, we decided to focus our comparisons on climate averages during 2013-2021, rather than dividing one section of Results for changes in climate variables over 2003-2012 to 2013-2021 and another section to climate averages over 2013-2021. Second, we only worked with 0.5° grid cells instead of additionally working with the 1.5° resolution. Third, we assessed the role of deforestation through comparisons among regions with different ranges of forest cover in 2021, rather than additionally assessing comparisons for different rates of forest loss during 2003-2021. Lastly, grid cells used in our two sections of Results were pooled from the same controlling mechanism of neighbors. We decided that keeping Results and Discussion separated in this new version would be more suitable, as merging them would make the sections too long. In this clearer and more cohesive version of the text, the Discussion section can be easily linked to Results.

8. Additionally, there are several sentences that are unclear. For example:

Responses:

L356-361: Unclear whether they discuss their own observations or others.
We were discussing our own observations, but this part was removed in the new version of the manuscript.

L362-364, "during 2003 to 2021" is it a "decadal" split evaluation or a continuous analysis?
That "during" was referring to the change from 2003-2021 to 2013-2021. This part was removed in the new version of the manuscript and we ensured our statements using "during" are better contextualized in this new version.

L373-375, "increase in driest period rainfall during the past two decades", increase in relation to what if the two "decades" are referred to?
That increase was referring to the change from 2003-2012 to 2013-2021. However, this part was not used in the new version of the manuscript.

L444-447: Unclear – check the sentence structure.
This sentence was modified in the new version of the manuscript as follows:
"In the same way our findings indicated that extensive forest loss can contribute to shift climate conditions away from those observed in highly forested areas, large-scale forest restoration can possibly bring climate conditions closer to this reference state, such as by reducing LST (Prevedello et al., 2019; Zhang et al., 2024) and increasing ET and recycled rainfall (Tuinenburg et al., 2022)."

L458-459: What are "optimal levels of ET"? Defined based on what?
Those optimal levels were referring to the magnitude of ET in regions with forest cover>80%. In this new version of the manuscript we did not use the word "optimal" to discuss our own results and ensured that comparisons with reference regions (forest cover >80%) were well contextualized.

References for reviewer #1

Aragão, L. E., Anderson, L. O., Fonseca, M. G., Rosan, T. M., Vedovato, L. B., Wagner, F. H., ... & Saatchi, S. (2018). 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature communications*, 9(1), 536.

Baker, J. C. A. & Spracklen, D. V. Climate Benefits of Intact Amazon Forests and the Biophysical Consequences of Disturbance. *Front. For. Glob. Change* 2, 47 (2019).

Khanna, J., Medvigy, D., Fueglistaler, S. & Walko, R. Regional dry-season climate changes due to three decades of Amazonian deforestation. *Nature Clim Change* 7, 200–204 (2017).

Khanna, J., Medvigy, D., Fisch, G., & de Araújo Tiburtino Neves, T. T. (2018). Regional hydroclimatic variability due to contemporary deforestation in southern Amazonia and associated boundary layer characteristics. *Journal of Geophysical Research: Atmospheres*, 123(8), 3993-4014.

Knox, R., Bisht, G., Wang, J., & Bras, R. (2011). Precipitation variability over the forest-to-nonforest transition in southwestern Amazonia. *Journal of Climate*, 24(9), 2368-2377.

Flores, B. M. et al. Critical transitions in the Amazon forest system. *Nature* 626, 555–564 (2024).

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M. & Börner, J. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nat Commun* 12, 2591 (2021).

Maeda, E. E. et al. Large-scale commodity agriculture exacerbates the climatic impacts of Amazonian deforestation. *Proc. Natl. Acad. Sci.* U.S.A. 118, e2023787118 (2021).

Negri, A. J., Adler, R. F., Xu, L. & Surratt, J. The Impact of Amazonian Deforestation on Dry Season Rainfall. *J. Climate* 17, 1306–1319 (2004).

Silveira, M. V. F., Silva-Junior, C. H. L., Anderson, L. O. & Aragão, L. E. O. C. Amazon fires in the 21st century: The year of 2020 in evidence. *Global Ecol Biogeogr* 31, 2026–2040 (2022).

Smith, C., Baker, J. C. A. & Spracklen, D. V. Tropical deforestation causes large reductions in observed precipitation. *Nature* 615, 270–275 (2023).

Staver, A. C., Archibald, S. & Levin, S. A. The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. *Science* 334, 230–232 (2011).

Theeuwen, J. J., Staal, A., Tuinenburg, O. A., Hamelers, B. V., & Dekker, S. C. (2023). Local moisture recycling across the globe. *Hydrology and Earth System Sciences*, 27(7), 1457-1476.

Xu, X. et al. Deforestation triggering irreversible transition in Amazon hydrological cycle. *Environ. Res. Lett.* 17, 034037 (2022).

Reviewer #2:

0. The manuscript is very interesting. Despite the large number of studies focused on the Amazon deforestation, the authors were able to evaluate deforestation-LST relationships with a novel approach.
I find the manuscript generally well written, though the methods were difficult to understand. As the manuscript analyses the feedback at two spatial resolutions (scale is composed of resolution and extension, thus in my opinion the use of “scale” should be exchange by “resolution”), I missed the evaluation of how the response to deforestation changes due to a change in resolution. On its current version, the manuscript does not discuss the implications of resolution on the temperature and ET response. Is the feedback dependent on the resolution? And if it is, which extend of deforestation is “visible” at a coarse resolution?

Response: We thank reviewer #2 for carefully reading our manuscript and providing valuable comments. We acknowledge the lack of detail about the role of spatial resolution on the previous version of the manuscript. In this new version, it was necessary to improve our control mechanisms when analyzing deforestation-climate relationships to reduce bias from climate drivers other than deforestation. Such updates led to fewer grid cells meeting the necessary criteria to be included in the analysis, so we decided to work only with 0.5° grid cells, instead of 1.5° as well, and differences in deforestation-climate feedbacks across spatial resolutions are not a central component of our manuscript in this new version.

We further elaborate on our justification for the 0.5° resolution here on Topic 7. We included a sentence in the Discussion highlighting that the impacts of deforestation on climate found in our study are constrained to the 0.5° resolution and could differ in other resolutions, as follows:

"We also stress that our findings for deforestation-induced impacts on climate are constrained to regions with 0.5° spatial resolution (~55 x 55 km). Different patterns or magnitudes for deforestation-climate relationships could be found at different spatial resolutions, such as larger impacts on LST and ET at higher resolutions, and larger reductions on rainfall at lower resolutions, as suggested by previous studies (Baker & Spracklen, 2019; Leite-Filho et al., 2021; Reygadas et al., 2023; Smith et al., 2023)."

Moreover, we now used the terminology "resolution" throughout the text when referring to our grid size of 0.5°, instead of scale. Lastly, we improved the readability of the Methods section.

Below I provide comments for each section.

Methods

1. I find the methods section very hard to understand. A flux diagram summarizing the section would be very helpful. I strongly recommend re-writing this section to make it clearer to the reader, as on its current structure, it does not provide enough information to reproduce the experiment.

Response: We rewrote a substantial part of the Methods section and this new version has a better readability. We acknowledge that part of the difficulty in understanding our methods was due to the different time intervals analyzed, different approaches to address the role of deforestation, different filtering approaches to select control neighbors, and different spatial resolutions. We have made substantial modifications in the analyzes that led to a more cohesive approach to assess our results and consequently a clearer and easier to reproduce Methods section. Theses modifications included removing analyses for the "Changes in climate during the past two decades across the Amazon" and "The effect of forest loss over 2003-2021 on decadal changes in climate variables" sections of Results, while using samples for the two current sections of Results ("The impact of Amazon forest cover on regional climate" and "The observed climate in highly deforested areas shares similarities with transitional regions between moist forests and savannas") that were pooled from the same selection of grid cells. Additionally, to better illustrate our approach to compute climate differences between deforested vs. forested regions, we created a figure showing the selected grid cells for the analyzes together with a panel exemplifying how these climate differences were calculated (Figure 1).

2. The reference for Andrade et al., (2024) is absent from the Reference section. As this is a key input in methodology, it is not possible to evaluate the manuscript's robustness.

Response: Thank you for pointing this out. The reference is now included.

3. Line 520-539: Why not use the MSWEB dataset for precipitation?. On this set biases due to lack of weather stations have been complemented by IMERG and ERA5.

Response: We thank reviewer #2 for the suggestion. However, in this study we aim to provide an observational approach to assess deforestation-climate relationships, so our climate data needs also to be as observational-based as possible. In this sense, CHIRPS uses daily precipitation from reanalysis data as a basis to define how their observational-based pentad precipitation will be proportionally disaggregated into daily values (Funk et al., 2015). On the other hand, MSWEP directly merges reanalysis data with gauge and satellite data to derive its precipitation estimates (Beck et al., 2019). When comparing the performance of gridded precipitation products against gauge observations in the Amazon, Sapucci et al. (2014) showed that CHIRPS presented a higher or as high performance than MSWEP for most sub-regions of the Amazon basin. Therefore, we decided to keep with CHIRPS in our analysis given its good performance and observational-based characteristics.

4. Line 509 states that the data from Andrade et al., (2024) yielded the highest accuracies but it is not clear if the statement comes from Andrade et al., or the current manuscript. Please clarify. If the second case is true then authors must demonstrate the statement.

Response: That statement was indicating results from Andrade et al. (2024), not ours. To make this sentence clearer, we rewrote it as follows:

In the "Climate variables" section of Methods:

"According to an assessment of ET products against flux tower data and water balance of river basins in the Amazon, performed by Andrade et al. (2024), geeSEBAL-MODIS yielded the highest accuracies, outperforming commonly used ET products such as MOD16 and ERA5."

5. The treatment of CHIRPS data is appropriate, and the uncertainty well assessed. As a comment, the authors could have used MSWEP since also is as accurate as CHIRPS for the Amazon (Sapucci et al., 2022).

Response: We thank the reviewer for the suggestion. In addition to the reasons provided in Topic 3 for our use of CHIRPS over MSWEP, in this new version of the manuscript we only worked with climate averages during the 2013 to 2021 period. Thus, bias from the highly divergent number of stations before to after 2010 in northern Peruvian Amazon is not a relevant technical issue to be addressed as it was in the previous version of the manuscript.

6. Cordeiro and Blanco (2021) not in references Section. Please add.

Response: Thank you for pointing this out. The reference is now included.

7. Lines 479-492 It is not clear to me the use of two grid sizes. Authors need to provide more methodological information on the approach to study the impacts on temperature and precipitation. The citation of the studies of Cohn et al., (2019) and Smith et al., (2023) is necessary but it is not clearly justified. Authors needs to expand on the mechanisms behind the use of the 0.5 and 1.5° grid size for temperature and precipitation, respectively.

Response: As previously mentioned, we expanded and improved controlling mechanisms on the role of deforestation from other climate drivers, in addition to updating the way in which we compare climate averages among regions with different extent of remaining forest cover. In light of these modifications, we decided to maintain only grid cells with 0.5° spatial resolution for our analyses. After applying all criteria to control the role of deforestation, according to grid cells grouped by the extent of forest cover, the group with the smallest number of samples (forest cover <≤40%) had 12 grid cells. If we had used the 1.5° grid size, the final selection would retrieve an even lower number of samples for this group. Moreover, in this new manuscript version, we compared climate averages between deforested grid cells and their neighboring forested grid cells. We assumed in this comparison that neighboring grid cells shared a similar influence of factors other than deforestation, which was important to estimate the isolated climate impacts of deforestation. If we had used the 1.5° spatial resolution, given its larger extent (~166 km), it would be less likely to assume that neighboring regions are sharing similarities for background factors. In the introduction, we provided more information on diverging results in previous studies for deforestation-rainfall relationships at scales smaller than 200 km, which shows the importance of additional studies using smaller grid sizes. We also extended our justification for the 0.5° resolution in the Methods section. Here are the updates in the text:

In the Introduction:

"However, deforestation-induced effects on climate may depend on several factors that remain open for investigation, including the scale of observation, seasonality, and the intensity of forest loss in terms of extent or rate. For instance, studies point to different effects of deforestation on rainfall at scales smaller than 200 km. Increased cloudiness and rainfall over deforested areas is suggested to occur in the dry season due to changes in mesoscale circulations, such as the vegetation breeze process (Khanna et al., 2017; Negri et al., 2004; Roy, 2009; Saad et al., 2010). As the extent of deforested area increases, rainfall can be redistributed to decrease in the interior of deforested regions and increase near forest edges in the prevailing wind direction (Khanna et al., 2018; Knox et al., 2011). However, rainfall decreases due to deforestation have also been suggested for scales of 0.5° or smaller for all seasonal periods, with larger reductions as the scale increases (Leite-Filho et al., 2021; Reygadas et al., 2023; Smith et al., 2024), or even no significant relationships at all (Baker & Spracklen, 2019). Moreover, deforestation has been suggested to negatively impact rainfall seasonality, such as by delaying wet season onset and increasing the occurrence of longer dry spells (Xu et al., 2022; Leite-Filho et al., 2019; Wright et al., 2017)."

In the Study region section of Methods:

"We worked with grid cells of 0.5° (~55 km) spatial resolution, a size that allows for a good number of samples considering the several criteria we applied to select grid cells and control the role of deforestation from other drivers. Part of our analysis consists of comparing neighboring grid cells with different extent of forest cover, assuming they share a similar climatic background. In this sense, the larger the grid size, the less likely would neighboring grid cells share similar climatic backgrounds. Moreover, according to Cohn et al. (2019), non-local forest loss can influence temperature in areas within 50 km of distance most likely through heat advection. By using the 0.5° resolution, we therefore minimize the influence of deforestation from a given grid cell on land surface temperature in another neighboring grid cell. In addition, previous studies have found diverging impacts of deforestation on rainfall at the 0.5° resolution (Leite-Filho et al., 2021; Smith et al., 2023; Xu et al., 2022), which reinforces the importance of additional studies for land-atmosphere interactions for grid sizes within this range."

8. Line 591-592 Can you please provide evidence of the minimum number of grid cells for statistical comparisons?. Please provide evidence of the minimum number of samples and confidence level.

Response: In this new version of the manuscript, we applied several criteria to select grid cells for comparisons of climate differences according to the extent of forest cover, which includes: deforested grid cells (grouped by forest cover ≤40%, 40-60%, 60-80%) neighboring reference grid cells (forest cover >80%) within a 3x3 window and vice-versa; grid cells with negligible forest loss during 2013-2021; pairwise climate differences between neighboring grid cells in the same Koeppen climate zone. There were additional criteria applied to quantify the isolated impact of deforestation on climate variables, as explained in the "Estimating the isolated effect of deforestation" from the Methods section. These criteria were important to minimize the role of confounding factors in our deforestation-climate assessments. Our final number of samples therefore was conditioned by the grid cells in each forest cover group that met such criteria. The lowest number of samples was found for the group with forest cover ≤40%, which had

12 grid cells and 17 pairwise comparisons with neighboring reference grid cells. Despite the small number of samples, we ensured these samples satisfied our controlling criteria and thus provide robust assessments for the role of deforestation on climate differences against reference grid cells.

We used the Welch's t-test and Two-sample Kolmogorov-Smirnov tests to compare climate differences between grid cells with forest cover ≤40% vs. their reference neighbors (17 pairwise differences) against climate differences between reference vs. reference neighbors (148 pairwise differences). This comparison aimed to indicate if climate differences driven by deforestation were larger than differences driven by background factors. The reference vs. reference neighbors in this first assessment included only grid cells that were also neighboring deforested grid cells. In a second assessment, to evaluate the consistency of patterns indicated by the first assessment, climate differences between grid cells with forest cover ≤40% vs. their reference neighbors (17 pairwise differences) were also compared against 1000 randomly selected samples with 150 pairwise differences between reference vs. reference neighbors across our entire study region. We then retrieved the 95% confidence interval of the 1000 p-values found for both Welch's t-test and Two-sample Kolmogorov-Smirnov test. More details on the approach can be found in the "Climate differences between deforested and reference regions" section of Methods and Figure 1. Even after 1000 tests against reference vs. reference distributions, our results confirmed that climate differences linked to deforestation remained consistently larger than those linked to background factors for some climate variables (Supplementary Material Table 1), reinforcing that our small number of samples provide robust patterns for deforestation-climate relationships. More information for these results can be found in the "The impact of Amazon forest cover on regional climate" section of Results.

We also included in the manuscript the 95% confidence intervals for estimates of the isolated impact of deforestation on climate, after offsetting the contribution of background factors in the climate differences between deforested vs. reference neighbors. The approach for calculating these estimates can be found in the "Estimating the isolated effect of deforestation" section of Methods. We applied a rigorous criteria to select grid cells viable for this estimation, which resulted in 9 grid cells with forest cover ≤40% and 20 with 40-60% forest cover, thus mentioning the 95% confidence intervals in the text helped to indicate the degree of certainty in our estimates. We also mentioned in the Discussion section the limitation in our estimates with respect to sample size, reinforcing the importance of additional estimates by future studies, as follows:

"One caveat from our estimates is the low number of samples, as a consequence of the high level of controls applied for confounding effects. The quantification of deforestation effects from observations is still an incipient field, so future studies will be essential to weigh the consistency of observational estimates provided in the scientific literature so far."

9. Authors do not provide the number of samples in the 1.5° resolution.

Response: Thank you for pointing this out. In this new version of the manuscript, we did not use grid cells with 1.5° resolution. For the 0.5° grid cells, the number of samples used for all analyses were properly listed in the Methods section.

10. Line 660 Add a sentence at the beginning of the subsection explaining the purpose of "Climate characteristics of biomes". On its current form, it is not clear the objective of this particular analysis in the Methods section.

Response: Thank you for the recommendation. We introduced a sentence explaining the objective of this analysis. Now the paragraph starts as follows:

"This analysis aimed to evaluate if climate averages in highly deforested regions have shifted away from reference conditions in highly forested regions to become more similar to other biomes. We used data for biome distribution in the Amazon provided by Dinerstein et al. (2017), based on the work of Olson et al. (2001), which provided a consistent evaluation and delimitation of biome boundaries. …."

Abstract

11. Lines 24-25 As the abstract does not explain previously what 0.5° and 1.5° scale means, this confuses the reading. Please remove or explain what these scales mean.

Response: Thank you for the recommendation. This sentence was removed from the abstract.

Introduction

12. Line 49 Need a citation at the end of the paragraph

Response: A citation was now included at the end of that sentence, as follows:
"Regional changes in the Amazon climate can be driven not only by the global increase of atmospheric concentration of greenhouse gases but also by extensive and ongoing deforestation (Bonan, 2008; Lawrence & Vandecar, 2015; Artaxo et al., 2022)."

14. The research has some level of novelty in addressing combining the effects of deforestation at two different scales, seasonality and heterogeneity in the Amazon.

Response: We are glad to know that reviewer #2 acknowledged the novelty presented in our study. Even though we only worked with the 0.5° spatial resolution in this new version, our study maintained its novelty in presenting an integrated approach to assess deforestation impacts on several climate variables for different seasonal periods and different levels of forest cover extent.

15. The results are very interesting and well presented. It is interesting that results are presented based on how LST relates to percentage of forest cover and seasonality.

Response: We are happy to know that reviewer #2 liked the way our results were presented. In this new version of the manuscript, Figure 2 provides a very clear and assertive demonstration on how deforestation-induced increases in LST are larger as the remaining forest cover decreases, especially during the driest period of the year.

Discussion

16. Line 335. In this line there is a very important sentence about the increase in LST not directly related to deforestation fall below 0.5°C. However, I do not see any evidence supporting this sentence. Please justify.

Response: The 0.5°C in that sentence was referring to the observation that most grid cells with no forest loss had average changes of LST from 2003-2012 to 2013-2021 of less than 0.5°C. In this new version of the manuscript, we did not work with the 2003-2012 to 2013-2021 change analysis, so that statement was removed from the discussion. However, for our analysis of differences in climate averages between deforested vs. reference (>80% forest cover) regions against reference vs. reference regions, we mentioned in the Results section the influence of deforested on larger LST values as follows:

"Differences in land surface temperature (LST) between neighboring reference regions have a balanced distribution of positive and negative values (Figure 2), ranging for example from -0.86° to 1.69°C (5th and 95th percentiles in driest period). The distribution of differences between deforested and reference regions, however, show most entirely positive values, indicating higher LST as the remaining forest cover decreases. For the regions with forest cover ≤40% or 40-60%, positive differences far exceed those found between reference vs. reference for background factors, reaching values as large as 4.3 °C (95th percentile in the driest period)."

17. It is very interesting that highly deforested areas still share climatic similarities with both moist forests and savannas.

Response: We are glad to know that reviewer #2 liked our finding for climatic similarities in deforested regions with both moist forests and savannas. Even in this new version of the manuscript, where the samples used to represent highly deforested regions and highly forested regions were altered, we still found climatic similarities in highly deforested regions with transitional regions between moist forest and savannas. The distribution of LST averages in highly deforested regions was closer to the distribution of savannas than moist forests. The annual rainfall and the number of rainy days, however, were not significantly different between highly deforested and highly forested regions. Nevertheless, the distribution of driest period rainfall in highly deforested regions was not significantly different from all other biome categories, and the means were not significantly different from highly forested regions and transitional regions. In summary, our findings indicate that deforested regions present climatic similarities with transitional regions, supporting climate conditions for both moist forest and savanna biomes.

References for reviewer #2

Andrade, B. C., Laipelt, L., Fleischmann, A., Huntington, J., Morton, C., Melton, F., ... & Ruhoff, A. (2024). geeSEBAL-MODIS: Continental-scale evapotranspiration based on the surface energy balance for South America. *ISPRS Journal of Photogrammetry and Remote Sensing*, *207*, 141-163.

Baker, J. C. A. & Spracklen, D. V. Climate Benefits of Intact Amazon Forests and the Biophysical Consequences of Disturbance. *Front. For. Glob. Change* 2, 47 (2019).

Beck, H. E., Wood, E. F., Pan, M., Fisher, C. K., Miralles, D. G., Van Dijk, A. I., ... & Adler, R. F. (2019). MSWEP V2 global 3-hourly 0.1 precipitation: methodology and quantitative assessment. *Bulletin of the American Meteorological Society*, *100*(3), 473-500.

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *science*, *320*(5882), 1444-1449.

Cordeiro, A. L., & Blanco, C. J. C. (2021). Assessment of satellite products for filling rainfall data gaps in the Amazon region. *Natural Resource Modeling*, *34*(2), e12298.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., ... & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific data*, *2*(1), 1-21.

Lawrence, D., & Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. *Nature climate change*, *5*(1), 27-36.

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M. & Börner, J. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nat Commun* 12, 2591 (2021).

Reygadas, Y., Spera, S. A., & Salisbury, D. S. (2023). Effects of deforestation and forest degradation on ecosystem service indicators across the Southwestern Amazon. *Ecological Indicators*, *147*, 109996.

Sapucci, C. R., Mayta, V. C., & da Silva Dias, P. L. (2022). Evaluation of diverse-based precipitation data over the Amazon Region. *Theoretical and Applied Climatology*, *149*(3), 1167-1193.

Smith, C., Baker, J. C. A. & Spracklen, D. V. Tropical deforestation causes large reductions in observed precipitation. *Nature* 615, 270–275 (2023).

Second Peer Review - COMMSENV-24-3350

Response to reviewers regarding the manuscript "Observed shifts in regional climate linked to Amazon deforestation"

We thank the editor and additional reviewers #3 and #4 for their valuable perspectives and recommendations, which have been addressed in this revised version of the manuscript. Thanks to these recommendations, our manuscript is now more readable and clear about the limitations of our approach. We provide below a summary of the major changes performed in the manuscript, followed by a point-by-point response to the reviewers.

Summary of Changes

Following recommendations from reviewers #3 and #4, we revised the entire text to improve its readability, extending the Methods section and providing clearer and additional explanations of our approach in the Introduction and Results subsections. Following the editor recommendations and points raised by reviewers #3 and #4, we provided a more detailed explanation in the Discussion about the uncertainties associated with our approach and the potential influence of moisture recycling in our findings. In line with comments from reviewer #3, we included paragraphs in the Discussion that mentioned the role of landscape configuration and wind direction in our comparison of deforested and forested neighboring cells, and how these factors can influence our comparisons. In line with comments from reviewer #4, we provided clearer statements in the Introduction about the novelties of our approach and how it diverged from previous studies, in addition to extending, in the Discussion, the comparison of our findings with those of previous studies.

We have also updated or extended some of the analyses to improve the quality and outreach of our work. We simplified our approach for estimating the impacts of deforestation on climate, providing a method that is easier to interpret. In the previous version, we estimated deforestation impacts for each group of deforestation extent, as previously shown on Figure 3. In this new version, we normalized the estimates among our deforestation groups by the forest cover differences between deforested and forested neighbors. These normalized estimates indicate the climate impact (i.e., change in the average of a climate variable) associated with deforestation per percentage point reduction in forest cover. The previous Figure 3 was then replaced by a table in which we show the mean and 95% confidence interval of normalized impacts of deforestation, which are estimates integrated over all our deforestation groups. These normalized estimates allow for a more direct comparison with estimates from other studies. The new Figure 3 now shows boxplots for the distribution of climate differences between our three groups of deforested cells vs. reference, indicating the significance of differences in the mean among groups, based on Welch's t-test. We also updated the right panel on Figure 1 to improve its interpretation and conform with this new approach. Moreover, the wettest-period and driest-period terms were replaced respectively by wet season and dry season, with the proper explanation in the text that we defined these seasons by the three consecutive wettest and driest months according to climatology from 1990-2020. The use of wet and dry season facilitates the interpretation of our findings in light of other studies, considering also that previous studies have defined seasonality using similar methods.

For the comparisons of climate envelopes between highly deforested regions and biome categories, we included a table in the Supplementary Information in which we show the percentages of highly deforested and forested samples that are in the climate envelope of savannas, for each climate variable. This table shows the climate variables that better distinguish highly deforested regions from the highly forested ones in terms of conformity with the climate envelope of savannas. We used these findings to choose the most suitable variables to comprise the map of Figure 5, which shows the level of similarity of moist forest cells across the Amazon with the climate envelope of Amazon savannas. Previously, the map was based on LST, ET, and rainfall during the dry season, plus the number of rainy days, but now is based on the annual LST, annual ET, wet season rainfall, and dry season rainfall.

Point-by-point response

Reviewer #3

0. As a second-round reviewer invited to evaluate the authors' response to Reviewer 1's concerns—particularly regarding moisture recycling—I found the manuscript interesting, and I believe the results are publishable.

The authors have made commendable efforts to revise their analysis in response to earlier critiques. Notably, they replaced the broad grouping of forested and non-forested areas with a more localized, paired comparison of adjacent cells within a moving window. This is a meaningful improvement, and the results are compelling.

Response: We thank Reviewer #3 for the time dedicated to evaluating our manuscript and acknowledging the efforts we have made to improve the robustness of our analyses. We further improved the quality of the manuscript in this new version by addressing the reviewer's recommendations.

1. However, spatial heterogeneity and scale effects remain only partially addressed. There is a key difference between selecting a few cells from a large, homogeneous deforested area and selecting cells that are part of a heterogeneous, small deforestation patch. This issue was highlighted in the review by D'Almeida et al. (2007). Introducing some form of scale grouping could provide additional insight. Additionally, scale itself is critical: how sensitive are the results to the size of the window used for pairing? A sensitivity analysis exploring the effect of varying window size would help assess the robustness of the patterns observed.

Response: We thank the reviewer for recommending points that needed further addressment in our manuscript. The selection of samples for comparing deforested and reference neighbors across the entire Amazon was a way to contemplate spatial heterogeneity in our study. Our findings have shown that deforestation impacts on climate show a consistent pattern across most of the samples (increases in LST and decreases in ET and dry season rainfall), in spite of spatial variations. Although directly evaluating the role of spatial heterogeneity was out of the scope of our study, we acknowledge that different amounts of forested areas surrounding our deforested cells, or even different spatial patterns of deforestation, can contribute to the observed variation of magnitude in climate differences between deforested and reference neighbors. We have now addressed this point as part of the Discussion section, as follows:

"In the comparison of rainfall between deforested and reference (forest cover>80%) neighboring regions, part of the variation of responses among our samples can come from processes such as landscape configuration and wind direction. For instance, the amount of forested areas surrounding the deforested area and how deforested areas are distributed across the landscape (e.g., large and continuous or small and fragmented patches) are suggested to be important factors for the deforestation-induced changes in mesoscale circulation and rainfall (Knox et al., 2011; Maeda et al., 2021; Roy et a., 2009)."

With respect to scale, we decided to focus on grid cells with 0.5° spatial resolution considering the limited evidence for deforestation impacts on land surface temperature and evapotranspiration at this resolution, while previous studies have found divergent evidence for deforestation impacts on rainfall at similar scales, which demands for additional evidence. Additionally, including other spatial resolutions in our study, and addressing them with the same rigor in the text, would compromise the readability of our manuscript. Nonetheless, we have improved our explanation in the Introduction about the variability of rainfall responses to deforestation depending on the spatial resolution. In addition, we have stressed in the Discussion that our findings are centered on the 0.5° resolution and different results could be found at different resolutions, as other studies have demonstrated.

The paragraph in the Introduction where we explain the role of scale is now as follows:

"However, deforestation-induced effects on climate may depend on several factors that remain open for investigation, including the scale of observation, seasonality, and the intensity of forest loss in terms of extent or rate. For instance, studies point to different effects of deforestation on rainfall at the mesoscale (~200 x 200 km or less). Increased rainfall over small-scale deforested areas is suggested to occur by changes in mesoscale circulations, such as the vegetation breeze process (Khanna et al., 2017; Roy, 2009; Saad et al., 2010). This effect has been identified for all seasons, and while most studies imply more pronounced deforestation-induced rainfall increases in the dry season and dry-to-wet season transition (Khanna et al., 2018; Negri et al., 2004; Saad et al., 2010), a predominant effect in the wet season has been recently suggested at spatial resolutions of up to 60 km (Qin et al., 2025). As the extent of the deforested area increases, rainfall can be redistributed to decrease in the interior of deforested regions and increase near forest edges in the prevailing wind direction (Khanna et al., 2018; Knox et al., 2011). However, rainfall decreases due to deforestation have also been detected with resolutions ranging from 0.05°(~5.5 km) to 1000 km at all seasonal periods, with increased reductions as spatial resolution decreases up to a certain threshold. Results, however, still diverge on the seasonal impacts and the spatial resolution in which rainfall changes are more pronouncedly detected (Franco et al., 2025; Leite-Filho et al., 2021; Leite-Filho et al., 2024; Reygadas et al., 2023; Smith et al., 2023; Qin et al., 2025). Even non-significant relationships between deforestation and rainfall have been found for resolutions of 50 km or smaller (Baker & Spracklen, 2019; Debortoli et al., 2016). Moreover, deforestation has been suggested to negatively impact rainfall seasonality, such as by delaying wet season onset and increasing the occurrence of long dry spells (Xu et al., 2022; Leite-Filho et al., 2019; Wright et al., 2017)."

Still in the Introduction, on the use of the 0.5° spatial resolution:

"...We divided the Amazon territory into grid cells of 0.5° spatial resolution, a scale in which additional evidence is needed for deforestation-induced effects on rainfall, land surface temperature (LST) and evapotranspiration (ET)."

In the Discussion, we mentioned the scale-dependence of deforestation impacts on climate as follows:

"...We also stress that our assessments were based on regions with 0.5° spatial resolution (~55 km), and different patterns or magnitudes for deforestation-climate relationships can be found at different resolutions, as other studies have been demonstrating (D'almeida et al., 2007; Leite-Filho et al., 2024; Qin et al., 2025; Smith et al., 2023)."

2. Another important aspect is the relative position of forested and deforested patches with respect to prevailing wind direction, which would be relevant for moisture recycling. For instance, is the forested patch located upwind or downwind of the deforested area? This distinction is crucial for interpreting fluxes, and previous studies—such as those by Spracklen et al. (2012), Poveda et al. (2014), and Molina et al. (2019)—may provide useful context for this discussion.

Response: We thank the Reviewer for raising a limitation of our study that needed to be addressed in the text. Indeed, in our comparisons of climate differences between deforested and reference neighboring cells, some of the reference neighbors can be upwind or downwind from the deforested cell. This distinction, though not explicitly addressed in our analysis, can be contributing to the observed variation among our samples in dry season rainfall differences between deforested versus reference neighbors. However, this variation of upwind or downwind reference cells is also contemplated in our comparison of climate differences between reference versus reference neighbors, which was used to indicate the influence of background factors. By showing that rainfall differences between deforested versus reference neighbors are larger and more negative, compared to reference versus reference neighbors, our findings indicate that deforestation impacts are consistent in spite of these possible variations in upwind or downwind comparisons. We have addressed the potential influence of wind direction in the Discussion section, as follows:

"...Additionally, because rainfall in the deforested area can be influenced by the redistribution or recycling of moisture from the surrounding forested areas, rainfall comparisons between deforested versus reference neighbors can possibly generate different outcomes depending if the reference cells are upwind, paralleled, or downwind from deforested cells (Spracklen et al., 2012; Knox et al., 2011). Our analysis partially addressed spatial heterogeneity by comparing deforested and reference neighbors across the entire Amazon, and, despite spatial variations, our findings indicate a consistent pattern among our samples for deforestation-induced reductions in dry season rainfall. Future studies are needed to explicitly evaluate how spatial heterogeneity influences assessments of deforestation-induced changes in rainfall by observational approaches."

3. To be clear, I do not believe that new analyses are strictly required, as the current results are already of interest. However, I encourage the authors to address these scale and directional effects—whether through additional analyses, expanded discussion, or suggestions for future work.

Response: We thank the Reviewer for his valuable recommendations. We have improved the explanation of scale in the Introduction and extended our Discussion section to discuss the roles of landscape configuration and wind direction, recommending future studies in these directions. This current version of the manuscript has clearer explanations about the limitations of our study.

4. Finally, a structural note: the manuscript places the full Methods section after the Discussion, with each Results subsection containing a brief methodological summary. However, I found these summaries insufficient to fully understand the analyses as I was reading. The structure made it difficult to follow the reasoning behind some choices until much later in the manuscript. While this format may be allowed by the journal, I encourage the authors to reconsider it. The IMRD structure—Introduction, Methods, Results, and Discussion—remains widely used for good reason, and adopting it, or at least including a clearer overview of the methods earlier on, could significantly improve readability.

Response: Unfortunately, the IMRD format is not accepted by Communications Earth & Environment. However, we acknowledged the need to improve the readability of our text and explanation of our approaches. We extended the overview of methods in the Results subsection named *The impact of accumulated deforestation in the Amazon on regional climate,* and improved the interpretation and clarity of our approach throughout the entire text.This current version has clearer explanations of our approach.

Reviewer #3 References

D'Almeida, C., et al. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. International Journal of Climatology, 27(5), 633–647.

Molina, R. D., Salazar, J. F., Martínez, J. A., Villegas, J. C., & Arias, P. A. (2019). Forest-induced exponential growth of precipitation along climatological wind streamlines over the Amazon. Journal of Geophysical Research: Atmospheres, 124(5), 2589–2599.

Poveda, G., Jaramillo, L., & Vallejo, L. F. (2014). Seasonal precipitation patterns along pathways of South American low-level jets and aerial rivers. Water Resources Research, 50(1), 98–118.

Spracklen, D. V., Arnold, S. R., & Taylor, C. M. (2012). Observations of increased tropical rainfall preceded by air passage over forests. Nature, 489(7415), 282–285.

References from the Author's response

D'Almeida, C., et al. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *International Journal of Climatology*, 27(5), 633–647.

Knox, R., Bisht, G., Wang, J., & Bras, R. (2011). Precipitation variability over the forest-to-nonforest transition in southwestern Amazonia. *Journal of Climate*, *24*(9), 2368-2377.

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., & Börner, J. (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications*, *12*(1), 2591.

Leite-Filho, A. T., Soares-Filho, B. S., & de Oliveira, U. (2024). Climate risks to soy-maize double-cropping due to Amazon deforestation. *International Journal of Climatology*, *44*(4), 1245-1261.

Maeda, E. E., Abera, T. A., Siljander, M., Aragão, L. E., Moura, Y. M. D., & Heiskanen, J. (2021). Large-scale commodity agriculture exacerbates the climatic impacts of Amazonian deforestation. *Proceedings of the National Academy of Sciences*, *118*(7), e2023787118.

Qin, Y., Wang, D., Ziegler, A. D., Fu, B., & Zeng, Z. (2025). Impact of Amazonian deforestation on precipitation reverses between seasons. Nature, 639(8053), 102-108.

Roy, S. B. (2009). Mesoscale vegetation-atmosphere feedbacks in Amazonia. *Journal of Geophysical Research: Atmospheres*, *114*(D20).

Smith, C., Baker, J. C. A., & Spracklen, D. V. (2023). Tropical deforestation causes large reductions in observed precipitation. *Nature*, *615*(7951), 270-275.

Spracklen, D. V., Arnold, S. R., & Taylor, C. M. (2012). Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, *489*(7415), 282-285.

Reviewer #4

0. In their reviewed manuscript, authors have used observational data (0.5deg pixels) to estimate seasonal impacts of deforestation on climate variables over the Amazon lowland biome forest. These climate variables come mainly from MODIS/CHIRPS as forest data comes from MapBiomas Amazonia Collection 4. Authors have claimed to find an explicit cause-effect relationship between extensive deforestation and regional trends of key hydroclimatic variables as LST, ET, and P with most pronounced effect during dry seasons. Similar findings have been previously reported by other studies (Nobre et al., 1990; Khanna et al, 2017; Baker and Spracklen, 2019; Silva et al., 2022; Longo et al., 2025 among others) but authors have claimed their novelty is based on their methodological approaches. Particularly, they conclude similar features of transitional moist forest-savannas correspond to highly deforested areas.
Among the most remarkable changes of their reviewed version, the authors have improved the manuscript by excluding 1.5deg data and focusing on 0.5deg data, reordering and renaming sections according to previous reviewer's comments, providing most robust statistical analysis of the differences as suggested by reviewer #1, and enhancing general readability of the manuscript. However, the core of the paper is still hard to understand necessitating repeated readings for comprehension.

Response: We thank Reviewer #4 for the time dedicated to evaluating our manuscript and for providing valuable recommendations to improve the quality of our work. We acknowledged the need to further improve the readability of our text. We have revised the entire text to improve its readability and the interpretation of our approach. In this line, we have also extended the overview of methods in our first Results subsection. This current version has clearer explanations of our approach and findings.

1. First, I have focused on the novelties authors have claimed to include in this new version regarding the assessment of deforestation-climate relationships in the study region:

i.Comparing two scenarios: deforested surrounded by forested vs forested surrounded by forested (Methodological advance?). Authors claim not clearly made in previous studies
i.Including more variables than previous studies (Methodological advance?)
ii.Observational approach vs modelling approach of previous studies (Methodological advance?)
iii.Analysis based on comparative assessments of deforested surrounded by forested regions vs forested surrounded by forested regions (Methodological advance?)

I find them very relevant and, evidently, there is an enormous effort in this sense; neverthless, my main concern is that they appear novelties directly connected to methodological approaches respect to previous studies leading to the same results. Can authors more explicitly connect how the methodological approaches increase our understanding of deforestation-climate relationships in the Amazon lowland biome?

Response: We thank the Reviewer for raising awareness to a topic that needed improvement in our manuscript. Our study has indeed some methodological advances and we have made them clearer in the current version of our Introduction. The assessment of deforestation impacts on eleven climate variables is, to the best of our knowledge, the largest set used in observational studies of deforestation-climate relationships in the Amazon. Our method is based on the rationale of comparing climate dynamics in deforested grid cells against their control neighboring cells. This rationale also served as a basis for other observational studies, but there are two major differences in our approach. Previous studies have usually assessed how changes in climate between two time intervals diverge between deforested and control neighbors (Baker and Spracklen, 2019; Smith et al., 2023). Conversely, we compared the climate averages of deforested and control neighbors for the same time interval. Thus, our findings bring the perspective of how historic deforestation in the Amazon has shifted climate averages away from reference conditions in highly forested regions. Moreover, we used the comparisons of control cells neighboring each other to indicate how factors other than deforestation influence the magnitude of climate differences. Therefore, climate differences between deforested versus control neighbors were compared against climate differences between control versus control neighbors to assess if climate impacts related to deforestation are larger than confounding factors. We addressed these points in the Introduction, as follows:

"...Here we use a comprehensive observational approach that analyzes the potential impact of Amazon deforestation on regional climate shifts by integrating different essential climate variables, seasonal periods, and extent of accumulated deforestation. We divided the Amazon territory into grid cells of 0.5° spatial resolution, a scale in which additional evidence is needed for deforestation-induced effects on rainfall, land surface temperature (LST) and evapotranspiration (ET). For each grid cell, we calculated descriptive statistics of satellite-based LST, ET, and rainfall in three time periods: annual, wet season (three consecutive wettest months in each cell), and dry season (three consecutive driest months in each cell), plus two climate variables related to rainfall seasonality: maximum dry spell duration (consecutive days with rainfall<1 mm) and number of rainy days (rainfall ≥ 1 mm), totaling eleven climate

variables. To the best of our knowledge, this is the most comprehensive set of variables tested for the impact of deforestation on the Amazon climate.

Our approach compares the climate averages during 2013-2021 across a gradient of deforested cells against their highly forested neighboring cells (>80% forest cover), which served as our reference for climate conditions little affected by accumulated deforestation. In contrast, other observational studies have usually assessed how changes in climate between two time intervals diverge between deforested cells and control neighbors (Baker and Spracklen, 2019; Smith et al., 2023). By comparing deforestated and forested neighbors by their climate averages in the same time interval, we aim to evaluate whether historic deforestation in the long-term shifts climate away from the reference condition of highly forested regions. Furthermore, by comparing climate differences between deforested and forested neighbors against those from forested cells neighboring each other, we assess if climate differences related to deforestation are larger than those potentially related to confounding factors. The comparison of climate averages also allows us to evaluate if climate characteristics in deforested regions have shifted to a point that could support ecosystem transitions. To do so, we compared climate envelopes (the distribution of climate averages among our samples) of highly deforested regions against the envelope of highly forested regions, savannas, and forest-savanna transitions within the Amazon."

With respect to how our approach increases the understanding of deforestation-climate relationships in the Amazon, we highlight that we connected the comparison of climate averages between deforested and control forested neighbors to the highly debated matter of ecosystem transitions in the Amazon. That is, in addition to comparing how climate in highly deforested regions deviates from the observed climate in highly forested regions, we have also assessed if the climate in highly deforested regions has shifted to the point of becoming more similar to the observed climate envelope of other biomes, such as savannas or forest-savanna transitions. For instance, we observed that the distribution of land surface temperature (LST), annual evapotranspiration (ET), and dry season rainfall is significantly similar between highly deforested regions and forest-savanna transitions, which was not observed when highly forested regions were compared with forest-savanna transitions. We have also shown that for variables such as annual LST, ET, and seasonal rainfall, highly deforested regions show a substantially higher frequency of grid cells under the savanna envelope, compared to their neighboring cells that are highly forested. We have now clarified, in the last paragraph of the Introduction, how the comparison of deforested and forested neighbors connects with the assessment of climate envelopes across biomes. This connection is also clearer now in the Discussion section.

We also extended, in the Discussion section, the comparison of our findings with those of previous studies. Studies assessing deforestation impacts on land surface temperature and evapotranspiration have been usually performed at the local scale, and we showed how these local-scale estimates diverge with the ones we found at the regional scale (0.5°). Additionally, we have now provided estimates for deforestation impacts on climate that are normalized by forest cover, which allowed for a direct comparison of our estimates for impacts on dry season rainfall with estimates from two previous studies at similar scales in the Amazon. We highlight, through this comparison, how the quantification of deforestation impacts on rainfall still has substantial uncertainties, which demands for additional studies. Despite variations in the magnitude of estimates, studies have been agreeing in the direction of response for dry season rainfall, and our study in this sense increases the evidence that historic deforestation in the Amazon has contributed to reducing dry season rainfall, mainly in the most deforested regions (forest cover <60%). However, our findings disagree with previous ones by not indicating clear evidence for deforestation impacts on annual and wet season rainfall, which highlights that additional studies are needed to uncover these uncertainties.

We addressed the comparison of our findings with other studies in the Discussion section as follows:

"Previous studies have reported LST and ET differences between deforested and forested areas at fine scales (1 km or greater spatial resolution), indicating local increases in LST during the dry season of 3-4°C and ET reductions of up to 35-48% (Maeda et al., 2021; Oliveira et al., 2019; Reygadas et al., 2023). Our estimates at 0.5° (~55 km) resolution differ by showing the contribution of deforestation to regional changes in climate, rather than local. We observed that dry season LST is on average 3°C higher in highly deforested areas, compared with highly forested areas, in line with the local-scale estimates, while dry season ET is 12% lower. At the regional scale, the reduced ET in deforested areas can be compensated by the high ET of remaining forests within the same grid cell, which may partially explain the differences between local and regional estimates.

Our findings indicate clear evidence for deforestation impacts on reduced rainfall during the dry season, while evidence for the annual and wet season periods was not clear. In contrast, findings from other studies at similar scales have indicated deforestation-induced reductions in the annual and all seasonal periods, or even increases during the wet season (Leite-Filho et al., 2024; Qin et al., 2025; Smith et al., 2023). Our mean estimate for the deforestation-related reductions in dry season rainfall was -0.37 mm month^{-1}(95% CI -0.62 - -0.11 mm) per percentage point (pp) reduction in forest cover, while other studies found estimates, at similar scales, of -1.5 mm month^{-1} and -0.09 mm month^{-1} (Smith et al., 2023; Qin et al., 2025). This large variation of magnitude among estimates highlights that, while studies have been agreeing on evidence for deforestation-induced reductions in dry season rainfall, the quantification of these reductions still holds substantial uncertainties. Although our findings also indicate deforestation-related reductions in the number of rainy days, we did not explore the specific periods of the year in which this reduction occurred. Previous studies have linked deforestation to delays in wet season onset and decreases in wet season length (Leite-Filho et al., 2019; Leite-Filho et al., 2020; Leite-Filho et al., 2023; Wright et al., 2017), which may suggest that reductions in rainy days can be occurring at the dry-to-wet season transition or wet season. Future studies will be important to clarify these knowledge gaps."

2. Second, another relevant point: the response to reviewer #1 in his/her comment #2, "how can one evaluate the impact of deforestation on precipitation when not taking into account the travelled distances of moisture?" Authors argue that the 0.5deg pixel resolution allows a better representation of local moisture recycling processes respect to the original 1.5deg, initially presented. This is true; however, reviewer #1 has also suggested that Amazon's rainfall in dry seasons comes from transpiration which is also connected with moisture transport and recycling. Precisely, it has been proven interconnected effects of deforestation and regional climate trends through the dynamics of moisture cascades (see Zemp et al. 2014, 2017 and Staal. et al, 2018).

So the controversial issue here is the spatial scale and maybe what reviewer #1 asked authors was to analyze the possible role of moisture recycling and transport in the overall hydroclimate scenario of the Amazon lowland biome and in the context of their observational approach. Staal et al. (2018) provides evidence of transpiration recycling ratios up to 50% in northern and southwestern Amazon where the median geographic distances are shorter (see their figures 1b,c); instead, the authors declare: "…less than 10% of regional evapotranspiration in the Amazon is suggested to be locally recycled (Theeuwen et al., 2023)". Notably, as remarked again by Theeuwen et al. (2023) : "…spatial scale at which moisture recycling is the dominant process for precipitation is unknown.", and also in this sense: "…with increasing distance from the Andes Mountains, the median travelling distance of transpired moisture from the Amazon forest increases (Staal et al., 2018),…". I think this is the point of reviewer #1. Since the proved connection between moisture recycling and deforestation which involves both local and regional mechanisms as moisture cascades: How your findings reconcile the interaction among deforestation, your on multiple space scales?

Response: We thank the Reviewer for raising a point that needed further clarification in our Discussion. Our previous explanation of local moisture recycling could have led to misinterpretations. What we actually meant was that less than 10% of local evapotranspiration usually returns as rainfall within a distance of approximately 0.5º from its source, as indicated by Theeuwen et al. (2023). Thus, although most of the rainfall in a given deforested cell may not be generated by ET recycled within that cell or immediate neighboring cells, a substantial portion of this rainfall may be coming from recycled ET of nearby regions, as the Reviewer mentioned and Staal et al. (2018) demonstrates. However, because we compared deforested and forested cells that are immediate neighbors and have a small size, we assumed that moisture sources in these cells come from similar locations. If our rainfall differences between deforested and forested neighboring cells would be biased by different external moisture sources in these cells, similar biases would also appear in the comparison of forested cells neighboring each other. Thus, as we have shown that rainfall differences in deforested versus forested neighbors are larger and more negative (lower rainfall), compared to differences between forested versus forested neighbors, our findings suggest that differences in external moisture sources is not the main contributing factor for the reduced rainfall in deforested cells. One alternative assumption for the observed lower rainfall in deforested regions is that, despite potentially receiving moisture from similar sources compared to adjacent forested regions, they are subjected to greater rainfall inhibition mechanisms. For instance, Xu et al. (2022) suggests that hotter and drier conditions during the dry season in the lower troposphere of deforested areas with 0.5º spatial resolution can enhance hot-dry updrafts that reduce the inflow of external moisture sources into the deforested area. Although explicitly addressing atmospheric tracking in our analyses was out of the scope of this study, we acknowledge that additional studies using this approach will be important to improve the scientific understanding of mechanisms behind deforestation-induced rainfall reductions, which is currently limited.

We have addressed these points in the Discussion section as follows:

"Amazon forests play an important contribution to dry season rainfall through evapotranspiration recycling (Qin et al., 2025; Staal et al., 2018). However, less than 10% of local evapotranspiration is suggested to return as rainfall within a distance of approximately 0.5° from its source (Theeuwen et al., 2023). Because moisture transpired by vegetation in the Amazon can travel, on average, 600 km before precipitating (Staal et al., 2018), rainfall in a given deforested cell can thus also be impacted by deforested regions that are a few hundreds of kilometers away. Despite not explicitly tracing moisture sources from our deforested cells, we compared deforested and reference forested cells that are immediate neighbors and have a relatively small size, so we assumed these cells are sharing similar external moisture sources and dynamics. Moreover, differences in external moisture sources would appear both in our comparison of deforested versus reference neighbors and reference versus reference neighbors, generating similar biases for these two kinds of comparisons. Because differences in dry season rainfall were more negative (lower rainfall) in deforested versus reference neighbors, compared to reference versus reference neighbors, it is very likely that different external moisture sources is not the main factor contributing to the lower rainfall in deforested cells.

Alternatively, it is also plausible that deforested cells may be experiencing greater rainfall inhibition mechanisms than surrounding forested cells. For instance, a warmer and drier lower troposphere during the dry season was found in deforested regions at the 0.5° resolution, which can enhance hot-dry updrafts and reduce the inflow of external moisture sources that contribute to rainfall in that region (Xu et al., 2022). Considering the scientific understanding of mechanisms behind deforestation-induced rainfall reductions is still limited, further studies linking changes in atmospheric moisture flow and rainfall will be important to help elucidate some of the current uncertainties."

3. Specific Comment: Please include in-line cites references of Staal et al (2010, 2018) and exclude Staal et al. (2020) from the reference list. Also, please revise again the coherence between in line and reference list.

Response: Thank you. We have now cited Staal et al. (2018) in the text, removed Staal et al. (2020) and revised all in-text citations, ensuring they are properly included in the reference list.

Reviewer #4 References

Baker, J., & Spracklen, D. (2019). Climate Benefits of Intact Amazon Forests and the Biophysical Consequences of Disturbance. Frontiers in Forests and Global Change. https://doi.org/10.3389/ffgc.2019.00047.

Khanna, J., Medvigy, D., Fueglistaler, S., & Walko, R. (2017). Regional dry-season climate changes due to three decades of Amazonian deforestation. Nature Climate Change, 7, 200-204. https://doi.org/10.1038/NCLIMATE3226.

Longo, M., Keller, M., Kueppers, L., Bowman, K., Csillik, O., Ferraz, A., Moorcroft, P., Ometto, J., Soares-Filho, B., Xu, X., De Assis, M., Görgens, E., Larson, E., Needham, J., Ordway, E., Pereira, F., Pinagé, E., Sato, L., Xu, L., & Saatchi, S. (2025). Degradation and deforestation increase the sensitivity of the Amazon Forest to climate extremes. Environmental Research Letters, 20. https://doi.org/10.1088/1748-9326/adc58c.

Silva, R., Lopes, A., & Santos, C. (2022). Deforestation and fires in the Brazilian Amazon from 2001 to 2020: Impacts on rainfall variability and land surface temperature. Journal of environmental management, 326 Pt A, 116664 . https://doi.org/10.1016/j.jenvman.2022.116664.

Staal, A., Tuinenburg, O. A., Bosmans, J. H., Holmgren, M., van Nes, E. H., Scheffer, M., ... & Dekker, S. C. (2018). Forest-rainfall cascades buffer against drought across the Amazon. Nature Climate Change, 8(6), 539-543.

Zemp, D. C., et al. On the importance of cascading moisture recycling in South America. Atmospheric Chemistry and Physics 14.23 (2014): 13337-13359.

Zemp, D. C., Schleussner, C. F., Barbosa, H. M., Hirota, M., Montade, V., Sampaio, G., ... & Rammig, A. (2017). Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. Nature communications, 8(1), 14681.

Note: I truthfully declare I have not used AI to produce this report

References from the Author’s response

Baker, J. C., & Spracklen, D. V. (2019). Climate benefits of intact Amazon forests and the biophysical consequences of disturbance. *Frontiers in Forests and Global Change*, *2*, 47.

Leite-Filho, A. T., Soares-Filho, B. S., & de Oliveira, U. (2024). Climate risks to soy-maize double-cropping due to Amazon deforestation. *International Journal of Climatology*, *44*(4), 1245-1261.

Maeda, E. E., Abera, T. A., Siljander, M., Aragão, L. E., Moura, Y. M. D., & Heiskanen, J. (2021). Large-scale commodity agriculture exacerbates the climatic impacts of Amazonian deforestation. *Proceedings of the National Academy of Sciences*, *118*(7), e2023787118.

Oliveira, G., Brunsell, N. A., Moraes, E. C., Shimabukuro, Y. E., dos Santos, T. V., von Randow, C., ... & Aragao, L. E. (2019). Effects of land-cover changes on the partitioning of surface energy and water fluxes in Amazonia using high-resolution satellite imagery. *Ecohydrology*, *12*(6), e2126.

Qin, Y., Wang, D., Ziegler, A. D., Fu, B., & Zeng, Z. (2025). Impact of Amazonian deforestation on precipitation reverses between seasons. Nature, 639(8053), 102-108.

Reygadas, Y., Spera, S. A. & Salisbury, D. S. Effects of deforestation and forest degradation on ecosystem service indicators across the Southwestern Amazon. Ecological Indicators 147, 109996 (2023).

Smith, C., Baker, J. C. A., & Spracklen, D. V. (2023). Tropical deforestation causes large reductions in observed precipitation. *Nature*, *615*(7951), 270-275.

Staal, A., Tuinenburg, O. A., Bosmans, J. H., Holmgren, M., van Nes, E. H., Scheffer, M., ... & Dekker, S. C. (2018). Forest-rainfall cascades buffer against drought across the Amazon. *Nature Climate Change*, *8*(6), 539-543.

Theeuwen, J. J., Staal, A., Tuinenburg, O. A., Hamelers, B. V., & Dekker, S. C. (2023). Local moisture recycling across the globe. *Hydrology and Earth System Sciences*, *27*(7), 1457-1476.

Xu, X., Zhang, X., Riley, W. J., Xue, Y., Nobre, C. A., Lovejoy, T. E., & Jia, G. (2022). Deforestation triggering irreversible transition in Amazon hydrological cycle. *Environmental Research Letters*, *17*(3), 034037.

Report from Reviewer #2

0. **Recommendation:** For the reasons explained below, I recommend the manuscript for publication only after the authors share the datasets, codes and all relevant information to make the study replicable.

Response: We thank Reviewer #2 for recommending our manuscript. We assure that datasets and codes that allow for the replicability of our study will be shared in the Zenodo repository. Additionally, we have also expanded and improved the explanation of our methods to facilitate replicability.

1. **Report**

Using satellite-based observational data, the study investigated how deforestation contribute to shifting the Amazon climate conditions away from those in highly forested and intact areas. The findings show compelling evidence that forest loss has contributed to climate shifts, particularly in regions with less than 60% remaining forest cover. The climate shift linked to deforestation include warmer LST, lower evapotranspiration, lower dry-season rainfall and fewer rainy days. Thy study that rain metrics (annual rainfall and the number of rainy days) in highly deforested regions still share similarities with highly forested regions, but LST, ET, and rainfall in the driest period of the year are like transitional regions.

The methodology involved analyzing satellite-based data for LST, ET, and rainfall variables across grid cells grouped by remaining forest cover in 2021. Grid cells with over 80% forest cover served as a reference for conditions under negligible deforestation influence. Control methods were applied to minimize the influence of factors other than deforestation, such as ensuring neighboring deforested and reference regions shared similar climatic backgrounds and were entirely within the moist forest biome (this is correct). Statistical tests confirmed that the magnitude of observed climate differences in deforested regions was significantly larger than differences related to background factors. These findings included analysis of drought years.

The authors emphasize the need to identify and quantify deforestation's impacts on regional climate to inform mitigation and adaptation strategies. They cite other studies and highlight that large-scale observational studies remain limited. The study addresses this gap with an observational approach that includes key atmospheric variables across different seasons. The study objective is clearly stated: to analyze the potential impact of deforestation on the change of essential climate variables at different seasonal periods and according to the regional extent of remaining forest cover.

Methods rely on satellite observation aggregated to 0.5° (they addressed my observation from my previous review) grid cells, and analyzed LST, evapotranspiration from the validated geeSEBAL-MODIS model, and rainfall (CHIRPS). The authors implemented multiple controls to isolated deforestation effects and chose representative cells for deforested cells.
A key limitation is the small sample size meeting all controls applied: 9 cells for ≤ 40%, 20 for 40- 60%, and 100 for 60-80%. The authors acknowledge this aspect constrains the precision of their estimates that are also scale-dependent. Despite limited sample size in some categories, the experimental design and the use

of good set of satellite products render the methodology allows to appropriately justify their results and conclusions.

The authors applied suitable statistical tests to compare climate variable distribution (Ks and Welch-s t-test) and report the confidence intervals for p-values from bootstrapping.

The authors demonstrate that deforestation drives climate shifts toward higher LST, lower ET, reduced dry season rainfall, and fewer rainy days in areas with less than 60% forest cover. These results support the conclusions and respond to the main study's question.

Response: We thank Reviewer #2 for carefully reading our manuscript and providing a thorough report of our study.