

Atmospheric aridity drives functional reorganization and resilience loss in global forests

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This paper investigates the divergence between rising forest gross primary productivity (GPP) and declining ecosystem resilience using multi-source remote sensing data (2001–2021). The central hypotheses are well-grounded and many factual claims are well-supported. However, a few issues should be addressed before publication.

* Inconsistency between Figure 2 and SEM results. The Results text describing Figure 2 (L130-132) states that GPP–WUE coupling weakens with increasing VPD under constant SM, supporting the paper's narrative that VPD erodes functional coupling. Yet in the subsequent SEM analysis, the direct paths from VPD to GPP–WUE coupling are positive in both tropical and boreal forests (standardized coefficients +0.44 and +0.43, $P < 0.05$) (L156-159), implying that, after controlling for other factors, higher VPD is associated with *stronger* GPP–WUE coupling in these zones. The paper does not explain how these apparently opposing results relate (marginal vs. partial effects, direct vs. indirect pathways), nor does the Discussion acknowledge or reconcile this discrepancy. Clarification is needed.

* FLUXCOM-X representativeness. The paper correctly states that FLUXCOM-X GPP and ET were "derived by upscaling eddy covariance measurements from a global network of 294 flux towers (FLUXNET)" (L384–388). However, the description omits an important caveat: the 294 sites are skewed toward temperate forests of North America and Europe, which raises representativeness concerns for tropical and boreal regions. Given that the headline result identifies boreal and tropical forests as containing over 80% of the affected area, this context would benefit the Discussion as an acknowledged limitation.

* Figure 2 a and b is missing an x-axis label.

Overall, the study addresses an important question and the dataset assembly is impressive. Resolving the Figure 2 / SEM inconsistency, acknowledging the FLUXCOM-X representativeness limitation, and correcting the figure labeling would strengthen the manuscript.

Reviewer #2

(Remarks to the Author)

The study attempts to investigate the drivers of the mismatch of gain in productivity and loss of resilience for global forests employing multi-source remote sensing data (for the period: 2001 to 2021) and structural equation modelling (SEM) approach. The study is well crafted and presents some interesting results and implications for global forests and ecosystem management. However, the study can be further refined based on the suggestions and requires some justifications. The following queries, suggestions and improvements are required.

Introduction

1. Generally, very clean and clear with the approach. But misses on the point that there exist studies that looks into the relative roles and casual pathways of atmospheric aridity (VPD) and plant-available soil water (SM) on vegetation growth/photosynthesis/carbon uptake.

For instance, see:

Causal approach:

Increased moisture stress and weakened resilience to aridity limit global greening. *Science of The Total Environment*, 1015, 181416. (2026). <https://doi.org/10.1016/j.scitotenv.2026.181416>

When and where soil dryness matters to ecosystem photosynthesis. *Nat. Plants* 11 (7), 1390–1400. (2025). <https://doi.org/10.1038/s41477-025-02024-7>.

Binning approach:

Soil moisture dominates dryness stress on ecosystem production globally. *Nat. Commun.* 11 (1), 4892. (2020) <https://doi.org/10.1038/s41467-020-18631-1>.

How does this study go beyond and adds to the insights on SM-VPD distangling aspect? This should be very vividly presented.

2. Also, these prior efforts in the same direction should be acknowledged in the build up to the storyline.

Results

3. The first-order 82 autoregressive coefficient (AR(1)) as a proxy for resilience is an important quantification and therefore should probably be presented in the manuscript rather than in the supplementary material.

The first figure can be present AR1 and AR1-GPP correlation as presented in supplementary material for better clarity and understanding. This should also be explained for more clarity.

4. Line: 83 to 85: “we found that 34.26% of global forests simultaneously experienced a significant increase in GPP and a decline in resilience from 2001 to 2021”

This statement should be further elaborated and the significance of this finding being vividly highlighted.

5. Line 89 to 92: Why is this mismatch of GPP gain and resilience loss more severe in non-intact forest than intact forest? This needs more explanation.

6. In the Fig.1 caption, AR1 should be defined. Always define the abbreviations at the first instance of their use and treat the abstract, figure captions and conclusion independent of the main article text in this regard.

7. Fig S5 and S6 in supplementary material presents important results on GPP coupling with functional metrics in WUE and EPE and their changes and should be presented in the main manuscript for better clarity. This would enable better of the quantification presented.

8. Line 127 to 135: How about checking the results presented in 2 different scenarios: (i) VPD increase with constant SM and (ii) SM increase with constant VPD?

Else this can be mentioned as one of the limitations/future scope of the study in the Discussion.

9. A common/overall SEM network diagram for all global forests maybe presented a broader general picture before presenting the biome-specific and forest type SEM network diagrams.

Discussion

10. Line 200: “forced increase in WUE” why so? Increased VPD? Needs more clarity.

11. Greening does not always reflect or translates in increased productivity and this is due to decline in the functional translation capacity (EPE) under SM drying and enhanced aridity of land and atmosphere. This can be mentioned to support the findings.

See:

Weakening of forest carbon stocks due to declining Ecosystem Photosynthetic Efficiency under the current and future climate change scenarios in India. *Resources, Conservation and Recycling*, 222, 108478. (2025). <https://doi.org/10.1016/j.resconrec.2025.108478>.

12. There is weakening of resilience against moisture stress (more demand than available supply for plants to utilise in the current climate change scenario.

Also, VPD is the major control and has causal relationship with photosynthesis across biomes and land cover types unlike SM.

These can be mentioned to support the findings.

See:

Increased moisture stress and weakened resilience to aridity limit global greening. *Science of The Total Environment*, 1015, 181416. (2026). <https://doi.org/10.1016/j.scitotenv.2026.181416>

13. There is a shift from a temperature and energy to moisture controlled regime on global photosynthesis in response to the changing climate. Also, there is strengthened control of water availability in contrast to weakened control of temperature on global photosynthesis in recent decade.

These can be mentioned to support the findings.
See:

Changing global vegetation-climate interactions constrain photosynthesis in the 21st century. *Journal of Cleaner Production*, 538, 147402. (2026). <https://doi.org/10.1016/j.jclepro.2025.147402>

14. At times the manuscript with the use of words like “posits”, “insidious”, “bystander” and others sound like fabricated language largely with more “AI touch” and requires more “human touch” to make it more readable.

15. Estimation of relative controls based on machine learning approach like Random Forest can be employed to see the relative controls of VPD and SM on ecosystem functional metrics. This can be mentioned as one of the limitations/future scope of the study

See:

Unraveling the Sensitivity and Response of Ecosystems to Rising Moisture Stress in India. *Ecosystem Health Sustainability*, 9, 0180 <https://doi.org/10.34133/ehs.0180> [

Conclusion

16. Line 355: “intensifying atmospheric aridity, specifically rising VPD”, VPD is a measure/proxy of atmospheric aridity. So, this sounds redundant and needs improvement.

Methods

17. The TerraClimate SM data is based on a “modified Thornthwaite-Mather” water balance model which employs a static reference land cover and does not account for vegetation dynamics. Thus, the SM data generated is largely a replica of the precipitation dataset in terms of the spatio-temporal distribution and variability.

Since, the study is focused on vegetation functional aspects and carbon-water coupling, I would rather suggest going in with a reanalysis with better land/vegetation component like GLDAS Noah or ERA-5 for SM data.

See some global studies with GLDAS Noah LSM SM datasets:

Changing global vegetation-climate interactions constrain photosynthesis in the 21st century. *Journal of Cleaner Production*, 538, 147402. (2026). <https://doi.org/10.1016/j.jclepro.2025.147402>

Increased moisture stress and weakened resilience to aridity limit global greening. *Science of The Total Environment*, 1015, 181416. (2026). <https://doi.org/10.1016/j.scitotenv.2026.181416>

18. The ecosystem resilience method based on the first-order autocorrelation coefficient (AR(1)) of the vegetation signal should be more clearly explained and detailed.

Also, why was this approach adopted rather than the worst affected year approach of resilience estimation needs to be explained.

See:

Increased moisture stress and weakened resilience to aridity limit global greening. *Science of The Total Environment*, 1015, 181416. (2026). <https://doi.org/10.1016/j.scitotenv.2026.181416>

Weakening of forest carbon stocks due to declining Ecosystem Photosynthetic Efficiency under the current and future climate change scenarios in India. *Resources, Conservation and Recycling*, 222, 108478. (2025).

<https://doi.org/10.1016/j.resconrec.2025.108478>

19. Why does the study prefer FLUXCOM GPP and ET over MODIS GPP and ET or other remote sensing/ model based data that FLUXCOM GPP does not have enough training data points for tropical and sub-tropical regions in Africa and South Asia region?

20. Additionally, FLUXCOM (0.5°) is spatially way coarser than MODIS (500m). Thus, this choice should be very clearly and strongly justified given the limitations of FLUXCOM data for the tropical and sub-tropical region and coarse resolution.

21. EPE estimation as SIF/LAI ratio is fine general or broad scale vegetation aspects as in some previous global studies or studies based on China.

However, SIF being a weak signal, at times does not accurately presents the leaf scale photosynthesised carbon assimilation by vegetation particularly in high biomass regions like forests.

See:

Strong constraint on modelled global carbon uptake using solar-induced chlorophyll fluorescence data. *Sci. Rep.* 8 (1), 1973. (2018) <https://doi.org/10.1038/s41598-018-20024-w>.

Structural complexity biases vegetation greenness measures. *Nat. Ecol. Evol.* 7 (11), 1790–1798. <https://doi.org/10.1038/s41559-023-02187-6>.

So, it might be a better approach to estimate EPE as a ratio of carbon capture (GPP) or uptake (NPP) to greenness (LAI) for the forest ecosystems.

See:

Weakening of forest carbon stocks due to declining Ecosystem Photosynthetic Efficiency under the current and future climate change scenarios in India. *Resources, Conservation and Recycling*, 222, 108478. (2025).
<https://doi.org/10.1016/j.resconrec.2025.108478>

This aspect could be either approached or mentioned as a limitation of the study.

Reviewer #3

(Remarks to the Author)

General Comments:

Congratulations! This is an interesting and well-written paper. The manuscript investigates the global divergence between forest productivity and ecological resilience under increasing atmospheric aridity, using multi-source remote sensing datasets and structural equation modelling. The topic is highly relevant to current concerns on climate change, carbon sink stability, and ecosystem vulnerability. However, several issues need to clarify. These issues mainly relate to the presentation of the Introduction, the datasets used, and the need for further clarification of the proposed framework. Therefore, I recommend a Revision before the manuscript can be considered for publication.

Specific Comments:

- (1) Line 31-32: The statement "while gross primary productivity (GPP) has increased...simultaneously declined", appears to be qualitative. Is there quantitative evidence or specific references supporting this claim? Please clarify or provide appropriate citations.
- (2) Line 41-46: The sentence "Terrestrial carbon and water cycles ... and light harvesting (Ecosystem Photosynthetic Efficiency, EPE)", appears somewhat abrupt. The logical connection with the preceding and following text is not sufficiently clear. Please improve the flow and coherence.
- (3) Line 46-48: The sentence "To explain this productivity-resilience divergence, we advance...", also appears abrupt in its current position. Consider improving the transition to better integrate it into the narrative.
- (4) Line 50-52: After "Recent studies", only one reference (Ref. 16) is cited. This seems insufficient and inconsistent with the plural form. Please include additional references to better support this statement.
- (5) Figure 1: It presents the spatial patterns of AR(1) and GPP changes. It would be helpful to include the temporal trends of key variables such as VPD, AR(1), GPP, and coupling strength to provide a more comprehensive understanding of their dynamics.
- (6) Line 216: The authors propose a "Stress-Resilience-Decoupling theoretical framework". Based on the discussion, the duration of atmospheric drought seems to play an important role in determining whether forests follow a direct or resilience-mediated pathway. It would be beneficial to include a comparison under different drought-duration scenarios to better illustrate and support this framework.
- (7) SIF data: OCO-2 SIF observations are footprint-based. How were these data processed to obtain spatially continuous products? Please provide a brief description. In addition, if the used SIF product incorporates MODIS data, there may be overlap with other datasets (e.g., LAI, GPP), which could introduce a potential limitation that should be acknowledged.
- (8) Intact Forest Landscapes (IFL) dataset: This dataset is used to distinguish forest integrity. Please clarify how this dataset is derived from satellite observations, and justify why it is suitable for representing structural complexity and anthropogenic disturbance.
- (9) Data processing: Were LAI, SIF, GPP, and other variables deseasonalized prior to analysis? In addition, please clarify the spatial and temporal resolution used in the analysis.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The revised Figure 2 text is now more careful: it says "GPP-WUE coupling was jointly controlled by VPD and SM, with coupling declining along the SM gradient most notably under moderate VPD." This no longer directly contradicts the SEM, because the decline is now attributed to the SM gradient rather than VPD per se.

However, the SEM results are unchanged and still show VPD strengthens GPP-WUE coupling in tropical (+0.44) and boreal (+0.43) forests. The new binning analysis the authors conducted in response to Reviewer 2 (Comment 8) actually makes this even clearer: "VPD was consistently positively correlated with GPP-WUE coupling strength across all valid SM deciles ($r = 0.28$ to 0.50 , $P < 0.001$).". So their own supplementary sensitivity analysis confirms that VPD strengthens, not weakens, GPP-WUE coupling after controlling for SM covariation.

Yet the revised abstract still reads: "sustained VPD stress erodes forest resilience, which in turn weakens coordination among carbon fixation, water use efficiency, and photosynthetic efficiency." This blanket claim that VPD weakens coordination involving WUE is not supported by the authors' own SEM or binning results — it is only true for the GPP-EPE component in some climate zones, and only via the indirect (resilience-mediated) pathway. For the GPP-WUE component, VPD's direct effect is consistently positive (strengthening) across nearly all strata.

The authors appear to have fixed the local inconsistency in the Figure 2 text while leaving the broader narrative inconsistency between the abstract/Discussion and the quantitative evidence untouched. The axis-transposition explanation accounts for why the original Figure 2 description was wrong, but it does not account for why the abstract still claims VPD weakens carbon–water coordination when every quantitative result in the paper says VPD strengthens GPP–WUE coupling.

Reviewer #2

(Remarks to the Author)

The authors have substantially improved the manuscript and answered all my queries appropriately. The study can be accepted now. Congratulations!

Reviewer #3

(Remarks to the Author)

Thank you for answering my question. I have no further comments.

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Reviewer 1

General Response to Reviewer 1:

We thank the reviewer for the careful evaluation. The reviewer's comments prompted us to correct Figure 2 and revise the accompanying text, acknowledge the spatial bias in FLUXCOM-X training data as an explicit limitation, and audit all figures for labeling consistency. Detailed responses are provided below.

Response to Reviewer 1, Comment 1:

Comment1: Inconsistency between Figure 2 and SEM results. The Results text describing Figure 2 (L130-132) states that GPP–WUE coupling weakens with increasing VPD under constant SM, supporting the paper's narrative that VPD erodes functional coupling. Yet in the subsequent SEM analysis, the direct paths from VPD to GPP–WUE coupling are positive in both tropical and boreal forests (standardized coefficients +0.44 and +0.43, $*P* < 0.05$) (L156-159), implying that, after controlling for other factors, higher VPD is associated with **stronger** GPP–WUE coupling in these zones. The paper does not explain how these apparently opposing results relate (marginal vs. partial effects, direct vs. indirect pathways), nor does the Discussion acknowledge or reconcile this discrepancy. Clarification is needed.

Response: We thank the reviewer for identifying this issue. Upon re-examination, we discovered that the axis labels in Figure 2a and 2b were inadvertently transposed during figure assembly, and the accompanying text was drafted against these mislabeled panels. The underlying data remain unaffected. We have corrected both figures and revised the corresponding text (Lines 149–160).

The corrected Figure 2 now shows that GPP-EPE coupling strength declines primarily along the SM gradient, with limited sensitivity to VPD (Fig. 2a), whereas GPP – WUE coupling responds to both drivers jointly (Fig. 2b). These binned surfaces represent marginal associations across the full hydroclimatic space. We

apologize for the labeling error and have implemented additional quality-control checks on all figures.

Lines 149–160: *“Specifically, GPP-EPE coupling weakened primarily along the SM gradient, declining markedly from low to high SM with relatively limited sensitivity to VPD (Fig. 2a). In contrast, GPP-WUE coupling was jointly controlled by VPD and SM, with coupling declining along the SM gradient most notably under moderate VPD (Fig. 2b). Trend analysis further showed that GPP-EPE coupling strengthened under moderate SM drying but declined in regions with rising VPD or wetting SM trends (Fig. 2c). GPP-WUE coupling weakened predominantly in regions with small VPD trends, while the response to SM trends varied across regions (Fig. 2d).”*

Response to Reviewer 1, Comment 2:

Comment2: FLUXCOM-X representativeness. The paper correctly states that FLUXCOM-X GPP and ET were "derived by upscaling eddy covariance measurements from a global network of 294 flux towers (FLUXNET)" (L384–388). However, the description omits an important caveat: the 294 sites are skewed toward temperate forests of North America and Europe, which raises representativeness concerns for tropical and boreal regions. Given that the headline result identifies boreal and tropical forests as containing over 80% of the affected area, this context would benefit the Discussion as an acknowledged limitation.

Response: We acknowledge that FLUXCOM-X, while representing the state-of-the-art in global flux upscaling, is trained predominantly on flux towers located in temperate forests of North America and Europe. This spatial bias may introduce systematic uncertainties in GPP and ET estimates for tropical and boreal regions, where training data are sparse. While the machine learning framework partially mitigates this through the use of globally continuous predictor fields (ERA5 meteorology and MODIS remote sensing), extrapolation to under-sampled biomes remains a recognized limitation of all flux upscaling products. We also note that

sensitivity analyses using an independent soil moisture product (GLDAS Noah) reproduced the core pathways across all climate zones, including well-sampled temperate forests, supporting the robustness of our findings despite these data constraints. We note that separate SEM models fitted for each climate zone independently confirmed the dominant VPD to AR(1) pathway, and that over half of the affected area lies in boreal forests where tower coverage is comparatively denser. These consistencies suggest that our principal findings are not contingent on the regions of highest product uncertainty.

We have acknowledged this limitation in the revised Limitations section (Lines 389–399): “*FLUXCOM-X similarly incorporates MODIS and ERA5 as training features. We selected FLUXCOM rather than MODIS-based GPP to avoid algorithmic circularity in the GPP-climate relationship, and sensitivity analyses using methodologically independent GLDAS soil moisture confirm the stability of the dominant pathways. Nonetheless, we interpret coupling strengths primarily in terms of spatial contrasts and temporal trends rather than as evidence of complete observational independence. FLUXCOM-X operates at 0.5 ° resolution and is trained predominantly on flux towers in temperate forests of North America and Europe. This spatial bias may introduce greater uncertainty in tropical and boreal regions where training data are sparse. Our conclusions are therefore best interpreted at regional to continental scales, and results in under-sampled biomes warrant caution.*”

Response to Reviewer 1, Comment 3:

Comment2: * Figure 2 a and b is missing an x-axis label. Overall, the study addresses an important question and the dataset assembly is impressive. Resolving the Figure 2 / SEM inconsistency, acknowledging the FLUXCOM-X representativeness limitation, and correcting the figure labeling would strengthen the manuscript.

Response: We thank the reviewer for noting this oversight. The missing x-axis labels have been added to Figure 2a and 2b. We have also audited all remaining figures to

confirm that axis labels are complete and consistent.

Reviewer 2

General Response to Reviewer 2:

We thank the reviewer for the thorough evaluation, which has strengthened both the rigor and clarity of our manuscript. The comments addressed three main areas: positioning relative to existing literature on SM and VPD effects, data product selection and independence, and resilience quantification methods. In response, we revised the Introduction to clarify how our study extends prior work by testing whether resilience loss mediates the effects of atmospheric aridity on functional coordination. We conducted sensitivity analyses using GLDAS Noah soil moisture at four depth configurations, which confirm the robustness of our findings. We expanded the Methods and Limitations sections to address FLUXCOM representativeness, TerraClimate SM independence, and EPE formulation. We also revised the manuscript for clarity and readability. Point-by-point responses follow.

Response to Reviewer 2, Comment 1-2:

Comment 1: Generally, very clean and clear with the approach. But misses on the point that there exist studies that looks into the relative roles and casual pathways of atmospheric aridity (VPD) and plant-available soil water (SM) on vegetation growth/photosynthesis/carbon uptake. For instance, see: Causal approach:

Increased moisture stress and weakened resilience to aridity limit global greening. Science of The Total Environment, 1015, 181416. (2026). <https://doi.org/10.1016/j.scitotenv.2026.181416>

When and where soil dryness matters to ecosystem photosynthesis. Nat. Plants 11 (7), 1390–1400. (2025). <https://doi.org/10.1038/s41477-025-02024-7>.

Binning approach: Soil moisture dominates dryness stress on ecosystem production globally. Nat. Commun. 11 (1), 4892. (2020) <https://doi.org/10.1038/s41467-020-18631-1>. How does this study go beyond and

adds to the insights on SM-VPD distangling aspect? This should be very vividly presented.

Comment2: Also, these prior efforts in the same direction should be acknowledged in the build up to the storyline.

Response: We thank the reviewer for this insightful comment. We agree that the previous version did not clearly articulate how our study differs from and builds on recent work that has examined the relative roles of soil moisture (SM) and vapor pressure deficit (VPD) in constraining vegetation productivity and resilience.

In response, we substantially revised the relevant paragraph in the Introduction and incorporated the reviewer-recommended studies, including the binning-based analysis of Liu et al. (2020, Nature Communications), the recent Nature Plants study on when and where soil dryness matters to ecosystem photosynthesis, and the recent pathway-oriented study on moisture stress, resilience decline, and global greening.

We now explicitly acknowledge that these studies have advanced the field by accounting for SM–VPD covariation, identifying the dominant stressor for ecosystem production under different conditions, and linking moisture stress to resilience decline.

We also revised the text to make our distinct contribution more explicit. Specifically, previous studies have primarily focused on disentangling the relative effects of SM and VPD on ecosystem production limitation, or on documenting resilience decline under increasing aridity. Our study goes beyond this by evaluating whether resilience decline constitutes an additional pathway through which atmospheric aridity is associated with ecosystem functional decoupling. In other words, rather than asking only which stressor more strongly constrains productivity, we ask whether hydroclimatic stress weakens the coordination among GPP, WUE, and EPE directly through intensified physiological trade-offs, indirectly through resilience loss, or through both pathways.

We believe these revisions now clearly position our study relative to the existing SM–VPD disentangling literature and better highlight its conceptual novelty.

Lines 64-78: *"Rising VPD and declining SM may force forests into physiological trade-offs between water conservation and carbon gain, thereby altering the coordination among GPP, WUE, and EPE^{24,25}. Recent studies have substantially the improved understanding of the respective roles of SM and VPD by*

accounting for their covariation and identifying when each stressor constrains ecosystem production^{26,27}. Other studies have further shown that increasing aridity is associated with declining vegetation resilience at broad spatial scales^{28–30}. However, these advances have largely examined productivity limitation and resilience decline as parallel responses to hydroclimatic stress, rather than testing whether resilience loss mediates the effects of atmospheric aridity on ecosystem functional coordination. Atmospheric aridity may weaken this coordination directly by intensifying physiological trade-offs, or indirectly by eroding ecosystem resilience. Distinguishing these direct and resilience-mediated pathways is therefore necessary for understanding how forest functioning reorganizes under intensifying climate stress.”

Response to Reviewer 2, Comment 3:

Comment3: The first-order autoregressive coefficient (AR(1)) as a proxy for resilience is an important quantification and therefore should probably be presented in the manuscript rather than in the supplementary material. The first figure can be present AR1 and AR1-GPP correlation as presented in supplementary material for better clarity and understanding. This should also be explained for more clarity.

Response: We thank the reviewer for this suggestion. We agree that the AR(1) metric, as our primary quantification of resilience, warrants presentation in the main text rather than in the supplementary material. Following the reviewer's recommendation, we have moved the AR(1) spatial distribution and AR(1)-GPP correlation from supplementary figures into the reorganized Figure 1, which now includes: (a) the spatial distribution of mean AR(1), (b) the trend-based classification of GPP–resilience divergence, (c) pixel-level temporal correlations between AR(1) and GPP, and (d) the breakdown by forest type and climatic zone. The corresponding text has been revised to explain the AR(1) metric more clearly, including an explicit statement that higher AR(1) values indicate slower system recovery and thus lower resilience. This reorganization provides readers with a more intuitive understanding of how

resilience was quantified and how it varies spatially across global forests.

Response to Reviewer 2, Comment 4:

Comment4: Line: 83 to 85: “we found that 34.26% of global forests simultaneously experienced a significant increase in GPP and a decline in resilience from 2001 to 2021”

This statement should be further elaborated and the significance of this finding being vividly highlighted.

Response: We appreciate this comment and agree that the significance of this finding deserved greater emphasis. In the revised text, we have expanded the surrounding context by first describing the spatial distribution of baseline AR(1) (Fig. 1a), which provides the necessary background for interpreting subsequent trends. We then more vividly highlight the ecological implications: "This pattern indicates that productivity gains were often accompanied by reduced ecological stability. In effect, over one-third of the world's forests are trading resilience for productivity." (Line 97-100). This framing more effectively conveys the striking nature of our finding: that a substantial portion of global forests appear to be gaining productivity at the cost of their capacity to recover from disturbance.

Response to Reviewer 2, Comment 5:

Comment5: Line 89 to 92: Why is this mismatch of GPP gain and resilience loss more severe in non-intact forest than intact forest? This needs more explanation.

Response: We thank the reviewer for this question, which prompted us to clarify the mechanistic basis for the contrasting mismatch patterns between forest types.

The divergence arises from how productivity gains are achieved in each system. In non-intact forests, structural simplification both reduces functional redundancy and channels resources toward growth, so productivity gains are obtained at the expense of stability. This trade-off is a consequence of management and has no counterpart in

intact systems, where structural complexity is preserved and productivity gains do not require the loss of functional redundancy. Resilience can therefore be maintained as GPP increases, resulting in a less pronounced mismatch.

We have revised the Discussion to incorporate this explanation. The added text reads:

Lines324-327: *"This vulnerability coexists with sustained or even enhanced GPP because the structural simplification that erodes resilience simultaneously concentrates resources into growth. Non-intact forests thus gain productivity at the direct expense of stability, a trade-off imposed by management that has no counterpart in intact systems."*

Lines348-350: *"In intact systems, structural complexity is preserved, so productivity gains do not come at the expense of functional redundancy. This allows resilience to be maintained even as GPP increases."*

We are grateful for the reviewer's suggestion, which has strengthened the mechanistic clarity of this section.

Response to Reviewer 2, Comment 6:

Comment6: In the Fig.1 caption, AR1 should be defined. Always define the abbreviations at the first instance of their use and treat the abstract, figure captions and conclusion independent of the main article text in this regard.

Response: We thank the reviewer for this reminder. We have now defined AR(1) at its first occurrence in the Figure 1 caption (Lines113-115) as "AR(1), the first-order autoregressive coefficient, was used as a proxy for forest resilience; higher AR(1) values indicate slower system recovery and thus lower resilience" We have also checked all other figure captions and the abstract to ensure that abbreviations are defined independently of the main text.

Response to Reviewer 2, Comment 7:

Comment7: Fig S5 and S6 in supplementary material presents important results on GPP coupling with functional metrics in WUE and EPE and their changes and should be presented in the main manuscript for better clarity. This would enable better of the quantification presented.

Response: We thank the Reviewer for this suggestion. The core quantitative relationship between resilience decline and functional decoupling is presented in Fig. 1e–f ($R^2 = 0.37$ for GPP-WUE; $R^2 = 0.26$ for GPP-EPE), while the key summary statistics from Figs. S5–S6 (e.g., 61.70% of areas showing declining EPE, 76.18% showing rising WUE) are already reported in the Results text. We therefore retain these figures in the SI to balance conciseness with completeness, while ensuring readers can access the essential findings without consulting supplementary materials.

Response to Reviewer 2, Comment 8:

Comment8: Line 127 to 135: How about checking the results presented in 2 different scenarios: (i) VPD increase with constant SM and (ii) SM increase with constant VPD?

Else this can be mentioned as one of the limitations/future scope of the study in the Discussion.

Response: We thank the reviewer for this suggestion. To separate the individual effects of VPD and SM on coupling strength, we performed a binning analysis in which forest pixels were stratified into deciles based on either SM or VPD. Within each decile, we calculated Spearman correlations between coupling strength and the non-stratified climate variable. Only deciles with weak residual correlations between VPD and SM ($|r| < 0.15$) were retained to ensure adequate separation of the two drivers.

We have added the methodological description to the Supplementary Materials (Supplementary Methods 2). The results (Supplementary Table 2) show that VPD was

consistently positively correlated with GPP–WUE coupling strength across all valid SM deciles ($r = 0.28$ to 0.50 , $P < 0.001$), whereas correlations between VPD and GPP–EPE coupling were weak and inconsistent. Conversely, SM was consistently negatively correlated with GPP–WUE coupling strength across all valid VPD deciles ($r = -0.08$ to -0.50). These findings confirm that VPD and SM exert separable effects on functional coupling even after controlling for their covariation. VPD consistently strengthened GPP–WUE coupling whereas SM consistently weakened it; in contrast, VPD showed limited influence on GPP–EPE coupling. These patterns corroborate the distinct regulatory roles of atmospheric and soil water stress on functional coupling as reported in Figure 2.

Response to Reviewer 2, Comment 9:

Comment9: A common/overall SEM network diagram for all global forests maybe presented a broader general picture before presenting the biome-specific and forest type SEM network diagrams.

Response: We thank the reviewer for this suggestion. We have restructured the SEM results following a general-to-specific logic. We now first report a global SEM pooling all forest pixels, which identified VPD as the dominant driver of resilience loss ($\beta = +0.59$, $P < 0.05$). Region-specific SEMs then revealed consistent hydroclimatic effects on resilience across all climate zones and forest types. The pathway diagram for the global model has been added as Figure 3.

Response to Reviewer 2, Comment 10:

Comment10: Line 200: "forced increase in WUE" why so? Increased VPD? Needs more clarity.

Response: We thank the reviewer for this suggestion. We removed "forced" and clarified the mechanism. Elevated VPD induces stomatal closure, which reduces transpiration relative to photosynthesis and raises the GPP/ET ratio. We have revised the text to clarify this mechanism (Lines 239–242):

"...this occurs alongside a decline in EPE and an increase in WUE, driven by VPD-induced stomatal closure that reduces transpiration relative to photosynthesis^{21,25}. This interpretation is consistent with flux-tower observations showing that rising VPD reduces canopy conductance and decouples carbon uptake from transpiration²⁰."

Response to Reviewer 2, Comment 11

Comment11: Greening does not always reflect or translates in increased productivity and this is due to decline in the functional translation capacity (EPE) under SM drying and enhanced aridity of land and atmosphere. This can be mentioned to support the findings. See: Weakening of forest carbon stocks due to declining Ecosystem Photosynthetic Efficiency under the current and future climate change scenarios in India. Resources, Conservation and Recycling, 222, 108478. (2025). <https://doi.org/10.1016/j.resconrec.2025.108478>.

Response: We thank the Reviewer for this suggestion. Verma et al. (2025) demonstrated that declining Ecosystem Photosynthetic Efficiency under moisture stress weakens forest carbon stocks in India despite continued greening, providing regional evidence of drought-induced decoupling between vegetation greenness and carbon uptake.

We have added this reference (Ref. 19) in the Introduction (Line 58-60), alongside our existing citation supporting the functional decoupling hypothesis.

Response to Reviewer 2, Comment 12

Comment12: There is weakening of resilience against moisture stress (more demand than available supply for plants to utilise in the current climate change scenario).

Also, VPD is the major control and has causal relationship with photosynthesis across biomes and land cover types unlike SM. These can be mentioned to support the findings. See: Increased moisture stress and weakened resilience to aridity limit global greening. Science of The Total Environment, 1015, 181416. (2026). <https://doi.org/10.1016/j.scitotenv.2026.181416>

Response: We thank the Reviewer for bringing this work to our attention. Verma et al. (2026) showed that VPD exerts dominant causal control on photosynthesis across biomes and that ecosystems have lost resilience specifically to soil moisture deficits despite gaining resilience to atmospheric aridity. These findings support our emphasis on VPD as a primary driver of resilience loss and highlight the value of multi-dimensional resilience assessment.

We have incorporated this reference in the Introduction(Line 69-71): *"Other studies have further shown that increasing aridity is associated with declining vegetation resilience at broad spatial scales²⁸⁻³⁰."*

Limitations section (Lines 400-404), where we discuss future directions for integrating continuous and event-based resilience metrics: *"Our SEM framework was designed to test hypothesized pathway structures and partition direct from indirect effects, not to rank the relative importance of individual predictors or to establish causality in an interventionist sense. Machine learning approaches such as Random Forest combined with SHAP values are better suited to variable attribution^{19,28} and represent a complementary direction for future work."*

Response to Reviewer 2, Comment 13

Comment13: There is a shift from a temperature and energy to moisture controlled regime on global photosynthesis in response to the changing climate. Also, there is strengthened control of water availability in contrast to weakened control of temperature on global photosynthesis in recent decade. These can be mentioned to support the findings. See: Changing global vegetation-climate interactions constrain photosynthesis in the 21st century. Journal of Cleaner Production, 538,147402. (2026). <https://doi.org/10.1016/j.jclepro.2025.147402>

Response: We thank the Reviewer for this recommendation. Verma et al. (2026) documented a shift from temperature-controlled to moisture-controlled photosynthesis at the global scale, with water availability strengthening its influence over recent decades. This regime shift corroborates the increasing importance of atmospheric aridity identified in our study.

We have added this citation(ref.36) in the Discussion, immediately after our reference to Yuan et al. (2025), where it provides complementary evidence for the physiological costs imposed by rising atmospheric water demand.

Lines 248-251”*This interpretation complements recent findings by Yuan et al.³⁵, reinforcing the view that atmospheric constraints impose profound physiological costs that may compromise the long-term stability of the terrestrial carbon sink³⁶.*”

Response to Reviewer 2, Comment 14

Comment14: At times the manuscript with the use of words like “posits”, “insidious”, “bystander” and others sound like fabricated language largely with more “AI touch” and requires more “human touch” to make it more readable.

Response: We thank the reviewer for this feedback on writing style. We have carefully reviewed the manuscript and revised passages that contained overly elaborate or stylized language. Specifically, terms such as "posits," "insidious," and "bystander" have been replaced with more direct, conventional scientific language. We have also streamlined several sentences throughout the Introduction and Discussion to improve clarity and readability. The revised manuscript aims for a tone that is precise, measured, and consistent with standard scientific prose.

Response to Reviewer 2, Comment 15

Comment15: Estimation of relative controls based on machine learning approach like Random Forest can be employed to see the relative controls of VPD and SM on ecosystem functional metrics. This can be mentioned as one of the limitations/future scope of the study.

Response: We thank the Reviewer for this suggestion. We agree that Random Forest is effective for ranking predictor importance and offers a complementary perspective to pathway-based inference. We adopted SEM here specifically to test whether VPD effects on functional decoupling are mediated by resilience loss, a question of causal pathway structure rather than variable ranking. We have revised the Limitations section to clarify this rationale and to acknowledge RF-based attribution as a direction for future work.

Lines 400–404: *"Our SEM framework was designed to test hypothesized pathway structures and partition direct from indirect effects, not to rank the relative importance of individual predictors or to establish causality in an interventionist sense. Machine learning approaches such as Random Forest combined with SHAP*

values are better suited to variable attribution^{19,28} and represent a complementary direction for future work."

Response to Reviewer 2, Comment 16

Comment16: Line 355: “intensifying atmospheric aridity, specifically rising VPD”, VPD is a measure/proxy of atmospheric aridity. So, this sounds redundant and needs improvement.

Response: We thank the reviewer for catching this. Since VPD is the metric we use to quantify atmospheric aridity, the original phrasing was redundant. We have revised the sentence to: "Our results provide large-scale evidence that rising VPD erodes ecosystem resilience." See revised Conclusion (Line 421-422).

Response to Reviewer 2, Comment 17

Comment 17: The TerraClimate SM data is based on a "modified Thornthwaite-Mather" water balance model which employs a static reference land cover and does not account for vegetation dynamics. Thus, the SM data generated is largely a replica of the precipitation dataset in terms of the spatio-temporal distribution and variability.

Response: We thank the reviewer for raising this concern about soil moisture data independence. We conducted a sensitivity analysis using GLDAS Noah v2.1 soil moisture at four depth intervals (0-10, 0-40, 0-100, and 0-200 cm). Unlike TerraClimate, GLDAS employs a physically based land surface model that solves Richards' equation, providing a methodologically independent estimate of soil moisture.

Three findings emerged. First, VPD to AR(1) coefficients remained positive and significant across all GLDAS configurations, ranging from +0.19 to +0.53. These values are consistent with TerraClimate-based estimates (+0.20 to +0.37). Second, the enhanced vulnerability of non-intact forests was replicated under all products, with VPD effects 2.3 to 2.5 times greater than in intact forests. Third, variance inflation factors remained below 2.0 (mean 1.15), confirming that multicollinearity does not compromise our estimates.

We note that SM to AR(1) coefficients for intact forests became non-significant under GLDAS. This product-sensitivity of soil moisture effects, combined with the product-invariance of VPD effects, strengthens our conclusion that atmospheric aridity is the dominant driver of resilience loss. Soil moisture signals appear more dependent on model-specific assumptions, whereas VPD effects remain stable regardless of the soil moisture product used.

We have updated the Methods (Lines 472-478 and 548-552), Results (Lines 205–216), and Supplementary Table S3 accordingly.

Response to Reviewer 2, Comment 18

Reviewer Comment: The ecosystem resilience method based on the first-order autocorrelation coefficient (AR(1)) of the vegetation signal should be more clearly explained and detailed. Also, why was this approach adopted rather than the worst affected year approach of resilience estimation needs to be explained. See: Increased moisture stress and weakened resilience to aridity limit global greening. *Science of The Total Environment*, 1015, 181416. (2026). <https://doi.org/10.1016/j.scitotenv.2026.181416> Weakening of forest carbon stocks due to declining Ecosystem Photosynthetic Efficiency under the current and future climate change scenarios in India. *Resources, Conservation and Recycling*, 222, 108478. (2025). <https://doi.org/10.1016/j.resconrec.2025.108478>

Response: We thank the reviewer for this comment on methodological clarity and method selection.

Methodological explanation. We have expanded the Methods section (Lines 499–507) with additional details on AR(1)-based resilience quantification, including STL decomposition parameters and the mathematical formulation of the autoregressive model.

Rationale for method selection. We have added a paragraph in the Limitations section (Lines 405–412) clarifying the distinction between AR(1) and event-based resilience metrics. AR(1) quantifies how slowly ecosystems return to equilibrium after perturbations, with higher values indicating lower resilience. The worst-affected year approach assesses resilience as the ratio of ecosystem performance during extreme years to the long-term mean, capturing resistance to acute stress. These two metrics address complementary aspects of resilience and we have cited both recommended studies.

Response to Reviewer 2, Comment 19

Comment: Why does the study prefer FLUXCOM GPP and ET over MODIS GPP and ET or other remote sensing/ model based data that FLUXCOM GPP does not have enough training data points for tropical and sub-tropical regions in Africa and South Asia region?

Response: We thank the reviewer for this important comment. We agree that the choice of flux products should be explicitly justified, especially given the sparse flux-tower coverage in parts of tropical and subtropical Africa and South Asia.

Our choice of FLUXCOM is primarily motivated by the objective of this study, which is to investigate large-scale climate controls on ecosystem carbon and water fluxes. MODIS GPP and ET are valuable products, but their retrieval frameworks explicitly incorporate meteorological and physiological constraints. In particular, MOD17 GPP calculates light-use efficiency as $LUE = LUE_{max} \times f(T_{min}) \times f(VPD)$, where the VPD attenuation function is parameterized by biome-specific thresholds (Running et al., 2015). Similarly, MOD16 ET incorporates prescribed surface conductance constraints that respond to meteorological forcing. Therefore, when these products are used to quantify the effects of climatic variables such as VPD or drought on GPP/ET, part of the inferred relationship may arise from structural dependencies embedded in the product algorithms rather than from independent observational constraints.

By contrast, FLUXCOM is a flux upscaling product trained against eddy-covariance tower measurements through machine learning without imposing prescribed physiological response functions. While FLUXCOM is not without limitations, it is less directly tied to prescribed biome-specific stress parameterizations of the kind used in MODIS-based algorithms. We acknowledge that FLUXCOM also uses meteorological variables as predictor inputs during upscaling. However, the key distinction is that FLUXCOM does not prescribe how fluxes should respond to these variables; rather, the relationships are learned empirically from tower observations. This is fundamentally different from algorithm-based products where stress responses are explicitly parameterized a priori. For our study, this makes FLUXCOM more suitable for assessing climate–flux relationships while reducing the risk of circularity in the interpretation.

We fully acknowledge, however, that FLUXCOM uncertainty can be larger in regions with sparse tower coverage, particularly in tropical and subtropical Africa and South Asia. We now explicitly state this limitation in the revised manuscript and note that the results in these regions should be interpreted with appropriate caution. Thus, our use of FLUXCOM does not imply that it is universally superior to MODIS or other products; rather, it reflects a dataset choice that is better aligned with the specific objective of this study.

We have revised the manuscript to clarify the rationale for using FLUXCOM GPP and ET and to explicitly acknowledge the associated uncertainties.(Line 451-458)

Response to Reviewer 2, Comment 20

Comment: Additionally, FLUXCOM (0.5°) is spatially way coarser than MODIS (500m). Thus, this choice should be very clearly and strongly justified given the limitations of FLUXCOM data for the tropical and sub-tropical region and coarse resolution.

Response: We thank the reviewer for this important comment.

FLUXCOM was selected over finer-resolution products such as MODIS GPP because of a methodological consideration central to our research question. MODIS GPP algorithms calculate carbon uptake using a light-use efficiency model in which VPD and temperature directly modulate photosynthetic rates (Running et al., 2004). Using such a product to examine how VPD influences ecosystem fluxes would risk circular reasoning, as the climate signal is already embedded in the flux estimate. FLUXCOM derives fluxes empirically from eddy covariance observations without imposing prescribed stress response functions, thereby avoiding this structural coupling between predictors and response variables.

We acknowledge that FLUXCOM has coarser spatial resolution and greater uncertainty in tropical regions where training data are sparse. However, our findings do not depend on these high-uncertainty areas. First, we constructed separate SEM models for each of four climate zones (Fig. 3b–e), and the dominant effect of VPD on resilience loss was confirmed independently in temperate and boreal forests, where eddy covariance coverage is substantially denser. Second, the productivity–resilience divergence is concentrated in boreal forests, which account for 55% of the affected

area, whereas tropical forests contribute only 26% (Fig. 1d). Third, sensitivity analyses using an alternative soil moisture product (GLDAS Noah at four depth configurations) reproduced the core results (Supplementary Table S3). Together, these findings demonstrate that our conclusions are robust across biomes and are not driven by regions with limited observational constraints.

We have revised the Methods to state our rationale for selecting FLUXCOM and expanded the Discussion to acknowledge these spatial limitations explicitly. Revised manuscript:

Methods, lines 451–458: *“Ecosystem-Scale Fluxes: Ecosystem carbon and water fluxes were obtained from the FLUXCOM-X dataset (0.5 ° native resolution), which provides global gridded Gross Primary Productivity (GPP) and Evapotranspiration (ET) through machine-learning-based upscaling of eddy-covariance measurements from 294 flux towers. The upscaling framework incorporates ERA5 meteorological reanalysis and MODIS remote sensing variables as predictive features, but does not impose prescribed physiological response functions; climate-flux relationships are instead learned empirically from tower observations⁸⁶.”*

Discussion, lines 389-399: *“FLUXCOM-X similarly incorporates MODIS and ERA5 as training features. We selected FLUXCOM rather than MODIS-based GPP to avoid algorithmic circularity in the GPP-climate relationship, and sensitivity analyses using methodologically independent GLDAS soil moisture confirm the stability of the dominant pathways. Nonetheless, we interpret coupling strengths primarily in terms of spatial contrasts and temporal trends rather than as evidence of complete observational independence. FLUXCOM-X operates at 0.5 ° resolution and is trained predominantly on flux towers in temperate forests of North America and Europe. This spatial bias may introduce greater uncertainty in tropical and boreal regions where training data are sparse. Our conclusions are therefore best interpreted at regional to continental scales, and results in under-sampled biomes warrant caution.”*

Response to Reviewer 2, Comment 21

Comment: EPE estimation as SIF/LAI ratio is fine general or broad scale vegetation aspects as in some previous global studies or studies based on China.

However, SIF being a weak signal, at times does not accurately presents the leaf scale photosynthesised carbon assimilation by vegetation particularly in high biomass regions like forests. See: Strong constraint on modelled global carbon uptake using solar-induced chlorophyll fluorescence data. *Sci. Rep.* 8 (1), 1973. (2018) <https://doi.org/10.1038/s41598-018-20024-w>. Structural complexity biases vegetation greenness measures. *Nat. Ecol. Evol.* 7 (11), 1790–1798. <https://doi.org/10.1038/s41559-2023-02187-6>.

So, it might be a better approach to estimate EPE as a ratio of carbon capture (GPP) or uptake (NPP) to greenness (LAI) for the forest ecosystems. See: Weakening of forest carbon stocks due to declining Ecosystem Photosynthetic Efficiency under the current and future climate change scenarios in India. *Resources, Conservation and Recycling*, 222, 108478. (2025). <https://doi.org/10.1016/j.resconrec.2025.108478>

This aspect could be either approached or mentioned as a limitation of the study.

Response: We thank the reviewer for this thoughtful comment and the relevant literature. The reviewer correctly notes that SIF signals can be attenuated by canopy structural complexity, particularly in high-biomass forests.

We acknowledge this limitation and have added a discussion in the revised manuscript (Lines 412–417). However, we respectfully note that adopting GPP/LAI as an alternative EPE formulation would introduce a methodological complication: since WUE is defined as GPP/ET, both metrics would share GPP as a common numerator, potentially generating spurious correlations in our coupling analysis. This statistical non-independence would confound our interpretation of the functional decoupling signal.

Additionally, SIF and GPP capture complementary aspects of photosynthetic function. SIF provides a near-instantaneous proxy for electron transport, making it sensitive to rapid physiological adjustments under stress that precede detectable changes in cumulative carbon assimilation. For our objective of detecting early-stage functional decoupling, this instantaneous sensitivity is advantageous.

We have noted in the revised Limitations that EPE estimates in structurally complex, high-biomass canopies should be interpreted with appropriate caution, and that future studies integrating ground-based measurements would help validate these satellite-derived signals.

Lines 412–417:” *Finally, SIF signals can be attenuated by canopy structural complexity in high-biomass forests, potentially affecting EPE estimates in dense tropical canopies. We adopted SIF/LAI rather than GPP/LAI to avoid spurious correlations arising from a shared GPP numerator in both WUE and EPE. Validation with ground-based fluorescence measurements would strengthen confidence in these satellite-derived estimates.*”

Review3:

General Response to Reviewer 3:

We thank the reviewer for the constructive comments, which improved the logical structure, methodological transparency, and completeness of our manuscript. In response, we added quantitative citations supporting key claims in the Introduction, improved paragraph transitions, and provided additional details on the SIF and IFL datasets. To address the reviewer's concern about potential seasonal confounding, we conducted a sensitivity analysis in which all coupling metrics were recalculated from STL residuals and SEM models were re-fitted; the principal findings were fully replicated. We also clarified all spatial and temporal resolutions in the Methods and added a supplementary figure presenting temporal trends of key variables. Point-by-point responses follow.

Response to Reviewer 3, Comment 1:

Comment 1: Line 31-32: The statement “while gross primary productivity (GPP) has increased...simultaneously declined”, appears to be qualitative. Is there quantitative evidence or specific references supporting this claim? Please clarify or provide appropriate citations.

Response: We thank the reviewer for raising this point. The original statement is

grounded in quantitative findings from Forzieri et al. (2022, Nature), who demonstrated that approximately 70% of global forests exhibit positive GPP trends, while nearly half of these areas simultaneously show declining resilience, as indicated by increasing temporal autocorrelation of vegetation indices. We agree that our original phrasing did not make this quantitative basis explicit. We have therefore revised the sentence to incorporate these figures directly.

Lines 31–34 : *"Gross primary productivity (GPP) has increased across approximately 70% of global forests, but ecosystem resilience, the capacity to withstand and recover from disturbances, has simultaneously declined in nearly half of these productive areas."*

This revision clarifies the empirical foundation of our claim.

Response to Reviewer 3, Comment 2:

Comment 2: Line 41-46: The sentence “Terrestrial carbon and water cycles ... and light harvesting (Ecosystem Photosynthetic Efficiency, EPE)”, appears somewhat abrupt. The logical connection with the preceding and following text is not sufficiently clear. Please improve the flow and coherence.

Response: We thank the reviewer for this suggestion. We agree that the original transition between the productivity-resilience paradox and the discussion of physiological mechanisms was abrupt.

We have added a bridging sentence at the beginning of the second paragraph (Line 41-42): "This paradox may originate in the physiological coordination that sustains forest function." This sentence explicitly links the paradox described in the first paragraph to the carbon-water coupling mechanisms that follow, improving the logical flow.

Response to Reviewer 3, Comment 3:

Comment 3: Line 46-48: The sentence “To explain this productivity-resilience divergence, we advance...”, also appears abrupt in its current position. Consider improving the transition to better integrate it into the narrative.

Response: We thank the reviewer for this observation. We agree that the transition

to our hypothesis needed improvement. In addition to inserting the transitional sentence, we restructured the entire paragraph (Lines 41–60) to improve logical flow.

The revised paragraph opens by proposing that the productivity-resilience paradox may originate in the physiological coordination sustaining forest function. We then provide mechanistic background on carbon-water coupling through stomatal regulation. A new transitional sentence, "The coexistence of rising productivity and declining resilience may signal a broader disruption of this internal functional coordination," bridges this background to our functional decoupling hypothesis. The hypothesis is then grounded in critical slowing down theory, which predicts that systems approaching instability exhibit declining recovery rates before functional collapse. We conclude with recent empirical observations of drought-induced decoupling between vegetation greenness and carbon uptake, providing independent support for our interpretation.

This structure guides readers from the observed phenomenon through mechanistic reasoning to our central hypothesis and its empirical basis.

Lines 41–60: *“This paradox may originate in the physiological coordination that sustains forest function. Terrestrial carbon and water cycles are intrinsically coupled through plant physiology, with photosynthesis assimilating atmospheric CO₂ while transpiration releases water⁹⁻¹². The functional integrity of forests hinges on the efficient coordination among carbon fixation, water regulation (Ecosystem Water Use Efficiency, WUE), and light harvesting (Ecosystem Photosynthetic Efficiency, EPE)^{13,14}. The coexistence of rising productivity and declining resilience may signal a broader disruption of this internal functional coordination. To explain this productivity-resilience divergence, we advance a functional decoupling hypothesis grounded in ecological resilience theory. Critical slowing down theory predicts that systems approaching instability exhibit declining recovery rates before functional collapse^{15,16}. Applying this principle to forest ecosystems, we hypothesize that chronic environmental stress progressively erodes ecosystem resilience, which in turn degrades the coordination among GPP, WUE, and EPE. Under this framework, functional decoupling is a downstream consequence of resilience loss, allowing*

forests to temporarily sustain productivity growth while their functional coordination deteriorates^{4,16,17}. Recent observations of drought-induced decoupling between vegetation greenness and carbon uptake provide empirical support for this interpretation^{18,19}.”

Response to Reviewer 3, Comment 4:

Comment4 : Line 50-52: After “Recent studies”, only one reference (Ref. 16) is cited. This seems insufficient and inconsistent with the plural form. Please include additional references to better support this statement.

Response: We thank the reviewer for this careful reading. We have moved this sentence to the end of the paragraph and added additional references. The revised text (Lines 59-61) now cites recent observations of drought-induced decoupling between vegetation greenness and carbon uptake (Refs. 18, 19), consistent with the plural form.

Response to Reviewer 3, Comment 5:

Comment5: Figure 1: It presents the spatial patterns of AR(1) and GPP changes. It would be helpful to include the temporal trends of key variables such as VPD, AR(1), GPP, and coupling strength to provide a more comprehensive understanding of their dynamics.

Response: We thank the reviewer for this suggestion. We have added a new supplementary figure (Supplementary Fig. 3) presenting the temporal dynamics of VPD, AR(1), GPP, and coupling strength. Together, these panels complement the spatial patterns in Figure 1 and provide a more comprehensive view of how key variables have evolved. A reference to this figure has been added to the main text (Line 109-110).

Response to Reviewer 3, Comment 6:

Comment6: Line 216: The authors propose a “Stress-Resilience-Decoupling theoretical framework”. Based on the discussion, the duration of atmospheric drought seems to play an important role in determining whether forests follow a direct or resilience-mediated pathway. It would be beneficial to include a comparison under

different drought-duration scenarios to better illustrate and support this framework.

Response: We appreciate this suggestion. Our resilience metric is calculated using a 60-month sliding window, which integrates ecosystem dynamics over multi-year timescales. This design captures cumulative responses to sustained atmospheric aridity but does not, by construction, permit separation of short-term drought pulses from prolonged dry conditions within a given window. Distinguishing discrete drought events by duration within the sliding window would require an event-based analytical framework rather than the temporally aggregated approach employed here. We have revised the Discussion (Lines 405-412) to acknowledge this methodological boundary and to identify event-scale drought partitioning as a direction for future research.

Lines 405-412: *"The AR(1)-based resilience metric quantifies recovery dynamics within a 60-month sliding window. This temporal aggregation detects gradual erosion of recovery capacity but cannot distinguish discrete acute drought events from chronic low-intensity aridity within a given window. AR(1) captures one dimension of resilience^{83,84}, namely recovery rate, while alternative frameworks assess performance during extreme years. Integrating event-scale drought classification with both continuous and event-based resilience metrics would yield a more complete picture of ecosystem vulnerability under different drought-duration scenarios^{19,28}."*

Response to Reviewer 3, Comment 7:

Comment 7: SIF data: OCO-2 SIF observations are footprint-based. How were these data processed to obtain spatially continuous products? Please provide a brief description. In addition, if the used SIF product incorporates MODIS data, there may be overlap with other datasets (e.g., LAI, GPP), which could introduce a potential limitation that should be acknowledged.

Response: Thank you for this helpful comment. We agree that both the construction of the SIF dataset and its potential overlap with other remote-sensing products should be clarified.

In this study, we used the GOSIF product rather than raw OCO-2 footprint observations. GOSIF is a global 0.05°, spatially continuous SIF dataset reconstructed from discrete OCO-2 SIF soundings using a data-driven model constrained by MODIS vegetation information and meteorological reanalysis variables. This

reconstruction was developed to overcome the sparse spatial sampling of footprint-based OCO-2 observations. We have now added a brief description of this processing workflow in the Methods section and clarified that the original 8-day product was aggregated to monthly resolution for use in this study.

We also agree that because GOSIF incorporates MODIS-based vegetation information, some degree of shared input information exists between GOSIF and other variables used in this study, particularly LAI and, more broadly, satellite-informed GPP products. We have therefore added an explicit limitation statement in the revised manuscript to acknowledge that such overlap may introduce partial non-independence among variables and may influence the magnitude of estimated coupling strengths. At the same time, we note that FLUXCOM GPP, rather than MODIS GPP, was used in our analysis to reduce direct algorithmic circularity in the GPP–SIF relationship.

These revisions have been incorporated into the Methods (Line 459-468) and Limitations (Line 385-394) sections of the manuscript.

Response to Reviewer 3, Comment 8:

Comment8: Intact Forest Landscapes (IFL) dataset: This dataset is used to distinguish forest integrity. Please clarify how this dataset is derived from satellite observations, and justify why it is suitable for representing structural complexity and anthropogenic disturbance.

Response: We thank the reviewer for this comment. We have revised the Methods and Limitations sections to clarify the derivation and scope of the IFL dataset.

The IFL product is a globally consistent remote-sensing dataset developed primarily from Landsat imagery to delineate large forest landscapes with no detected signs of human activity or fragmentation. The mapping excludes areas affected by infrastructure, logging, agriculture, and mining, and applies minimum size and width criteria for intact patches.

We use IFL status as an indicator of landscape-scale forest integrity and anthropogenic disturbance, not as a direct measure of canopy structural complexity. IFL distinguishes forests embedded within large, contiguous landscapes from those exposed to human modification and fragmentation. This landscape-level contrast is associated with differences in ecological buffering capacity. We have clarified this

distinction in the revised Methods (Lines 481-492) and acknowledged the measurement scope in the Limitations (Lines 379–385).

Response to Reviewer 3, Comment 9:

Comment9: Data processing: Were LAI, SIF, GPP, and other variables deseasonalized prior to analysis? In addition, please clarify the spatial and temporal resolution used in the analysis.

Response: We thank the reviewer for this important methodological question.

Deseasonalization. In our primary analysis, the resilience metric (AR(1)) was computed from STL residuals of monthly kNDVI, which removes both seasonal and trend components prior to autoregressive fitting. For functional coupling strength, we calculated Pearson correlations from monthly time series. To address the reviewer's concern about potential seasonal confounding, we conducted a sensitivity analysis in which coupling was recalculated from STL monthly residuals and all SEM models were re-fitted.

The sensitivity analysis confirms that our principal findings are robust. The VPD to AR(1) pathway was replicated across all major climate zones (path coefficients: +0.20 to +0.37, all $P < 0.001$). The resilience-mediated pathway was preserved and in temperate forests strengthened (AR(1) to GPP–WUE coupling: +0.37, $P < 0.001$). Chi-square statistics are sensitive to sample size; elevated χ^2/df values in strata with $n > 1,000$ reflect this sensitivity rather than model misspecification. Incremental fit indices ($\text{CFI} \geq 0.94$, $\text{RMSEA} \leq 0.07$) confirm acceptable model fit in these strata. In the Arid zone ($n = 73$), the small sample size produced a near-saturated model; fit indices are unreliable and path coefficients should be interpreted with caution. These results are reported in Supplementary Methods 3 and Supplementary Table 4.

Spatial and temporal resolution. We have revised the Methods to explicitly state all resolutions. All datasets were harmonized to 0.5° spatial resolution and monthly temporal resolution over 2001–2021.

Reviewer 1

General Response to Reviewer 1:

Thank you for your rigorous review. We fully accept your assessment that our previous revision addressed only the local inconsistency in the Figure 2 description without resolving the broader disconnect between the abstract and the quantitative evidence. In hindsight, we did not grasp the full scope of your concern during the first round, and we apologize for the incomplete response. Your detailed feedback on this point has been invaluable and has led to a substantially more accurate manuscript. We have now conducted a comprehensive revision across the title, abstract, introduction, results, discussion, figure captions, and conclusion to bring the entire narrative into alignment with our data. We detail these changes below.

Response to Reviewer 1, Comment 1:

Comment1: The revised Figure 2 text is now more careful: it says "GPP-WUE coupling was jointly controlled by VPD and SM, with coupling declining along the SM gradient most notably under moderate VPD." This no longer directly contradicts the SEM, because the decline is now attributed to the SM gradient rather than VPD per se.

However, the SEM results are unchanged and still show VPD strengthens GPP-WUE coupling in tropical (+0.44) and boreal (+0.43) forests. The new binning analysis the authors conducted in response to Reviewer 2 (Comment 8) actually makes this even clearer: "VPD was consistently positively correlated with GPP-WUE coupling strength across all valid SM deciles ($r = 0.28$ to 0.50 , $P < 0.001$)." So their own supplementary sensitivity analysis confirms that VPD strengthens, not weakens, GPP-WUE coupling after controlling for SM covariation.

Yet the revised abstract still reads: "sustained VPD stress erodes forest resilience, which in turn weakens coordination among carbon fixation, water use efficiency, and photosynthetic efficiency." This blanket claim that VPD weakens coordination involving WUE is not supported by the authors' own SEM or binning results — it is

only true for the GPP-EPE component in some climate zones, and only via the indirect (resilience-mediated) pathway. For the GPP-WUE component, VPD's direct effect is consistently positive (strengthening) across nearly all strata.

The authors appear to have fixed the local inconsistency in the Figure 2 text while leaving the broader narrative inconsistency between the abstract/Discussion and the quantitative evidence untouched. The axis-transposition explanation accounts for why the original Figure 2 description was wrong, but it does not account for why the abstract still claims VPD weakens carbon-water coordination when every quantitative result in the paper says VPD strengthens GPP-WUE coupling.

Response: We fully accept this criticism. Our previous abstract contained a blanket claim that VPD weakens coordination among all three functional dimensions. As you correctly noted, our SEM results show that VPD's direct effect on GPP-WUE coupling is positive in tropical (+0.44), boreal (+0.43), and non-intact forests (+0.10), and our binning analysis confirms this across all valid soil moisture deciles ($r = 0.28$ to 0.50 , $P < 0.001$). That claim was therefore inaccurate. In the first revision, we corrected the Figure 2 description but failed to propagate the correction through the rest of the manuscript. We have now done so comprehensively.

The revision rests on three linked changes.

First, we now explicitly distinguish two functional dimensions throughout the manuscript. VPD weakens GPP-EPE coupling through a resilience-mediated pathway (significant in boreal forests: $AR(1)$ to $GPP-EPE = -0.16$, $P < 0.05$), while VPD directly strengthens GPP-WUE statistical covariation in most strata.

Second, we provide a mechanistic interpretation for the positive VPD effect on GPP-WUE coupling. Under elevated VPD, stomatal closure suppresses transpiration and compresses its variability. Because WUE is defined as GPP/ET , reduced ET variability makes WUE track GPP more closely, producing tighter statistical covariation that reflects atmospheric constraint rather than improved physiological coordination. We note in both the Results and the Discussion sections that the ratio definition of WUE requires interpretive caution when evaluating this coupling.

Third, we address the apparent tension between the negative cross-regional

relationship shown in Fig. 1e (faster resilience loss correlates with weaker GPP-WUE coupling) and the positive direct VPD to GPP-WUE path coefficients identified by SEM. These patterns are not contradictory. The SEM decomposes total effects into direct and indirect components. While VPD directly strengthens GPP-WUE covariation through stomatal constraint, it also erodes resilience, and resilience loss can weaken GPP-WUE coupling through an indirect pathway. Fig. 1e captures the aggregate net relationship across regions where these two opposing effects combine in different proportions depending on climate zone and forest type. We now explain this explicitly in the Discussion.

To reflect this revised understanding, we changed the title from "functional decoupling" to "functional reorganization" and renamed the central theoretical framework from "Stress-Resilience-Decoupling" to "Stress-Resilience-Reorganization." The term "decoupling" implies a uniform weakening of all coupling dimensions, which is contradicted by the positive VPD to GPP-WUE path coefficients. "Reorganization" accurately captures the heterogeneous pattern: one coupling dimension weakens (GPP-EPE) while another is reshaped by atmospheric constraint (GPP-WUE).

No underlying data, SEM model specifications, or quantitative results have been altered. All changes are confined to the textual narrative.

Changes in Manuscript:

We provide below the key passages that have been revised, organized by manuscript section. All quotations are taken verbatim from the revised manuscript.

1. Title :

The title has been changed from "Atmospheric aridity drives functional decoupling and resilience loss in global forests" to:

"Atmospheric aridity drives functional reorganization and resilience loss in global forests"

"Reorganization" accurately captures the multi-directional changes in functional

coupling (weakening of GPP-EPE, reshaping of GPP-WUE) rather than implying uniform decoupling.

2. Abstract:

The previous abstract stated: "sustained VPD stress erodes forest resilience, which in turn weakens coordination among carbon fixation, water use efficiency, and photosynthetic efficiency."

This blanket claim has been replaced with differentiated statements:

"Global forests are gaining productivity while losing resilience, yet the mechanisms underlying this divergence remain unclear. Here we show, using multi-source remote sensing data spanning 2001-2021, that over one-third of global forests simultaneously gain gross primary productivity and lose resilience, linked to shifts in ecosystem functional coupling. Rising vapour pressure deficit was the primary driver of resilience loss. This resilience erosion weakened the coupling between gross primary productivity and ecosystem photosynthetic efficiency in boreal forests. By contrast, vapour pressure deficit directly strengthened gross primary productivity-water use efficiency covariation in tropical and boreal forests. This tighter coupling reflects stomatal constraint on transpiration variability rather than improved carbon-water coordination. In intact forests, vapour pressure deficit instead weakened this coupling. Human-disturbed forests were twice as sensitive to resilience loss as intact forests, indicating that structural simplification disproportionately amplifies climate-driven vulnerability to atmospheric aridity. These findings call for integrating resilience and functional coupling into forest monitoring to safeguard carbon sink stability."

3. Introduction:

The hypothesis name has been changed from "functional decoupling hypothesis" to "functional-reorganization hypothesis," and we added an a priori expectation that the carbon-water and carbon-light dimensions respond through distinct mechanisms:

"Applying this principle to forest ecosystems, we hypothesize that chronic environmental stress reorganizes the functional coupling among carbon fixation, WUE, and EPE through two potentially distinct pathways: indirectly, by progressively

eroding ecosystem resilience, and directly, through physiological stress responses. Because the carbon-water and carbon-light dimensions are governed by distinct physiological processes, namely stomatal regulation of coupled CO₂ and water fluxes and biochemical regulation of photosynthetic capacity, we expect these two dimensions to respond via distinct mechanisms under intensifying hydroclimatic stress. Under this framework, functional reorganization may arise both as a downstream consequence of resilience loss and as a direct response to intensifying atmospheric demand. Forests may temporarily sustain productivity growth even as the coordination among these processes is differentially altered."

4. Results :

We added an interpretive caveat immediately after reporting the positive VPD-to-GPP-WUE path coefficients:

"These positive coefficients indicate stronger statistical covariation between GPP and WUE, not necessarily improved physiological coordination. Because WUE is defined as GPP/ET, stomatal limitation that constrains ET variability under high VPD can mechanically tighten the GPP-WUE correlation."

This caveat is placed immediately after the SEM coefficients, preventing misinterpretation at the point of first encounter.

5. Figure 2 caption:

The caption now reads:

"Stronger positive values indicate tighter statistical covariation with GPP but do not necessarily reflect genuine physiological coordination; interpretation requires joint consideration of EPE and WUE trends."

6. Discussion:

The Discussion has been substantially rewritten. Because the changes are extensive, we summarize the logical architecture here, with key passages quoted verbatim.

The opening paragraph introduces the productivity-resilience divergence and frames functional reorganization as comprising two distinct components

(GPP-EPE weakening and GPP-WUE reshaping), directly addressing the Reviewer's core concern that these dimensions cannot be described with a single "weakening" narrative:

"We identified a productivity-resilience divergence affecting approximately 34% of global forests, where rising GPP co-occurs with declining resilience. This prevalence underscores the limitations of carbon uptake as a sole indicator of ecosystem health and points to a growing mismatch between short-term productivity and long-term stability. We propose that this divergence arises from a mechanistic cascade in which resilience erosion progressively decouples carbon assimilation from photosynthetic efficiency (GPP-EPE), while the coupling between carbon and water fluxes (GPP-WUE) becomes increasingly shaped by atmospheric demand in ways that conflate stress-driven covariation with physiological coordination."

The Stress-Resilience-Reorganization framework is then formalized with two mechanistically distinct pathways:

"This reorganization, expressed as a progressive decoupling of GPP from EPE alongside stress-constrained GPP-WUE covariation, is not a uniform passive response to stress but arises through two mechanistically distinct processes: resilience erosion weakens the coordination between carbon fixation and photosynthetic efficiency, while rising atmospheric demand independently reshapes carbon-water covariation through stomatal constraint. We formalize these dynamics in a Stress-Resilience-Reorganization framework comprising two context-dependent pathways."

The resilience-mediated pathway, documented with boreal-forest SEM:

"The resilience-mediated pathway operates more gradually in temperate and non-intact forests where resources are less acutely limiting. Chronic VPD elevation does not immediately disrupt functional synergy, but progressively erodes intrinsic stability, as reflected in rising AR(1). This critical slowing down, in which forests require longer to recover from perturbations, eventually compromises the regulatory

network coordinating carbon-light-energy exchange and weakens GPP-EPE coupling. SEM results for boreal forests exemplify this pathway: VPD drives resilience loss (path coefficient = +0.20), which in turn weakens GPP-EPE coupling (path coefficient = -0.16; $P < 0.05$). This indirect mechanism explains how forests can maintain high productivity even as their core functional integrity declines."

A dedicated passage addresses the positive VPD to GPP-WUE effect and reconciles it with Fig. 1e :

"Regardless of pathway, functional reorganization produces a seemingly contradictory physiological pattern of rising WUE alongside declining EPE. The positive association between VPD and GPP-WUE coupling should not be interpreted as improved carbon-water regulation. Under elevated VPD, stomatal closure suppresses transpiration and compresses its variability. Because WUE equals GPP/ET , reduced ET variability causes WUE to track GPP more closely, producing tight covariation shaped by atmospheric demand rather than by physiological coordination. This mechanism reconciles the positive direct VPD effect in our SEM and binning analyses with the negative aggregate cross-regional relationship in Fig. 1e, where areas with faster resilience loss tend to exhibit weaker GPP-WUE coupling because direct and indirect effects combine differently across climate zones and forest types."

"The co-occurrence of rising WUE and declining EPE confirms that tighter GPP-WUE covariation reflects tightening water constraints rather than adaptation to aridity. Because the ratio definition of WUE entangles physiological regulation with mechanical compression of ET variability, GPP-WUE coupling alone cannot reliably distinguish stress-constrained covariation from coordination gains. We therefore argue that the joint trajectory of GPP-EPE and GPP-WUE coupling provides a more mechanistically informative indicator of ecosystem vulnerability than AR(1) alone. AR(1) captures the statistical signature of critical slowing down but cannot identify which regulatory processes are failing or how instability propagates through the system. Monitoring functional coupling reveals the specific physiological shifts underlying resilience loss: AR(1) detects that stability is declining, while shifts in

functional coupling reveal why."

The intact-forest mechanism, including the negative VPD to GPP-WUE coefficient that differentiates intact from non-intact systems:

"Intact forests buffer stress through a fundamentally different mechanism. Multi-layered canopies, diverse age structures, and species mixtures create functional redundancy that enables varied physiological responses rather than uniform stomatal closure. The negative VPD effect on GPP-WUE coupling in intact systems (path coefficient = -0.54) is consistent with heterogeneous physiological responses across a structurally complex canopy, distinct from the constrained covariation observed in simplified stands. Because structural complexity is preserved, productivity gains do not compromise functional redundancy, and resilience can be maintained even as GPP increases. Under chronic stress, however, gradual resilience erosion can ultimately undermine the structural complexity that initially conferred stability. Non-intact forests, lacking functional redundancy, are inherently predisposed to the resilience-mediated pathway, whereas intact forests resist through functional adjustments and exhibit systemic resilience loss only when their structural complexity is chronically eroded."

7. Conclusion :

The Conclusion now differentiates the two coupling dimensions and provides the interpretive key:

"Our study shows that the concurrent rise in forest carbon uptake and decline in resilience reflects a reorganization of ecosystem functioning. Rising VPD was the dominant driver of resilience loss. This resilience loss was linked with weaker GPP-EPE coupling, most clearly in boreal forests. GPP-WUE followed a different pattern: VPD directly strengthened this coupling in tropical and boreal forests, but weakened it in intact forests. We interpret the stronger GPP-WUE correlation as a sign of tightening water limitation rather than enhanced carbon-water coordination."

This interpretation is supported by the coexistence of rising WUE and declining EPE, which indicates increasing water stress rather than improved physiological performance. Non-intact forests lost resilience more rapidly under rising VPD than intact forests, exposing high-yield but high-risk landscapes shaped by disturbance and fragmentation. Forest management should therefore track resilience and functional coupling alongside carbon uptake to identify emerging vulnerabilities and support the long-term durability of forest carbon sinks."

We believe these changes, applied consistently across the title, abstract, introduction, results, discussion, figure captions, and conclusion, fully resolve the narrative inconsistency you identified. We are grateful for your careful reading, which has made the manuscript more precise and more faithful to our data.

Reviewer 2

We thank the reviewer for the time and effort invested in evaluating our manuscript.

Reviewer3

We thank the reviewer for the time and effort invested in evaluating our manuscript.